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Arch. Metall. Mater. **70** (2025), 4, 1627-1635

DOI: https://doi.org/10.24425/amm.2025.156242

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PERFORMANCE OF SELF-COMPACTING CONCRETE WITH COAL BOTTOM ASH UNDER FIRE AND POST-FIRE CONDITIONS

The rise in demand for self-compacting concrete (SCC) results in an associated rise in the use of primary components like cement and aggregate. Furthermore, environmental deterioration, climate change, and pollution are significant environmental concerns. The problem of environmental degradation caused by the disposal of industrial waste, particularly coal bottom ash (CBA) from thermal power plants, requires urgent attention. Given the significant shortage of essential materials like cement and aggregates, it is crucial to find alternative materials to replace cement. There is a pressing need for high-quality materials that can effectively substitute for cement and withstand high temperatures. A key challenge in improving the fire resistance of concrete at elevated temperatures is maintaining its compressive strength. This research seeks to explore the effects of substituting ground CBA for cement on the compressive strength and fire resistance of self-compacting concrete (SCC). Four SCC-CBA mixtures were created by replacing 0%, 10%, 20%, and 30% of the cement weight with ground CBA. Both CBA-SCC and control SCC specimens were subjected to elevated temperatures of 200, 400, 600, and 800°C for one hour, and mass losses along with compressive strength reductions were assessed post-heating. The results indicate that the highest compressive strength for SCC is achieved with 10% ground CBA. All mixtures met the specified strength requirements in 28 days, with compressive strength values ranging from 30 MPa to 39 MPa. At 400°C, the SCC with 10% ground CBA showed greater mass and strength degradation compared to the control samples.

Keyword: Coal Bottom Ash (CBA); Elevated Temperatures; Self-Compacting Concrete (SCC); Strength Properties; Cement Substitution

1. Introduction

Concrete structures must meet key requirements such as safety, strength, durability, and fire protection according to building codes [1-3]. Fire is a major risk for most buildings and structures [4,5]. Since concrete is widely used in construction, it's important to understand how it behaves under fire [6]. High temperatures can reduce a concrete structure's strength, stability, and performance, and also threaten the safety of people inside [7,8]. The deterioration in concrete performance arises from physical and chemical changes in the cement and aggregate phases, along with fluctuations in pore pressure within concrete composites during a fire [9,10]. At temperatures of 400°C and between 500-900°C, physicochemical reactions occur in concrete due to fire exposure. These reactions involve the decomposition of calcium hydroxide ($Ca(OH)_2$ or portlandite) and calcium silicate hydrate (C-S-H) gel, respectively [11-13]. Extensive research and practical applications have clearly demonstrated that concrete structures have a greater tolerance to elevated temperatures compared to those made from other materials. The compressive strength of concrete remains largely unaffected at temperatures below 300°C, but significant changes are expected beyond this threshold [14,15]. These changes can be attributed to the degradation of hydrated cement, deterioration of aggregates, and thermal inconsistencies among concrete components, leading to stress buildup and the formation of small cracks. Additionally, studies have shown that the pore size in cement paste increases due to the breakdown of $Ca(OH)_2$ and C-S-H, which contributes to a reduction in compressive strength at higher temperatures [16,17]. In recent years, there has been increasing interest among researchers in the concrete industry in improving the fire resistance of concrete using silica-rich

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pozzolanic minerals [18]. Studies have shown that replacing cement with pozzolanic materials is a highly effective approach for enhancing the fire-resistant properties of concrete [18,19]. The pozzolanic reaction enhances the strength and durability of cement paste, mortar, and concrete by reducing permeability and generating additional calcium silicate hydrate (C-S-H) gel. This reaction occurs when the silicon dioxide (SiO_2) present in pozzolanic materials reacts with calcium hydroxide ($Ca(OH)_2$) in the mortar. Commonly used pozzolanic materials include silica fume (SF), fly ash (FA), metakaolin (MK), and CBA [20,21]. The resulting effects include the disintegration of hydration products and aggregates, loss of water content, increased permeability, and fragmentation of the substructure. Therefore, it is crucial to gain a deeper understanding of the fundamental components of concrete, such as cement, and their responses to elevated temperatures [11,13,22]. When concrete reaches a critical temperature, significant degradation occurs, resulting in the loss of its properties due to the aforementioned physicochemical processes [10,23]. Furthermore, prior studies have indicated that the response of self-compacting concrete (SCC) to fire differs from that of conventionally compacted concrete.

SCC is an advanced version of traditional concrete that can be easily poured into confined spaces with closely spaced reinforcement without requiring mechanical vibration [24,25]. Developed by Prof. Okamura in the early 1980s [26], SCC is designed to effectively fill heavily reinforced areas and improve the performance of the concrete mix due to its highly fluid consistency. Over the past twenty years, SCC has garnered considerable attention in the construction industry [27,28]. This highly fluid concrete is ideal for efficiently covering densely reinforced sections and enhancing the effectiveness of concrete mixtures [29], [30]. Additionally, it exhibits a high level of fluidity, making it possible to create a uniform and consistent concrete mix, with potential for further advancements in this area. Given its numerous advantages, there is a growing trend towards the use of SCC in construction [31,32]. Since that time, it has been widely adopted as a building material in various countries, improving the quality of concrete structures in diverse environments. Moreover, in the last two decades, researchers have focused on developing sustainable concrete by incorporating industrial waste materials. The use of waste materials in concrete has rapidly increased due to their economic benefits, environmental efficiency, and improved structural performance compared to natural resources. Evaluating the suitability of sustainable concrete for withstanding harsh conditions is crucial. With the rising population and inadequate fire prevention measures, structures and buildings face significant fire risks [33]. Therefore, it is vital to assess the fire resistance of concrete structures, particularly those incorporating industrial byproducts.

Consequently, several prior studies have evaluated the fire resistance of (SCC) incorporating various industrial byproducts. Pathak and Siddique [34] investigated the impact of adding class F fly ash on the mechanical properties of SCC subjected to temperatures ranging from 20 to 300°C. Their findings revealed a significant mass loss between 200 and 300°C, which was associated with a marked reduction in splitting tensile strength, attributed to the evaporation of bound water. Bakhtiyari et al. [35] studied the fire behavior of SCC made with limestone and quartz powder, identifying the temperature range of 480-650°C as critical for spalling in both SCC and conventional concrete, with SCC showing a higher susceptibility to spalling. The method of fire was used in the previous studies direct fire exposure After the required curing period.

However, SCC retained its mechanical properties better at elevated temperatures compared to traditional concrete. Li et al. [36] analyzed the fire resistance of high-strength concrete (HSC) within a temperature range of 200 to 1000°C using a fuel furnace. At 200°C, they noted a decline in compressive and splitting tensile strengths, alongside spalling, and the formation of yellow, off-white, and crimson straws. Their results differed from previous studies, particularly below 400°C, as other researchers utilized an electric furnace with a slower heating rate that did not accurately simulate real fire conditions. The observed alterations may be ascribed to the degradation of hydrated cement, degradation of aggregates, and thermal inconsistencies among components of the concrete, which lead to the accumulation of tension and the formation of microcracks. In addition, it is observed that the pore size of cement paste expands due to the degradation of $Ca(OH)_2$ and C-S-H, hence contributing to the decline in compressive strength at elevated temperatures). Kodur et al. [37] conducted pioneering research on the thermal properties of HSC at temperatures ranging from 0 to 1000°C, concluding that incorporating carbonate particles significantly improves fire resistance, highlighting the importance of aggregate selection on the fire performance of HSC.

However, a research conducted by Yüksel et al. [38] examined the strength properties of concrete incorporating coal bottom ash (CBA) as fine aggregate under high-temperature conditions. The research divided the concrete samples into two groups: the first used ground granulated blast-furnace slag (GBFS) as a fine aggregate substitute, with proportions ranging from 0% to 50%, while the second utilized CBA as a fine aggregate replacement, also ranging from 0% to 50%. The findings revealed that the strength properties of concrete with alternative aggregates, such as CBA, were inferior to those of conventional concrete. This decline in strength was attributed to the samples being subjected to high temperatures (800°C) and the instability of CBA at elevated temperatures. These points underscore the necessity and significance of researching self-compacting concrete (SCC) containing coal bottom ash (CBA) when exposed to prolonged high temperatures. The aim of this investigation was to assess the performance of SCC exposed to high temperatures, utilizing materials that were obtained locally. Furthermore, this research aims to assess the impact of using ground CBA as a cement replacement on the compressive strength and fire resistance of SCC. The aim of the present study was to assess the behavior of self-compacting concrete (SCC) made with locally available materials when exposed to elevated temperatures. The investigation focused on the effects of temperatures ranging from 200°C to 800°C on compressive strength and mass loss. The 28-day compressive strength of the developed mixes ranged between 30 MPa and 35 MPa. For the CBA-SCC mixtures, a water-to-cementitious material ratio of 0.34 was used, with a total cementitious content of 550 kg/m^3. Cement was partially replaced with ground coal bottom ash (CBA) at levels ranging from 10% to 30% of the total powder content. The study evaluated the thermal performance of SCC incorporating different CBA replacement levels under elevated temperature conditions

2. Experimental programme

2.1. Materials

The experimental study used ordinary Portland cement (OPC), fine aggregate, coarse aggregate, water, and superplasticizer (SP) as its components. Specifically, the OPC employed was YTL ORANG KUAT MS EN 197-1 CEM I 52.5 N, with a surface area of 0.866 m²/g, adhering to the EN 197-1 standard. This OPC was used for experimental purposes and to assess various properties according to MS EN 197-1, along with identifying the specific limitations outlined in that standard. The SCC samples were prepared using a mix of fine and coarse aggregates sourced from readily available river sand, with the river sand having a maximum particle size of 4.75 mm and the coarse aggregate a maximum particle size of 14 mm. In this study, the mix designs' for materials selections are consistents with the EFNARC, 2005 standard [39]. Pure tap water was utilized for mixing and curing. The initial CBA was sourced from a thermal location near Johor, Malaysia. Visual inspection revealed that the original CBA had a coarse and porous texture, similar to volcanic material, as shown in Fig. 1a. Fig. 1b depicts the ground CBA, which served as a cement replacement in the SCC mixture. The CBA was dried in an oven at 110±5°C for 24 hours, then passed through a 300-micron sieve and subjected to 7000 cycles in a Los Angeles machine to ensure compliance with ASTM C618 standards for suitable pozzolanic materials [40]. The sieved CBA was further ground using a Los Angeles grinding machine, which included 20 stainless steel spheres of 35 mm diameter to achieve a refined texture. The particle size of the CBA was assessed every 2000 cycles using the wet sieving method with a 45 μm sieve, following ASTM C430 guidelines.

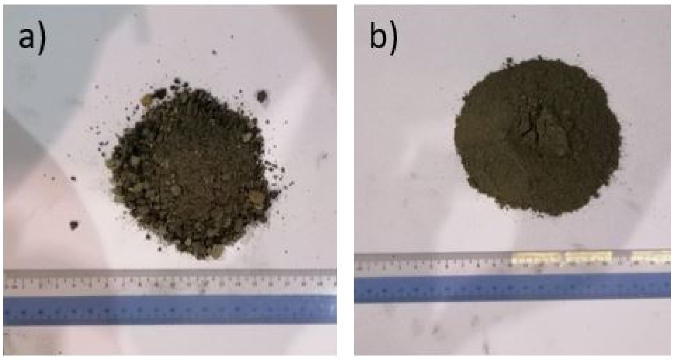

Fig. 1. a) Original CBA b) Ground CBA

After a specified grinding duration, 95% of the material passed through the 45 μm sieve, exceeding the ASTM C618 threshold of 66% [41]. TABLE 2 presents the chemical composition of both CBA and OPC, confirming that the CBA meets ASTM C618 [41] criteria and is classified as class F ash. The physical properties of CBA are detailed in TABLE 1. The original grey color of CBA deepened to a darker shade after grinding.

TABLE 1

Physical properties of cement

	Cement	**CBA**
Bulk density (kg/m^3)	1440	2350
specific gravity	3.15	2.37
Blaine surface area	0.867	0.494
Fineness modulus	3.38	2.56
Water absorption	—	5.30
Color	Gray	Blackish or dark gray

TABLE 2

Chemical composition of cement and coal bottom ash

Chemical composition (%)	**Cement**	**Coal bottom ash**
Silicon Dioxide (SiO_2)	14.4	50.8
Aluminum Oxide (Al_2O_3)	3.55	14.2
Ferric Oxide (Fe_2O_3)	3.10	16.6
Sulphur Trioxide (SO_3)	3.17	0.460
Calcium Oxide (CaO)	63.8	11.2
Magnesium oxide (MgO)	0.693	1.55
Potassium Oxide (K_2O)	0.818	1.66
Titanium Dioxide (TiO_2)	0.228	1.30

2.2. Mix Proportion and Specimen Preparation

The mix design process aims to choose the most appropriate and cost-effective materials for the self-compacting concrete (SCC) mixture and to adjust their ratios to enhance both its fresh and mechanical properties. In this study, the mix designs adhere to the EFNARC guidelines [39]. The methods for creating SCC mixes are quite different from those used for conventional concrete. Four distincts mix variations were created, each maintaining consistent ratios of coarse and fine aggregates, water, (CBA), and superplasticizer (SP), as outlined in TABLE 3. CBA was incorporated in varying percentages of 0%, 10%, 20%, and 30% to partially replace cement in the SCC formulation. A rotary mixer with a capacity of 0.025 cubic meters was utilized to prepare the SCC mixes. The mixing process involved continuous operation of the mixer's rotor for two minutes while gradually adding two-thirds of the water, followed by an additional two to three minutes of mixing with the remaining water, which included the superplasticizer. The casting was performed at ambient temperatures ranging from 25°C to 30°C. A release agent (demolition oil) was applied to the molds before pouring the concrete to prevent sticking. After one day, the samples were removed from the molds and placed in a curing tank filled with

TABLE 3

Mixture design proportion for 1 m^3 SCC mixture

Percentages	Water content (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	CBA content (kg/m^3)	Superplasticizer (% Binder)
0%	185	550	952	620	0	1.8
10%	185	495	952	620	55	1.8
20%	185	440	952	620	110	1.8
30%	185	385	952	620	165	1.8

water maintained at 28±3°C until they reached the required age for testing. The mix design (Kg/m^3) proportions of the SCC mixtures developed in this study are detailed in TABLE 3.

2.3. Testing involved

To assess the flowability of the SCC mixtures and ensure they meet the standards set forth by in accordance to EFNARC, 2005 [39] workability tests were carried out. A slump flow test was performed to analyze the flow characteristics of the developed SCC mixture. This test was specifically designed to evaluate the flowability of the SCC. Additionally, a compressive strength test was conducted in accordance with the criteria and specifications outlined in ASTM C109 [42] to determine the SCC's capacity to withstand loads that could lead to failure. Fire resistance testing followed the procedures established by Nathe et al. in their study [36]. The initial mass of the samples was measured and recorded prior to exposure to high temperatures. The samples were then subjected to thermal conditions at 200°C, 400°C, 600°C, and 800°C for one hour using a digitally controlled furnace. The reason to avoid of the explosive spalling in the samples as well as to avoid any cracks or damage in the samples. After this exposure, the specimens were allowed to cool to room temperature within the furnace. The mass of the samples was evaluated after cooling to assess the extent of mass loss due to heating. A compressive strength test was then performed to measure the reduction in strength of the SCC after exposure to elevated temperatures. Mechanical properties were assessed at both 7 and 28 days, while the fire resistance test was conducted after 28 days. All specimens underwent water curing, and cubes measuring 100×100×100 mm were prepared for each test.

2.4. Heating details

After 28 days of two phases of water curing, the samples were taken out of the tank and dried in an oven at a temperature of 110±5°C for one day. They were then placed in an electric muffle furnace, where they were subjected to gradually increasing temperatures of 200°C, 400°C, 600°C, and 800°C. This process aimed to reduce moisture content through evaporation, thereby reducing the risk of premature explosive spalling when the samples were later exposed to high temperatures. The electric furnace was used to increase the temperature of the samples at a rate of 10°C per minute. The samples were exposed to the specified temperatures for one hour, simulating the actual conditions that concrete faces when subjected to elevated temperatures, as shown in Fig. 2(a)-(b). After this exposure, the samples were analysed for weight loss and compressive strength. Calculations for weight loss and compressive strength were performed using Eqs. (1) and (2), respectively in accordance with the previous studies [43,44].

$$\text{Weight loss}\,(\%) = \frac{M_1 - M_2}{M_1} \times 100 \tag{1}$$

where,

M_1 – Weight of samples before heated,

M_2 – Weight of samples after heated

$$\text{Strength loss}\,(\%) = \frac{f_{wc} - f_h}{f_{wc}} \times 100 \tag{2}$$

where,

F_{wc} – Average compressive strength of samples before exposure to elevated temperature,

F_h – Average compressive strength of samples after exposure to elevated temperature.

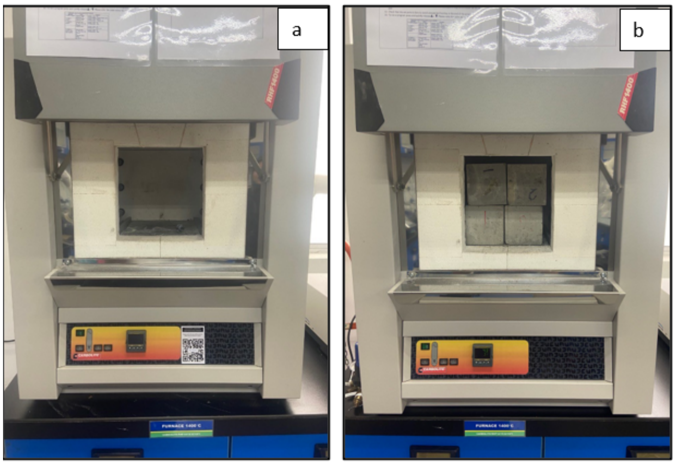

Fig. 2. Furnaces with samples: a) Electric furnace b) Samples exposure to elevated temperature

3. Results and discussion

3.1. Flowability

The properties of fresh SCC were evaluated using the slump flow test, which aimed to determine the impact of ground

CBA content on the workability of the SCC mixture. Fig. 3 illustrates the slump flow results for both the control sample and the SCC with ground CBA used as a partial cement replacement. The control specimen exhibited a slump flow of 674 mm, based on the selected mix design from the trial mixes. As ground CBA was added to replace cement in the mixture, the slump flow of the SCC specimens steadily decreased. This reduction is attributed to the porosity of CBA, which absorbed more fluid as its content increased in the SCC mixture. According to the EFNARC, 2005 standards [39] specify that slump flow values for SCC should be between 550-850 mm. SCC mixes with a slump flow exceeding 700 mm may be prone to segregation, while those below 500 mm may lack sufficient flow to pass through tightly packed reinforcement. Additionally, a slump flow above 700 mm increases the likelihood of segregation during the flow of the concrete. The slump flow test results presented in Fig. 3 are consistent with the range outlined in the EFNARC, 2005 guidelines [39]. For SCC formulations where ground CBA is used as a partial cement substitute in proportions ranging from 10% to 50%, the slump flow measured between 675 and 585 mm. These results fall within the slump flow rate 2 (SF2) slump flow classification outlined in the standards. The slump flow test results indicated a decrease in flow as the proportion of ground CBA in the SCC mix increased. This decline is primarily due to the pores present in the SCC mix with ground CBA, which leads to greater fluid absorption at higher levels of CBA replacement. Additionally, the irregular structure of ground CBA contributes to reduced particle interaction. This is due to CBA high porous which is led to absorb the water in the concrete mixture. The results showed that incorporating ground CBA decreased the slump flow diameter, whereas replacing cement typically increases it, as CBA is finer and has a greater surface area. Using CBA in SCC production also heightens water demand. In this study, while the water content was held constant, the dosage of superplasticizer (SP) was raised to 1.8% to comply with SCC standards. Moreover, the inclusion of ground CBA reduced the viscosity of the SCC mixes. The best flow ratios for SCC were achieved with a 10% replacement of cement with ground CBA, a finding supported by several other researchers [24,45,46]. These results proved that the ground CBA with fine particle size and porosity could decreases the workability as reported by [47,48]. Many studies reported that the ground CBA in concrete mixture decrease the workability remarkably [49-51].

3.2. Compressive strength

Fig. 4 displays the compressive strength of SCC with CBA as a partial cement substitute after curing for 7 and 28 days. Compressive strength increased for all mixes as curing time progressed. The compressive strength values ranged from 21 MPa (for mixes with 30% CBA) to 39 MPa (for control specimens) after 28 days. The differences in compressive strength among the mixes varied depending on the amount of CBA in the SCC. Control specimens recorded compressive strengths between 36.329 MPa and 39.599 MPa at 7 and 28 days, respectively. The study found that a 20% CBA replacement yielded optimal results, with values ranging from 36.893 MPa to 40.2133 MPa after 7 and 28 days of curing. This strength increase is likely due to the delayed pozzolanic reaction of CBA, which densifies the material and enhances compressive strength. According to Argiz et al. [52] noted that the pozzolanic properties of fine (CBA) lead to a delayed pozzolanic reaction that affects strength properties. Previous research by Oruji etl. [53] has shown that concrete mixtures with 20% finer CBA achieve satisfactory strength levels. The findings of this study align with previous research [54,55]. Overall, the investigation into the use of CBA as a partial cement replacement in (SCC) concluded that incorporating up to 20% CBA significantly improves strength characteristics compared to conventional SCC mixtures. Additionally, earlier studies Singh et al. [56] indicated that adding small amounts of CBA to SCC notably enhances mechanical properties, such as compressive strength, which can increase by up to 20% at different curing stages. This strength gain is attributed to the pore refinement effect from the pozzolanic activity of CBA, which also slightly increases porosity. Importantly, the silica in ground CBA plays

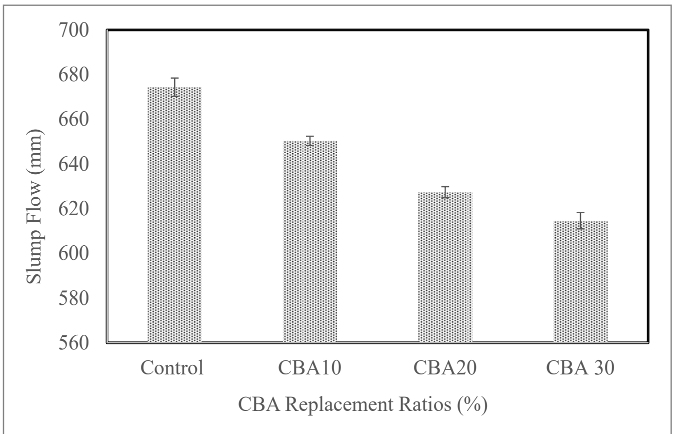

Fig. 3. Slump flow of SCC mixes containing different replacement levels of ground CBA and control

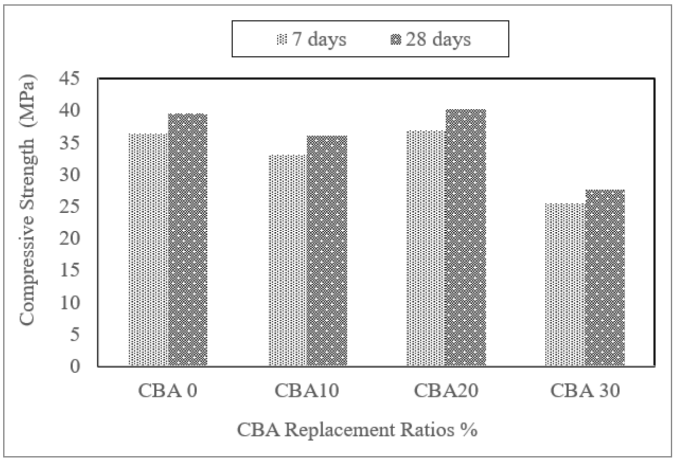

Fig. 4. Compressive strength results of SCC containing ground CBA with various replacement ratios at different curing ages

a vital role in forming calcium-silicate-hydrate (C-S-H), a gel-like compound that greatly enhances the material's strength. The increase in strength is connected to the higher concentration of C-S-H in SCC samples containing ground CBA, resulting from the chemical reaction between calcium hydroxide released during cement hydration and the reactive silica in the CBA. Argiz et al. [52] demonstrated that the pozzolanic characteristics of tiny particles of CBA enhance the pozzolanic reaction, hence improving strength properties. Oruji et al. [53] demonstrated that concrete mixtures with 20% finer CBA attain sufficient strength. Moreover, the incorporation of finely ground CBA resulted in enhanced compressive strength due to the natural pore refinement effect, since smaller particles occupied the pores in the mixture, facilitating higher hydration of the paste produced during the pozzolanic reactions.

3.3. Fire resistance

3.3.1. Mass loss

Concrete, being a heterogeneous material composed of multiple phases, undergoes various physicochemical changes when exposed to high temperatures. Experimental observations indicate that specimens containing ground coal bottom ash (CBA) exhibit lower resistance to high-temperature spalling compared to those made with conventional or high-strength concrete reported in the literature. This reduced resistance is partly attributed to the high surface area of CBA and the presence of a thin film of chemical binder impurities on its surface, which diminishes its reactivity and increases its susceptibility to sudden expansion under thermal stress and elevated pore pressure. The analysis indicates the mass loss of SCC incorporated with ground CBA as a partial cement replacement when subjected to elevated temperatures of 200°C, 400°C, 600°C, and 800°C for one hour, as illustrated in Fig. 5. Across all SCC mixtures, mass loss increased with rising temperatures. The results demonstrate a notable reduction in mass for SCC specimens as temperatures rose, compared to their pre-exposure mass. Overall, mass loss ranged from approximately 6.928% to 10.533% at temperatures of 200°C, 400°C, 600°C, and 800°C. According to Nathe et al. [57] a significant reduction in weight loss was observed in specimens containing CBA when subjected to elevated temperatures from 100°C to 800°C. Additionally, the mass loss ranged from 1.540% to 2.850%, primarily attributed to moisture loss from the concrete samples. In this study, at 200°C, the highest mass loss was observed in the SCC mixture with 10% CBA, which recorded a mass loss ratio of 6.99%, compared to 6.92% for the control samples. The other replacement ratios of 20% and 30%, ground CBA showed weight losses of 5.81% and 6.90%, respectively, when subjected to 200°C. The weight losses in the SCC samples containing ground CBA were similar due to moisture removal after heating at this temperature. As the temperature increased to 400°C, mass loss for both SCC with ground CBA and control samples also increased. This increase is attributed to the release of capillary and gel water from samples at 400ºC. According to Kanagaraj et al. [58] the mass loss due to the evaporation of free and chemically bound water accounts for weight loss for up to 60 minutes of exposure to elevated temperatures. Beyond 600°C, the mass loss showed only a slight increase for both SCC with ground CBA and control samples. Notably, the highest percentage of mass loss occurred at 800°C, where the percentages for mortars containing 0%, 10%, 20%, and 30% CBA were 9.87%, 10.09%, 9.64%, and 10.37%, respectively. The results clearly indicate that the mass loss in SCC specimens containing CBA was greater than that of the control SCC samples. Overall, for all mixtures, a slight improvement in residual strength was observed at 200°C compared to the control samples. This increase in strength is attributed to enhanced surface forces between gel particles, resulting from the loss of moisture. The likely cause is a dense microstructure, which contributes to the buildup of vapor pressure generated by the evaporation of both physically and chemically bound water.

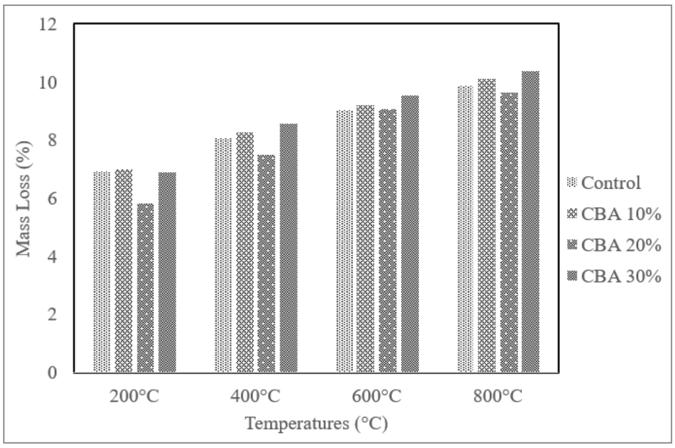

Fig. 5. Mass loss of SCC specimens containing ground CBA and control exposed to elevated temperatures

3.3.2. Strength loss

Fig. 7 illustrates the residual strength or strength loss values of SCC specimens after exposure to elevated temperatures of 200°C, 400°C, 600°C, and 800°C. The results show a decrease in SCC strength as the exposure temperature increases from 200°C to 800°C. According to Ahn et al. [59], one of the main effects of high temperatures on concrete structures is the reduction of compressive strength in concrete containing coal ashes. Consistent with the findings of this study Yüksel et al. [38] observed increased strength deterioration with rising temperatures up to 500°C. The significant strength losses in concrete containing CBA are likely due to the dehydration of calcium-silicate-hydrate (C–S–H) in the hardened cement paste at higher temperatures. In summary, a marked reduction in strength was noted when concrete samples were heated to 800°C. At 200°C, the compressive strength of SCC containing ground CBA decreased compared to the control SCC with various replacement levels prior to exposure to elevated temperatures. The percentage of strength loss for SCC containing ground CBA at different replacement ratios CBA0%, CBA10%, CBA20%, and CBA30%, were 8.311%, 10.79%, 9.32%, and 13.733%, respectively. According to Mello et al. [60] strength losses were observed in SCC with higher additive contents, which are linked to lower levels or the absence of calcium hydroxide (C-H) in their compositions. This deficiency leads to greater strength losses due to the dissociation of $Ca(OH)_2$ at 200°C. As the temperature increased to 400°C, further strength loss occurred in SCC containing ground CBA, especially in mixtures with replacement ratios from CBA10% to CBA30%, as well as in the control SCC samples. According to Rafieizonooz et al. [61] noted the effects of coal bottom ash (CBA) as a replacement material in concrete exposed to elevated temperatures of 400°C. The findings indicated that strength loss increased with rising temperatures, resulting in a decrease in compressive strength, which can be attributed to ongoing dehydration and decomposition of the cement paste in the concrete samples. When heating extended beyond 600°C, a continuous increase in strength loss was also noted in SCC with ground CBA and in the control samples. Notably, the highest strength loss in SCC was recorded at 800°C, with strength loss levels for SCC containing CBA at 0%, 10%, 20%, and 30% being 44.5%, 40.61%, and 46.05%, respectively. The results indicate that the strength loss in SCC specimens with ground CBA was greater than in the control SCC, attributed to the decomposition of ground CBA at high temperatures, which results in the formation of pores and cracks in the matrix. The researchers also noted that these pores facilitate heat dissipation and contribute to crack formation as shown in Fig. 6.

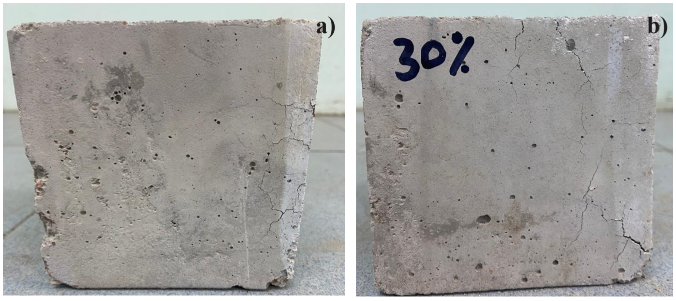

Fig. 6. The samples after exposed to fire resistance a) 10 CBA at 800°C b) 30 CBA at 800°C

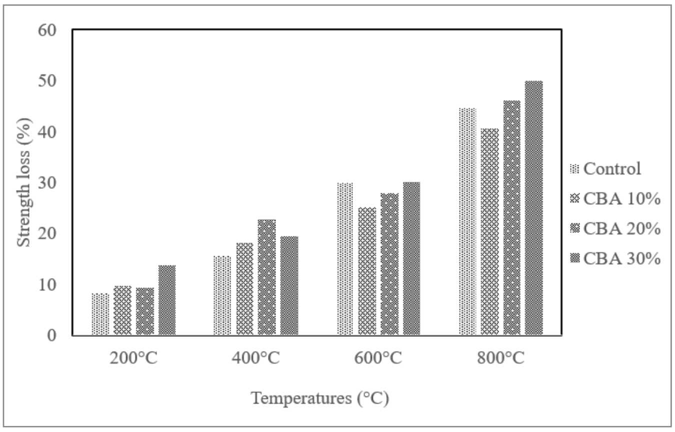

Fig. 7. Effect of temperature towards strength loss of SCC containing ground CBA when subjected to elevated temperature

4. Conclusion

This research highlights the effects of using ground CBA as a cement replacement on fire-resistant properties. The following points outline the mechanical properties and fire resistance of self-compacting concrete (SCC), including compressive strength, strength loss, and mass loss:

i. All SCC mixtures can be produced with appropriate fresh characteristics, such as slump, by substituting cement with ground CBA, which falls within standard ranges.
ii. The partial replacement of cement with coal bottom ash (CBA) in mortar produced favorable mechanical performance. At 28 days, the compressive strength of all samples met the required standards. Furthermore, the optimal replacement level for maintaining adequate strength was identified to be up to 20%.
iii. The mass loss in SCC using CBA as a partial cement replacement was found to significantly increase as the temperature rose, peaking at 400ºC. This increase in pore volume can be attributed to the lower specific gravity of CBA.
iv. Visual inspection reveals minimal color change up to 200°C. However, once the temperature exceeds 400°C and approaches 600°C, the samples begin to crack and exhibit noticeable color changes.
v. The study indicates that the residual compressive strength of SCC with CBA as a partial cement substitute shows a slight increase at 200°C.
vi. Additionally, the residual hardened properties of the SCC mix that achieved the highest strength (i.e., containing up to 20% CBA) were experimentally evaluated after exposing the concrete samples to elevated temperatures of 200, 400, 600, and 800°C
vii. Furthermore, incorporating ground CBA as a replacement material in SCC not only meets the necessary strength requirements but also benefits the environment by reducing the depletion of natural resources and minimizing CBA waste in landfills.

Acknowledgement

The authors would like to express their heartfelt gratitude to the Ministry of Higher Education for the financial support provided through the Fundamental Research Grant Scheme (FRGS) No. (FRGS/1/2022/TK01/UMP/02/5, university reference RDU (220112). They also wish to thank Universiti Malaysia Pahang AL-Sultan Abdullah (UMPSA) for offering laboratory facilities. Additionally, the authors appreciate the further assistance received from internal grant No. RDU 223313 and the financial aid provided by the Doctoral Research Scheme (DRS).

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