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Investigating the Impact of Coal Bottom Ash on the Mechanical Performance of Self-Compacting Concrete Bricks

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Abstract
This study investigates the impact of coal bottom ash (CBA) on the mechanical properties of self-compacting concrete bricks (SCCB) through experimental analysis. The primary aim is to determine how the partial replacement of fine aggregates with CBA affects critical mechanical characteristics. Experimental tests encompassed compressive strength, density, Young's Modulus, and Poisson's Ratio using CBA substitutions ranging from 10% to 30%. Results indicated that as CBA content increased, concrete density decreased, which is attributed to CBA's lower specific gravity and higher water absorption properties. Notably, compressive strength improved up to a 20% CBA replacement, benefiting from enhanced particle packing and filler effects, with optimal strength observed at this level. The modulus of elasticity showed increased stiffness with CBA incorporation, particularly at lower replacement levels, while Poisson's ratio exhibited varied trends across different CBA percentages. This study enhances the understanding of SCCB performance when incorporating CBA, offering insights for optimizing material usage in sustainable construction practices and enhancing structural efficiency.

Keywords: Coal Bottom Ash (CBA), Self-compacting Concrete Brick (SCCB), Mechanical properties, Density reduction, Compressive strength, Young's Modulus, Poisson's Ratio

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1. Introduction

Concrete is globally recognized as a foundational building material renowned for its affordability, durability, and versatility in construction applications with Ordinary Portland Cement (OPC) serving as the primary binder. A major sustainability concern with Ordinary OPC is its substantial contribution to global greenhouse gas emissions, accounting for approximately 5–8% of total atmospheric emissions (Kusuma et al., 2022). The CO_2 emissions, primarily due to the extensive use of concrete in construction rather than the inherent CO_2 content of cement. These emissions originate from two main sources: process-related emissions from the decarbonation of limestone and energy-related emissions from fuel combustion during cement production (Barcelo et al., n.d.). The adoption of alternative materials, particularly supplementary cementitious materials (SCMs) as partial replacements for cement, is a common strategy in low-carbon concrete production. Various forms of low-carbon cement have been developed using industrial by-products such as fly ash, slag, and rice husk ash. The incorporation of SCMs reduces CO_2 emissions while enhancing concrete durability and improving resistance to aggressive environmental conditions. Although higher SCM contents generally lead to improved durability, compressive strength tends to decrease when the replacement level exceeds approximately 20–30%. This strength reduction presents a significant challenge in producing ultra-durable, low-carbon concrete with high SCM replacement levels, particularly at cement substitutions of up to 50% (Huseien, Joudah, et al., 2025; Joudah et al., 2025; Mhaya et al., 2020).

In parallel, the escalating generation of non-biodegradable waste compounds the environmental burden, straining waste management systems worldwide. The imperative to reduce waste and enhance resource efficiency has spurred interest in utilizing industrial by-products as viable substitutes in construction materials

(Perumal et al., 2011). Among these materials, coal bottom ash (CBA), a granular residue from coal-fired power plants, presents both challenges and opportunities. CBA, comprising approximately 10-20% of coal combustion residuals, poses disposal challenges due to its large quantities and environmental risks (Mohammed et al., 2021). Coal remains a primary global energy source, driving substantial CBA production. The efficient utilization of CBA in construction materials not only addresses waste disposal issues but also offers potential benefits such as improving material efficiency and reducing environmental impact (Tamanna et al., 2023). Incorporating CBA into concrete has shown promise in enhancing mechanical properties and sustainability metrics, thereby aligning with efforts to mitigate environmental impacts associated with traditional concrete production.

Self-compacting concrete (SCC) is a special type of concrete that can flow, fill formwork, and compact under its own weight without the need for external vibration, owing to its high deformability while maintaining sufficient cohesion to prevent segregation and bleeding (Shi et al., 2015). SCC offers several significant advantages, including the reduction of labour-intensive construction activities, which improves site efficiency and lowers construction costs. It also eliminates the need for vibration, thereby providing a safer and more comfortable working environment with reduced noise and physical strain for workers. In addition, the absence of vibration during casting helps preserve the internal structure of the concrete, leading to improved durability compared to conventionally vibrated concrete (Liana & Bob, 2010). In brief, SCC facilitates better bonding with congested reinforcement, allows faster placement, and reduces overall labour requirements, while often achieving superior surface finish, mechanical performance, and durability compared to conventional concrete, making it an attractive material for modern construction applications.

Several studies have extensively examined the compressive strength of concrete incorporating CBA as a partial replacement for fine aggregates. Ahmad Maliki et al. (2017) reported that M35-grade concrete incorporating CBA and fly ash achieved a compressive strength of 30 MPa at 28 days, with an optimal CBA replacement level of 60% of natural sand. Similarly, Park et al. (2021) observed that compressive strength decreased with increasing CBA content, where the F40-B050-28(S) specimen containing 50% CBA by volume exhibited a 4.3% lower strength compared to the F20-B025-28(S) specimen with 25% CBA. Siddique (2013) demonstrated that self-compacting concrete (SCC) incorporating CBA achieved compressive strengths ranging from 25.8–20.8 MPa at 7 days, 35.1–25.8 MPa at 28 days, and 46.5–36.2 MPa at 90 days. In addition, Singh and Siddique (2015) found that the use of high volumes of CBA as fine aggregate had no significant effect on the 28-day compressive strength and pulse velocity of concrete. Conversely, Ali Mangi et al. (2019) reported a gradual reduction in compressive strength with the incorporation of ground CBA, although concrete mixes containing 10% ground CBA ground for 20 and 30 hours still achieved the target strength of 35 MPa, despite reductions of 12% and 5% relative to the control mix, and exceeded the design strength by 12% and 20%, respectively. Overall, the literature indicates that CBA can effectively replace a portion of fine aggregates in concrete while maintaining satisfactory compressive strength, although excessive CBA content generally results in strength reduction, highlighting the need to determine an optimal replacement level.

Ali Mangi et al. (2019) reported that the incorporation of ground CBA significantly affects the density and water absorption of hardened concrete, with density consistently decreasing over a 28-day curing period as the CBA content increased. Concrete mixes containing 10% CBA ground for 20 and 30 hours exhibited density values comparable to those of the control specimen, whereas the use of CBA ground for 40 hours resulted in noticeably lower densities. Similarly, Ali Alhokabi and Shu Ing (2019) evaluated the feasibility of using bottom ash in fly-ash brick production by replacing 20% of cement with fly ash and substituting fine aggregate (river sand) with 5%, 10%, 15%, and 20% CBA, and found that the control sample without CBA exhibited the highest weight and density, while the specimen containing 20% CBA showed the lowest density. The reduction in air-dried density observed in both studies is primarily attributed to the lower specific gravity of coal bottom ash compared to natural sand.

Hasim et al. (2021) reported that the modulus of elasticity, which reflects the stiffness and elastic behavior of concrete, decreases with increasing coal bottom ash (CBA) and fly ash content after 28 days of curing. The measured modulus of elasticity values were 5.63 GPa for the control mix, followed by 5.39, 5.19, 5.17, and

5.03 GPa for the C'CBA50–F'CBA50, C'CBA100–F'CBA50, C'CBA50–F'CBA100, and C'CBA100–F'CBA100 mixes, respectively, indicating a progressive reduction with higher CBA and fly ash replacement levels; additionally, the flexural strength of CBA concrete was generally lower than that of the control mix. Consistent findings were reported by Andrade et al. (2007), who observed that at a constant water–cement ratio, increasing CBA aggregate replacement up to 100% resulted in a reduction in the modulus of elasticity, primarily due to excessive water absorption by CBA particles that impaired concrete compaction during hydration. Poor compaction consequently reduced aggregate–binder bonding and elastic stiffness, a conclusion further supported by Kim and Lee (2011), who highlighted the critical role of cement–aggregate bonding strength in governing the modulus of elasticity. Overall, these studies show that higher proportions of coarse and fine CBA significantly affect the elastic behaviour of concrete, leading to a reduced modulus of elasticity.

Experimental results reported by Villa and Estores (2023) indicated inconsistent trends in the dynamic Poisson's ratio of concrete incorporating coal bottom ash (CBA). For cylindrical specimens, the control mix without CBA exhibited Poisson's ratio values ranging from 0.33 to 0.47, while mixes containing 20% and 30% CBA showed ranges of 0.34–0.48 and 0.24–0.52, respectively. A more pronounced variation was observed in beam specimens, where Poisson's ratio values ranged from 0.25 to 0.66 for CBA0, 0.20 to 0.57 for CBA20, and 0.20 to 0.39 for CBA30, highlighting a significant divergence between beam and cylinder responses. Findings by Poudel et al. (2024) reported Poisson's ratio values between 0.18 and 0.20 for concrete containing 50% ground coal bottom ash as a cement replacement, while Nguyen et al. (2016) observed Poisson's ratio values in the range of 0.16 to 0.21 for fly ash–based geopolymer concrete, values comparable to those of conventional concrete.

Although SCC is widely studied and used in construction, research on Self-Compacting Concrete Bricks (SCCB) remains limited, particularly regarding the use of CBA and its effects on structural properties. The incorporation of CBA can influence concrete performance, including compressive strength, highlighting the need to determine optimal replacement levels for durability and efficiency. The study focuses on evaluating the effects of CBA content on key mechanical properties, including density, compressive strength, modulus of elasticity, and Poisson's ratio. The findings provide valuable insight into optimizing the use of CBA in concrete brick production, contributing to resilient infrastructure development in line with Sustainable Development Goal (SDG) 9 and promoting sustainable material use and waste reduction in accordance with SDG 12.

2. Research Method

2.1 Materials Preparation

The preparation of materials for manufacturing SCCB is pivotal as it directly influences the quality and performance of the final product. It is essential to accurately proportion and select raw materials such as cement, water, aggregates, and additives to achieve desired strength, durability, and workability in concrete bricks. In this study, OPC meeting MS EN 197-1:2014 - CEM 1 42.5N standards, acts as a binding agent ensuring high compressive strength and facilitating rapid setting which is crucial for efficient brick production. Sand, sieved to 5mm for uniform hydration and removal of impurities, enhances durability by ensuring proper density and reducing shrinkage during curing. CBA classified as a Class F pozzolan under ASTM C618 standards were selected to improve concrete properties like strength, durability, and resistance to chloride penetration. Water plays a critical role in concrete hydration, with a fixed water-to-cement ratio of 0.45 optimizing strength and workability. Quarry dust, a by-product of mineral aggregate processing, serves as an alternative to river sand, enhancing cementitious strength, workability, and sustainability. Sika ViscoCrete SKY 8611, a polycarboxylate ether (PCE)-based superplasticizer, further improves workability and strength by reducing water content, minimizing segregation and bleeding, and enhancing overall performance in concrete mixture production. Each material component is selected and prepared meticulously to ensure the production of high-quality, durable SCCBs, aligning with contemporary construction practices and environmental standards.

2.2 Experimental Method

In this experimental study, six (6) different concrete mixtures were prepared, varying the percentage of fine aggregate substitution with CBA from 0% to 30%. A total of 18 SCCB samples, each measuring 215mm x 101mm x 65mm, were produced following BS EN 772-1:2011+A1:2015 specifications. These samples underwent a standardized curing period of 48 days to ensure uniform hardening prior to mechanical testing. At the hardened state, comprehensive experimental tests were conducted to evaluate key mechanical properties including compressive strength, density, Modulus of Elasticity, and Poisson's Ratio of each SCCB variant incorporating coal bottom ash. This methodological approach ensures comprehensive analysis of the influence of CBA content on the performance characteristics critical for assessing the suitability of these bricks in construction applications.

2.3 Mix Proportion

Six (6) mixtures of SCCB with CBA were produced, varying the substitution of fine aggregate from 0% to 30%. Three (3) brick samples were tested for each mix to ensure reliable and representative results. The mix proportions are detailed in Table 1, where each ratio was named based on the level of bottom ash replacement, with M0 representing the control specimens. Volumetric replacement was chosen due to significant differences in specific gravities between natural sand and CBA. Additionally, a constant water-to-cement ratio of 0.45 was maintained throughout the mixtures.

Table 1 Designated Mix Proportion

Mix #	**Materials (kg/m^3)**							**CBA-to-Sand Replacement Ratio (%**
	CBA	**OPC**	**Total Binder Content**	**Sand**	**Water**	**Superpla Sticizer**	**Quarry Dust**	
M0	0.00	565.71	565.71	921.43	254.28	4.52	597.86	0
M10	67.86	565.71	633.57	828.57	254.28	4.52	597.86	10
M15	100.71	565.71	666.42	783.57	254.28	4.52	597.86	15
M20	134.29	565.71	700.00	737.14	254.28	4.52	597.86	20
M25	167.14	565.71	732.85	690.71	254.28	4.52	597.86	25
M30	201.43	565.71	767.14	645.00	254.28	4.52	597.86	30

2.4 Casting and Curing

Steel molds measuring 215 mm x 101 mm x 65 mm were utilized for brick production. Prior to use, the molds underwent disassembly for cleaning, employing WD-40 rust remover to facilitate the removal of rusted components. Concrete residues from previous castings were meticulously removed using a scraper and brush. After cleaning, the molds were tightly reassembled to prevent any potential leakage during the pouring process. Subsequently, a fine layer of oil was applied to each mold to ensure effortless extraction of the solidified bricks. Water curing was employed to maintain optimal moisture levels and temperature for concrete hydration. The ponding method was chosen due to its cost-effectiveness and efficiency in keeping concrete surfaces continuously moist. All specimens were maintained fully submerged in water throughout the curing period to ensure uniform hydration and consistent curing conditions.

Concrete curing duration significantly affects its strength, durability, and resistance to corrosion. Karthiga et al. (2020) found that concrete containing calcium carbide remains and ground granulated blast furnace slag reached maximum compressive strength at 48 days, compared to 7 and 28 days. Accordingly, a 48-day curing period was adopted in this study based on literature evidence, ensuring full strength development and reliable assessment of mechanical properties.

2.5 Testing procedures

The density of hardened concrete samples was determined in accordance with *BS EN 12390-7:2019*. This standard prescribes a specific method for measuring the mass and volume of concrete specimens to calculate density. Compression tests were conducted using a loading machine equipped with a load cell, crossheads, compression test tools, electronics, and a drive system. This apparatus applies gradually increasing force to assess the maximum load a material can withstand before failure. *BS EN 7721:2011+A1:2015 Methods of test for masonry units Determination of compressive strength* were referred to test the 215 mm x 101 mm x 65 mm brick. The modulus of elasticity of SCCB was evaluated using a Linear Variable Differential Transformer (LVDT) to measure longitudinal strain. The LVDT, widely used in civil engineering for displacement and deformation measurements, was employed due to height constraints of the SCCB sample. Longitudinal strain was calculated by dividing vertical displacement measured by the LVDT by the initial length of the brick. Poisson's ratio was concurrently measured with compressive strength and Young's Modulus using strain gauges affixed perpendicular to the applied force on the brick surface. The strain gauges were installed meticulously following cleaning and adhesive application procedures. Calibration of the strain gauges ensured accurate measurement of lateral strain during varying loading conditions, contributing to the comprehensive assessment of concrete structural performance.

3. Results and Analysis

3.1 Density Test of SCCB

In this study, the influence of CBA on the density of SCCB was investigated by varying the percentage of CBA as a replacement for fine aggregate. The density measurements were conducted according to *BS EN 12390-7:2019* standards. Table 2 and Figure 1 show the density of SCCB with different CBA percentages.

Table 2. Density results of SCCB with different percentages of CBA

Mix #	**% CBA**	**Density (kg/m^3)**
M0	0	2407.07
M10	10	2302.67
M15	15	2285.77
M20	20	2280.85
M25	25	2277.80
M30	30	2270.91

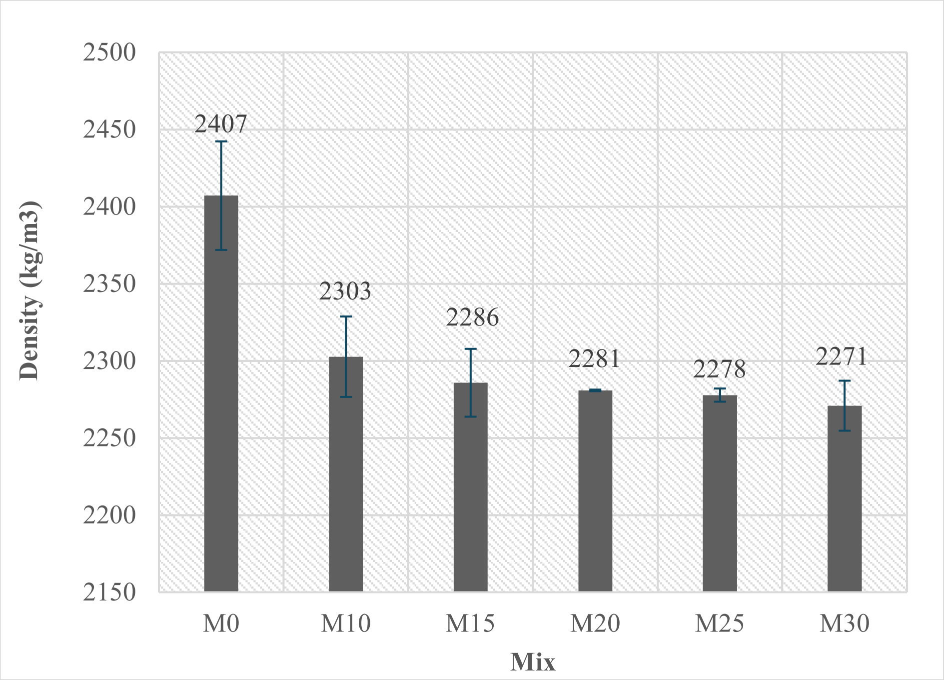

Figure 1 Effect of coal bottom ash on the density of SCCB.

Figure 1 depicts the density trend in SCCB with differing CBA percentages replacing fine aggregate. According to Table 2, the control mix (M0) without CBA exhibits a density of 2407 kg/m³. Introducing 10% CBA (M10) lowers the density to 2303 kg/m³, a 4.34% reduction. Mix M15, containing 15% CBA, records a density of 2286 kg/m³, 5.04% lower than M0. Density decreases further with higher CBA content, M20 and M25, with 20% and 25% CBA respectively, show densities of 2281 kg/m³ and 22778 kg/m³, reductions of 5.24% and 5.37% compared to M0. The highest CBA content, 30% in mix M30, yields the lowest density at 2271 kg/m³, marking a 5.66% decrease from M0. The low standard deviation values demonstrate high repeatability and consistency in the density measurements for each mix. In particular, mixes M20 and M25 show minimal variability, indicating uniform compaction and homogeneous material distribution despite the incorporation of CBA.

The results show a clear decreasing trend in concrete density with increasing replacement of fine aggregate by coal bottom ash (CBA). This reduction is attributed to the lower specific gravity and higher porosity of CBA compared to natural sand. The incorporation of CBA introduces a more porous internal structure within the concrete matrix, which consequently reduces the overall density of the concrete.

3.2 Compression Test of SCCB

Compressive strength tests were conducted on self-compacting concrete bricks with varying percentages of coal bottom ash. Differences in strength reflect changes in material composition, internal structure, and bonding, which influence the bricks' structural performance. The results are presented in Table 3 and Figure 2.

Table 3. Compressive Strength of SCCB with different percentages of CBA

Mix	%CBA	Compressive Strength (N/mm^2)
M0	0	51.99
M10	10	51.57
M15	15	52.76
M20	20	59.12
M25	25	49.31
M30	30	43.83

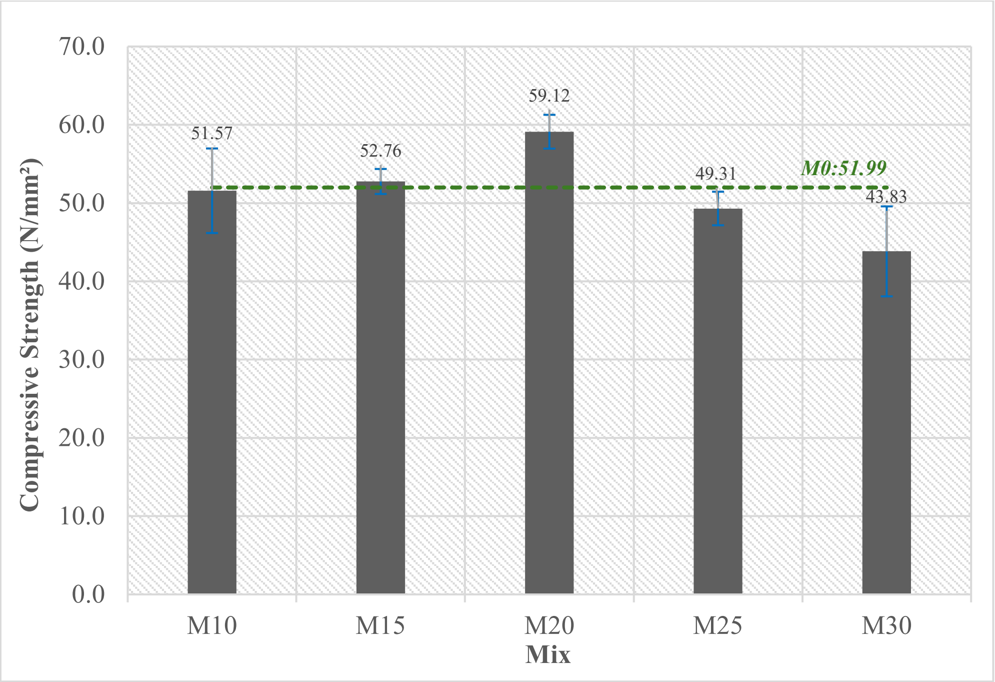

Figure 2. Effect of coal bottom ash to the compressive strength of SCCB

Figure 2 illustrates the compressive strength of SCCB with varying CBA percentages. Based on Table 3, the control mix (M0) shows a compressive strength of 51.99 N/mm². Mix M10, with 10% CBA, exhibited a slight decrease in strength to 51.57 N/mm² (-0.8% compared to M0), while M15 demonstrated a slight increase to 52.76 N/mm² (+1.48% compared to M0). Mix M20 achieved the highest strength at 59.12 N/mm² (+13.71% compared to M0). Conversely, M25 (25% CBA) and M30 (30% CBA) exhibited decreases in strength to 49.31 N/mm² (-5.16% compared to M20) and 43.83 N/mm² (-15.69% compared to M20), respectively. The standard deviation values for all mixes remained low, demonstrating consistent compressive strength behaviour across different coal bottom ash replacement levels.

The incorporation of CBA significantly affects the compressive strength of SCCB. At a 10% replacement level, a slight reduction in strength is observed due to the dilution effect associated with reduced cement content. As the replacement level increases to 15%, the filler effect of fine CBA particles enhances particle packing and promotes cement hydration, resulting in a marginal strength improvement. The optimum compressive strength is achieved at a 20% replacement level, where the filler effect is most effective. Beyond this level (25%–30%), compressive strength decreases due to excessive CBA content, increased porosity, and weakened matrix structure. These findings indicate that CBA can enhance compressive strength when used at an optimum replacement level of 20%.

3.3 Modulus of Elasticity Test of SCCB

Strain measurements, represented by the reduction in brick height under compressive loading, are used to assess the deformation behaviour of the concrete. Abnormal or excessive strain responses may indicate material weaknesses and potential failure mechanisms, providing insight into the structural performance of the specimens. The experimental elastic modulus results are presented in Table 4 and Figure 3.

Table 4. Elastic Modulus of SCCB with different percentages of CBA

Mixes	CBA %	Elastic Modulus (N/mm^2)
M0	0	16051.95
M10	10	9723.40
M15	15	25450.39
M20	20	23299.89
M25	25	15754.09
M30	30	15752.91

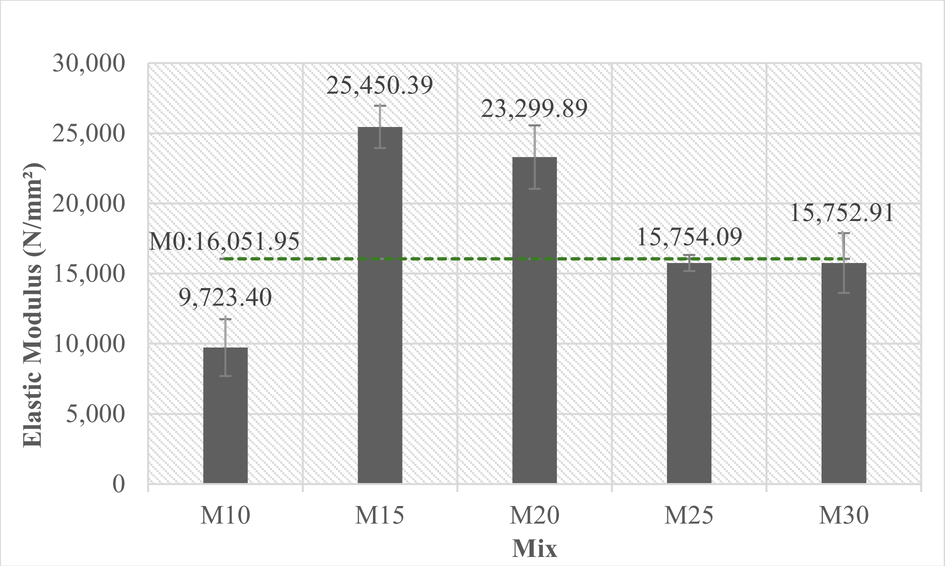

Figure 3. Effect of coal bottom ash to the elastic modulus of SCCB

The control mix (M0) recorded an elastic modulus of 16,051.95 N/mm². A reduction in stiffness was observed for M10, which achieved an elastic modulus of 9,723.40 N/mm², representing a 39.4% decrease compared to the control. In contrast, the M15 mix exhibited the highest elastic modulus of 25,450.39 N/mm², corresponding to an increase of 58.6%. Similarly, M20 maintained a relatively high modulus of 23,299.89 N/mm², reflecting a 45.2% improvement over M0. However, further increases in CBA content resulted in a decline in stiffness, with M25 and M30 recording elastic modulus values of 15,754.09 N/mm² and 15,752.91 N/mm², indicating a marginal reduction of approximately 1.9% relative to the control mix. The majority of the mixes demonstrated elastic modulus values exceeding those of conventional concrete bricks, which typically exhibit an elastic modulus of about 14,000 N/mm². The standard deviation values are relatively small for all mixes, indicating good consistency and reliable elastic modulus measurements. Slightly higher variability is observed for M15 and M20, while M25 and M30 show more uniform and stable behaviour.

As shown in Figure 3, the elastic modulus of SCCB increases with the incorporation of CBA up to an optimal replacement level. The improvement observed in mixes M15 and M20 can be attributed to the filler effect of CBA, which enhances particle packing and reduces internal voids, resulting in a stiffer concrete matrix. In addition, the pozzolanic reaction between the amorphous silica and alumina in CBA and calcium hydroxide produced during cement hydration contributes to the formation of additional C–S–H gel, further improving stiffness. However, at higher replacement levels beyond 20% CBA, the elastic modulus decreases, likely due to increased porosity and reduced effectiveness of cement hydration, which limits further stiffness enhancement.

3.4 Poisson's Ratio Test of SCCB

The Poisson's ratio of self-compacting concrete bricks was observed to vary with the incorporation of CBA. As presented in Table 5, concrete mixes containing CBA exhibit non-uniform trends in Poisson's ratio, with values ranging from 0.21 to 0.41. In comparison, the control mix without CBA recorded a Poisson's ratio of 0.23.

Table 5. Poisson's Ratio of SCCB with different percentages of CBA

Mixes	CBA %	Mean Poisson's Ratio	Standard Deviation
M0	0	0.23	28.845
M10	10	0.21	52.652
M15	15	0.41	16.244
M20	20	0.19	117.528
M25	25	0.29	45.865
M30	30	0.30	29.792

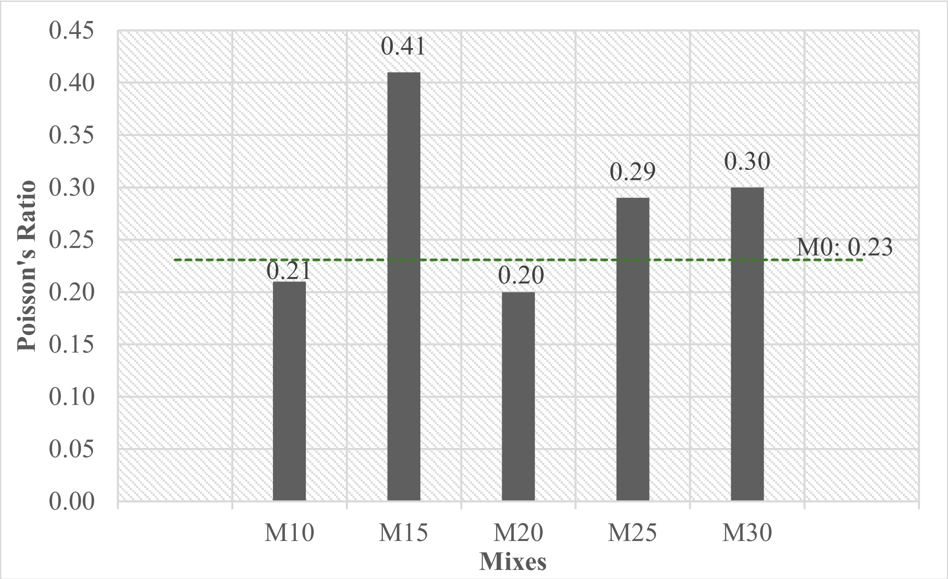

Figure 4. Effect of coal bottom ash to the Poisson's Ratio of SCCB

Based on Figure 4, the Poisson's ratio of self-compacting concrete bricks (SCCB) varies considerably with different levels of coal bottom ash (CBA) replacement. The corresponding values for each mix are summarised in Table 3.4. The control mix (M0) recorded a Poisson's ratio of 0.23. A slight reduction was observed for M10, which exhibited a ratio of 0.21, representing an 8.14% decrease relative to the control. In contrast, the M15 mix showed the highest Poisson's ratio of 0.41, corresponding to a substantial increase of 76.1% compared to M0. Further replacement led to a reduction in M20, with a Poisson's ratio of 0.20, indicating a 13.04% decrease relative to the control mix. The Poisson's ratio increased again for M25 and M30, recording values of 0.29 and 0.30, which correspond to increases of 24% and 32%, respectively, compared to M0.

The standard deviation values of Poisson's ratio indicate varying levels of measurement consistency among the SCCB mixes. Lower standard deviations observed for M15 and M30 suggest more uniform lateral deformation behaviour and improved material homogeneity at these CBA replacement levels. In contrast, the higher variability recorded for M10, M20, and M25, particularly for M20, reflects inconsistent strain responses, likely due to heterogeneity in the concrete matrix and the sensitivity of lateral strain measurements.

The increase in Poisson's ratio with higher CBA contents, particularly for M20–M30, is attributed to microstructural changes arising from the porous and angular nature of CBA particles, which increase micro-voids and reduce aggregate interlock. These characteristics promote greater lateral deformation under compressive loading. At moderate replacement levels (M15), improved particle packing and cement–aggregate bonding contribute to a more uniform matrix and stable lateral strain behaviour. These results indicate that Poisson's ratio in SCCB is highly influenced by CBA content and should be interpreted with caution where high dispersion is observed.

4. Conclusion and Recommendations

The study investigated the influence of CBA on mechanical properties in SCCB. Increasing CBA content led to a predictable decrease in concrete density, ranging from approximately 4.34% to 5.66% compared to the control mix (M0), due to CBA's lower specific gravity and higher water absorption. Compressive strength showed an improvement up to 20% CBA replacement, with a peak increase of 13.71% in M20, attributed to filler effects and enhanced particle packing. However, at higher CBA contents (25% and 30%), compressive strength declined by 5.16% and 15.69%, respectively, relative to the control. The optimal replacement level for maximizing strength was determined to be 20% CBA. Modulus of elasticity exhibited an overall increase across all CBA mixes compared to M0, with the most significant rise of 58.6% observed in M15. Beyond 20% CBA, diminishing returns were observed, potentially due to increased porosity and incomplete hydration reactions The Poisson's ratio of SCC bricks peaked at 0.41 for the M15 mix, likely due to improved particle packing and enhanced cement–aggregate bonding, which promoted a more uniform matrix. This demonstrates that incorporating CBA can optimize the mechanical behaviour of SCCB, offering a sustainable alternative with tailored lateral deformation characteristics. The study emphasizes the importance of a balanced approach in CBA replacement to achieve optimal mechanical properties in SCCB. The incorporation of CBA into SCCB at an optimal replacement level of 15–20% markedly improves mechanical performance, including compressive strength, modulus of elasticity, and Poisson's ratio, thereby demonstrating its potential to provide both sustainable material utilization and enhanced structural performance in concrete applications.

CBA is expected to exhibit promising pozzolanic properties and has shown satisfactory strength performance of SCCB. To enhance the utilization of CBA in SCCB production, several recommendations for future research include:

i. Investigating a broader range of CBA replacement levels to identify critical area where mechanical properties such as compressive strength, modulus of elasticity, and Poisson's ratio significantly decrease.
ii. Studying the influence of different particle sizes of CBA on mechanical properties to understand how particle size distribution affects strength and deformation characteristics.
iii. Analyzing the impact of curing conditions, such as temperature and humidity, on the development of mechanical properties in SCCB containing CBA to optimize curing methods and enhance overall performance.
iv. Utilizing numerical simulations via Finite Element Method (FEM) to complement experimental results and gain deeper insights into the structural behavior of SCCB incorporating CBA. FEM can predict stress distribution, deformation patterns, and failure mechanisms under various loading conditions, facilitating the optimization of concrete mix designs and improving structural integrity for practical construction applications.

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Author Contribution

Ilyani Akmar Abu Bakar and Warid Wazien Ahmad Zailani were responsible for the study’s conceptualization. Qaisara Azizah Amranudin led the methodology, investigation, and data curation, and prepared the original draft. Ilyani Akmar Abu Bakar and Noor Irinah Omar oversaw validation and resources, co-managed data curation, and conducted the final review and editing of the manuscript.

Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

Declaration of Generative Ai in the Writing Process

During the preparation of this work, the authors used *Perplexity* and *ChatGPT* in order to find related academic articles, identifying relevant references, and improving the clarity of written paragraphs. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Data Availability/Supplementary Materials

All data generated or analysed during this study, including the results of density, compressive strength, modulus of elasticity, and Poisson’s ratio of SCCB mixes, are included in this published article.

Ethics Statement

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA (UiTM) Shah Alam, Faculty of Civil Engineering.

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