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REVIEW ARTICLE

Engineering properties of self-compacting concrete incorporating coal bottom ash (CBA) as sustainable materials for green concrete: a review

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Abstract

Over the past two decades, concrete has been frequently employed in the construction sector because of its features. The development of massive concrete buildings with more complicated geometries and dense reinforcing has been growing progressively. Moreover, there is an increased need for improving the current practices of concrete technology to create new forms of concrete with better qualities, which encouraged scholars to advance further investigations in this area of research. Consequently, an innovative type of concrete called Self-Compacting Concrete (SCC) has been improved. Simultaneously, one key challenge, confronted by the civil engineering sector, is how to go more environmentally friendly. Using reused waste materials, e.g., coal bottom ash (CBA), is one of the carefully utilized techniques in construction and building applications. The CBA's pozzolanic characteristic with high silica and its useful pozzolanic capabilities have effectively turned CBA into a beneficial substitute in self-compacting concrete. Therefore, CBA has been successfully employed in producing SCC. Research into CBA function in SCC production not only contributes to increasing its use but also helps decrease the cost of landfills and provides a clean, sustainable, and environmental solution by conserving energy and reducing the depletion of natural resources. In this study, an overview of previous studies on CBA's physical and chemical characteristics has been thoroughly presented. Moreover, the impact of CBA on the self-compacting concrete's fresh and mechanical properties is discussed. Results indicated that using up to 10% CBA in SCC as sand replacement resulted in improved fresh and hardened properties.

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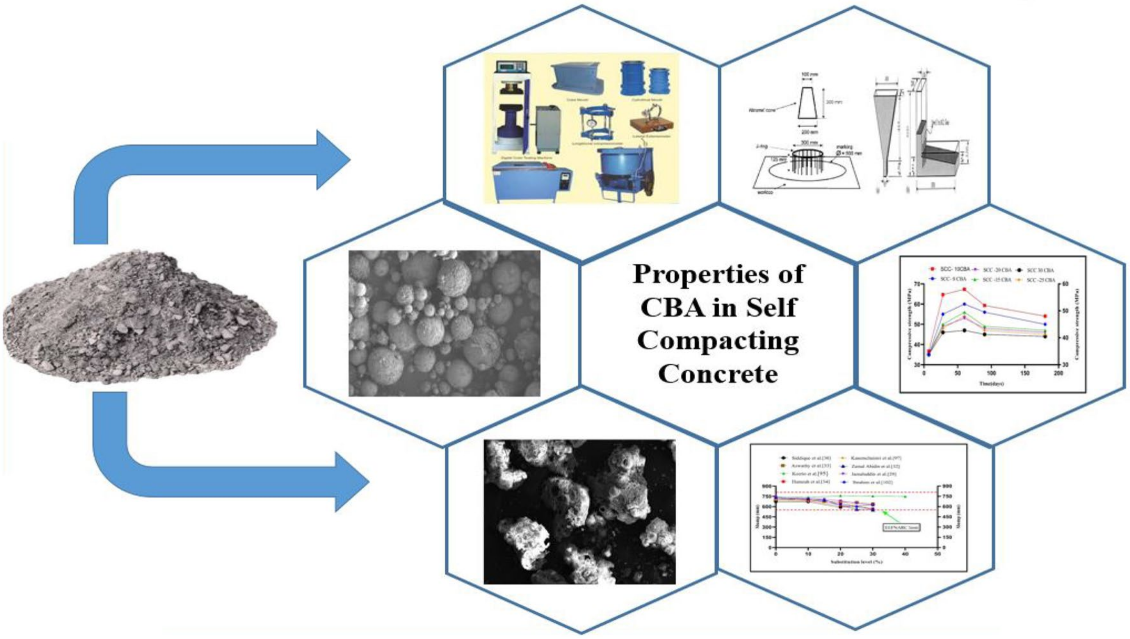
Graphical abstract



Keywords Coal bottom ash · Self-compacting concrete · Compressive strength · Green concrete · Mechanical properties · Sustainable concrete · Replacement material · Fresh properties

Abbreviations

SCC	Self-compacting concrete
CBA	Coal bottom ash
FA	Fly Ash
EIA	Environmental impact assessments
EDX	Energy dispersive X-ray spectroscopy
W/B	Water to binder ratio

1 Introduction

Concrete is a significant component in construction [1]. Concrete has been developed from a material, which mainly incorporates cement, aggregate, water, in addition to a few admixtures to a specifically engineered material, which is made of various additional ingredients that enhance performance in a range of exposure circumstances [2, 3]. Concrete is a frequently utilized building material due to its beneficial characteristics [4, 5]. However, conventional concrete has some flaws in the commercial use of ordinary concrete. To tackle several issues of limited construction, such as intricate designs, the density of reinforcing steel in structural components, a shortage of skilled labor, the construction industry's fast development, and the poor quality of construction, have altogether prompted the implementation of self-compacting concrete (SCC) to address these issues [6–8]. In 1988, Okamura was the first engineer to introduce the utilization of SCC, which was developed to tackle various problems related to building extremely overcrowded reinforced concrete components [9–12]. The aim of developing self-compacting concrete primarily involves creating an innovative concrete type. This concrete can flow through and fill the mold corners and reinforcing spaces without using vibrations or compacting throughout the casting process [13, 14].

Self-compacting concrete, shortened as (SCC) is defined as a concrete process that uses a specialized technology for flowing and filling the space in between reinforcing and the high-performance concrete [15]. Furthermore, this type of concrete, i.e., SCC amalgamates appropriately under self-weight, and it increases the resistance of hardened concrete without segregation, bleeding, or any other heterogeneity of components [16–18]. Such concrete qualifies are useful for practical uses [16–18]. Using plasticizers and powder admixtures is, thus, critical for the flowability, stability, and impermeability of self-compacting concrete as the hardened concrete longevity can be enhanced and compressive, tensile, and bending strengths are improved [19]. Sulphates and chlorides exhibit an increase in their concrete resistance. Also, it is eco-friendly and effectively minimizes carbon dioxide emissions and noise generated by dynamic compaction [20, 21]. The efficiency and long-term benefits of using mineral admixtures and additional cementitious materials like fly ash and Coal Bottom Ash (CBA) are relevant to SCC to achieve durability growth and maintain a wider economy towards a cost-cutting strategy [22, 23]. Besides, the incorporation of mineral admixtures allows for the preservation of workability and long-term properties [22, 24].

The growing exploitation of natural resources has resulted in a noticeable increase in industrial waste and environmental pollution [25, 26]. Therefore, it is essential to minimize the use of natural resources considerably so that future generations' activities will not be endangered [27–29]. As a result, it has become increasingly critical to find innovative, alternative materials for sustainable development. The coal-fired power plant is, however, the main energy-generation source in almost every country worldwide [30]. Coal thermal power stations have been generating huge FA and CBA amounts for many years so far, which accounted for 20 to 80%, respectively of total emissions in the environment [31, 32]. Malaysia contributes to approximately 1.7 mil tons of CBA and 6.8 mil tons of fly ash production each year. CBA utilization in the building sector is a practical replacement option for reducing a variety of ecological problems [31, 33]. Previous studies delivered a list of various management techniques for using CBA. The incipient concerns of CBA are directly linked to the scarcity of disposal locations, the unrelenting growth of production, and the continuous loss of natural resources [30, 34]. Previous findings on using CBA as a suitable construction material provided several advantages to the industry, such as the fact that it is relatively inexpensive, light, and suitable for utilization as a suitable sand aggregate substitute in the SCC the application [35–37].

The use of CBA, in the current and future construction sector has been promoted because it has a similar particle size distribution, as well as additional pozzolanic characteristics as a replacement material in SCC. Therefore, it has been widely researched and debated as an alternative material [38, 39]. According to previous researchers [37, 40–42], SCC is made by mixing CBA with cement additives, including metakaolin and fly ash. However, with the inclusion of a water reduction agent, fine aggregate is substituted with 10 to 30% of CBA. Similarly [43, 44] found that SCC containing fly ash and CBA has been made to conform to the required criteria of fresh SCC and, as determined. According to [42] the optimum replacement level of fine aggregate with CBA can be up to 10% that would provide comparable performance to concrete made with 100% fine aggregate. Upon employing the mechanical characteristics of the SCC mix as a guide, it was shown that the optimum proportion of CBA can be replaced in the combination of up to 20% of fine aggregate. Moreover, studies highlighted CBA's significant benefits, as the bulk of the SCC mechanical characteristics produced by adding 10% to 15% of CBA instead of fine aggregate, enhanced overall performance [41]. For utilizing CBA, the physical and chemical properties, together with fresh, as well as mechanical properties in the SCC mixture should be investigated. The review in this paper aims to outline the findings of previous studies about the utilization of CBA in self-compacting concrete. This paper also aims to provide a critical and comprehensive review of previous research on the CBA utilization as a suitable alternative material in SCC mixes. Furthermore, this paper aims to examine the CBA effect on concrete performance.

2 Research significance

In the construction industry, awareness about sustainable development has been growing considerably in recent years accompanied by the need to mitigate the industry's environmental negative impact. A variety of industrial wastes have, therefore, been utilized in construction, especially in the production of concrete. Different industrial wastes can be exploited as partial or whole replacements for various concrete components. Using an industrial waste like CBA as a substitute material in making SCC is a good example. Several studies investigated the parameters, which affect the SCC's mechanical behavior, as well as fresh concrete properties by using industrial wastes. In construction, resources are being recycled to produce sustainable concrete. CBA is a problem that affects people's health and the environment as well. Recycling CBA and replacing it with main components of concrete could help conserve primary resources and reduce the emission of gases, which unfavorably influence human health. This review paper demonstrates that the utilization of CBA in producing SCC can help mitigate the depletion of raw materials. Limited studies that conducted with the aim of providing a comprehensive review analysis of previous researches regarding the use of CBA in SCC. Therefore, this review presents and discusses previous studies on using CBA as a substitute material in construction. The present review also investigates the CBA effects on the SCC fresh and mechanical properties. To this end, previous findings are examined and evaluated, and the main concrete properties are reviewed and compared to achieve optimal results. It is believed that providing a conclusions regarding the best practice of utilizing such material (CBA) in SCC is viable for guiding future researchers.

A Schematic diagram of the procedures used to conduct this review paper is presented in Fig. 1.

3 Coal bottom ash

3.1 CBA As waste material

CBA is a key source of industrial waste, which is produced by coal thermal power stations. Using CBA can potentially

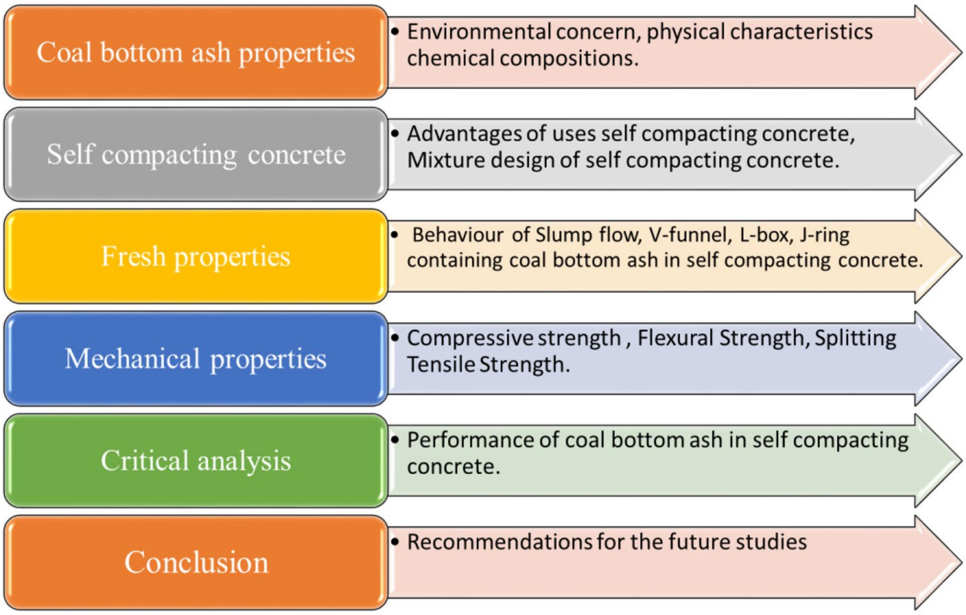


Fig. 1 Schematic diagram of the procedures used within this review paper

Table 1 Utilization of recycled CBA waste in various applications in (tones) [48]

Application	CBA (tons)
Concrete/concrete production./grout	785,527
Blended cement/raw feeder for clinker	1,622,612
Structural fill/embankment	871,875
Road bases/sub-bases	159,084
Aggregate	10,237

contribute to sustaining the global economy in construction because CBA plays a key role in mitigating the depletion of natural resources [45]. In the whole world, and particularly in the Malaysian context, eliminating CBA constitutes a crucial issue because of an acute shortage in dumping sites, in addition to the rising environmental impacts. CBA's chemical properties incorporate high silica (SiO_2), which is the reason why CBA enjoys good pozzolanic properties [32, 46]. Previous studies stated that the use of CBA in producing concrete contributes to enhancing concrete's durability and its compressive strength. This is because CBA has an increasing pozzolanic reactivity and filler impact. Therefore, CBA constitutes a beneficial supplementary cementitious material in produced concrete [40, 47]. Furthermore, according to what has been mentioned in 2018 by the American Coal Ash Association, CBA has been broadly utilized in the fill and embankment, as well as other construction applications as demonstrated in the subsequent Table 1 [48].

3.2 Environmental sustainability and health Assessment of CBA

The CBA environmental sustainability can be periodically assured by conducting environmental impact assessments (EIA) throughout a product's life cycle. However, the open disposal of CBA by coal thermal power plants, as well as many industrial sectors led to creating considerable ecological contamination, which resulted in major health hazards [49]. From an environmental perspective, utilizing CBA in the civil engineering application is a feasible solution for the significant disposal problems of such waste materials [50, 51]. PÖYKIÖ et al. (2016) emphasized that CBA disposal must be carefully handled either to avoid or mitigate environmental problems since CBA use is currently limited and at a low percentage [52]. Siddique et al. and Laura et al. [53, 54] conducted a CBA chemical analysis to determine the percentages of several existing elements like copper, zinc, barium, arsenic, mercury, and nickel. Several previous studies found that the existence of excessive amounts of heavy metals can inflict serious damage to living organisms' tissues. Accumulating CBA in wide-open areas increases the likelihood of inhaling dangerous metals, such as copper, zinc, arsenic, barium, nickel, cadmium, mercury, aluminum, antimony, selenium, chromium, etc. The amount of metals, therefore, increases the risk of irreversible damage to the respiratory system, the genital system, and the gastrointestinal system, as well as lungs, kidneys, and raises the risk of birth abnormalities, and can lead to decreasing bone density in children [55–57]. Furthermore, Hashemi et al. and Aggarwal et al. [58, 59] examined concrete features of CBA radiation safety. In order of radioactive exposure, using CBA exerts a more beneficial environmental effect in the concrete industry compared to using it in heaps and ponds. Fly ash is utilized in the cement industry, and certain facilities have arranged with power plant operators to collect their fly ash regularly [60, 61]. Therefore, it is essential to research the CBA chemical composition to determine the risk and behavior associated with its influence on the environment.

3.3 Physical characteristics and chemical composition of CBA

The CBA physical characteristics and chemical composition in SCC differ not only based on the coal source but also the process of day-to-day manufacture and the production of coal in coal-fired power plants. This, in turn, affects the performance of CBA in SCC. The physical characteristics and chemical composition were investigated as reported by previous studies in the following sub-section.

3.3.1 Physical characteristics

Table 2 provides the CBA's physical properties according to previous studies. The CBA physical characteristics in SCC depend on the size of particles and behavior [41, 42]. The color of raw CBA is grey; however, it becomes rather a dark grey after its grinding process, i.e., blackish [39]. Moreover, following the findings by several researchers, CBA is a substance of a dark grey color with most of its constituent particles being angular in shape and can be handled as a porous material of a gruff surface textile of low unit weight. Furthermore, according to the microstructure FESEM test, various CBA's are obtained from different sources. As shown in Fig. 2 and Fig. 3, CBA is a material, which is characterized by a porous irregular shape of a dense structure [45] and [62], respectively.

Table 2 CBA physical characteristics according to previous studies

References	Specific gravity	Fineness modulus	Water absorptions %
[63]	2.08	1.5	6.8
[64]	2.1	2.93	9.7
[65]	2.08	2.93	9.6
[66]	1.8	–	17
[67]	1.11	2.36	28.85
[68]	2.51	2.77	5.10
[69]	3.83	1.84	6.87
[70]	2.21	2.79	–
[35]	2.08	1.5	6.8
[58]	1.80	–	2.77
[71]	2.1–2.5	1.5	6.8
[72]	1.9	2.4	8.1

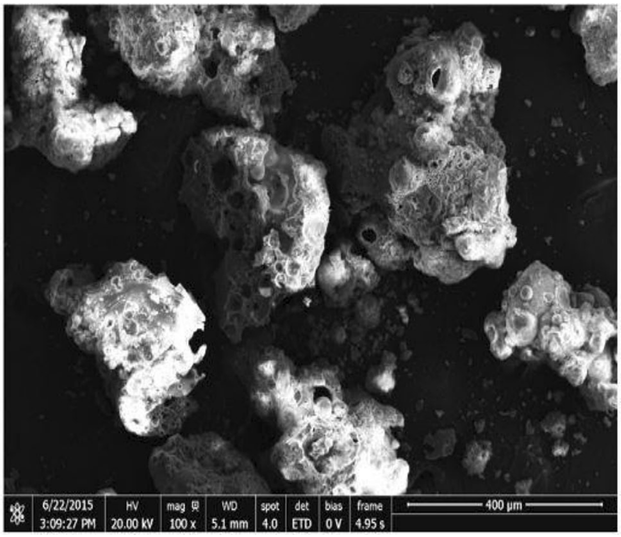


Fig. 2 Original CBA particles obtained from the Mae Moh thermal power plant [62]

3.3.2 Chemical composition

Scholars have examined the CBA chemical properties, as provided in Table 3 and the chemical composition of CBA was studied using microstructure analysis like energy dispersive X-ray Spectroscopy (EDX) as mentioned in previous studies [59, 73]. Its chemical composition depends on the source of coal, as well as the technique of combustion. CBA has significant concentrations of alumina, silica, and

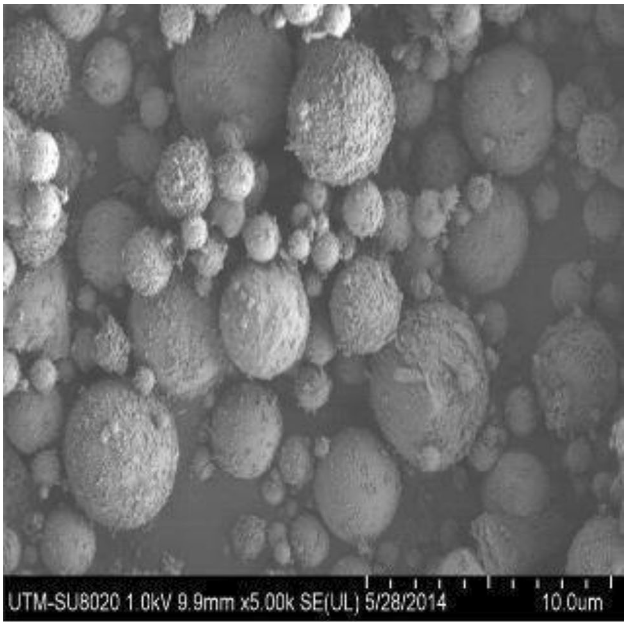


Fig. 3 Original CBA particles obtained from Tanjung Bin Power Plant [45]

Table 3 CBA's chemical composition properties based on previous studies

Chemical elements/References	[75]	[51]	[76]	[77]	[78]	[79]	[80]	[81]	[82]	[83]
SiO_2	52.4	45.37	59.82	56.44	42.51	48.0	62.32	41.70	58.7	44.10
Al_2O_3	27.5	25.12	27.7	26.24	23.52	20.1	27.21	17.10	20.1	9.21
Fe_2O_3	6.6	5.81	3.77	8.44	10.2	8.77	3.57	6.63	6.2	24.30
CaO	2.4	0.99	1.86	0.75	12.55	7.11	0.50	22.50	9.5	13.00
MgO	1.83	1.16	0.7	0.4	2.45	3.13	0.95	4.91	1.6	1.88
SO_3		–	1.39	0.24	–	–	–	0.42	0.4	
K_2O	3.48	3.87	1.61	1.29	2.12	–	2.58	0.40	1.0	1.25
Na_2O	0.36	0.64	0.33	0.09	2.2	–	0.70	1.38	0.1	–
TiO_2	0.97	2.84	–	3.36	0.41	1.11	2.15	3.83	–	–
P_2O_5	0.12	0.18	–	–	0.17	–	–		1.0	–
Loss on ignition	3.8	13.1	4.69	0.89	3.82	8.10	–	1.13	0.8	–
$SiO_2+Al_2O_3+Fe_2O_3$	86.5	76.3	91.29	91.12	76.23	76.87	93.10	65.43	85.0	77.61

iron; these are frequently found in such pozzolanic materials, whose total amounts make up between 70 and 93% of the overall chemical composition of coal. The loss on ignition of CBA has been reported by previously conducted studies, ranging between 0.8 and 13.0. CBA is categorized as either (Class C or Class F) pozzolanic material, following ASTM C618 [74] and following data gathered from a variety of studies. Nonetheless, the CBA coarse particle size can lead to a lower degree of pozzolanic reactivity. Therefore, when CBA is ground to smaller sizes, this enhances silica and CBA reactivity.

4 Self compacting concrete

4.1 Advantages use of self-compacting concrete

Recently, a considerable significance has been directed towards SCC due to the benefits it provides, such as minimizing building time, lowering labor costs, and improving structural compaction for reinforced complicated shapes [14, 84, 85]. The SCC containing CBA has fresh characteristics to guarantee that it functions very well in the mixture [63, 86]. The SCC fresh characteristics, including mobility, filling capability, passing capability, and segregation resistance, are critical criteria that influence the effectiveness of SCC with the CBA use [87, 88]. In general, SCC can be obtained by utilizing a new superplasticizer generation by reducing the ratio of water/binder (w/b in concrete). SCC has one downside, which involves the increased costs due to using chemical admixtures like superplasticizers [42]. Additionally, supplementary material ingredients, such as CBA are utilized to enhance the SCC viscosity and lower its cost [47]. Moreover, previous scholars examined self-compacting concrete, utilizing various additives, namely CBA. They found that CBA is an effective ingredient for SCC because of its lightweight and hard nature in reducing environmental contamination caused by this waste. Furthermore, the utilization of natural resources linked with main materials production causes severe environmental impacts [89–91].

4.2 Mixture design of self-compacting concrete

In 1995, H. Okamura introduced the first recommended SCC mixture design, dubbed as the Japanese or rational technique at that time. SCC is capable of flowing under its weight for filling gaps in the piece of work, flowing freely all through the reinforcing bars without external vibrator support. Also, it allows further concrete's accurate leveling when placed without any segregation [92–94]. Therefore, when the SCC mixture design was developed, various assessments were conducted, such as V-Funnel, slump flow, and L-Box to evaluate fresh state properties and the SCC limitation according to EFNARC guidelines as illustrated in Table 4 [95]. This method is referred to as an empirical design [95]. Nan Suet al. [96] presented the conventionalized empirical design

Table 4 Recommended values of SCC fresh properties following EFNARC [95]

Slump flow		V-funnel test		L-box test	
Slump flow classes	Slump flow (mm)	Viscosity classes	V-funnel times (s)	Passing ability classes	Blocking ratio (H2/H1)
SF1	550–650	VF1	≤8	PA1	≥0.8 with 2 bars
SF2	660–750	VF2	9–25	PA2	≤0.8 with 3 bars
SF3	760–850	–	–	–	–

approach's simple application for implementation and stated that this method may significantly decrease the amount of time, binders, and expense involved. This approach primarily aims to enhance workability via the utilization of a specified amount of paste material for keeping every aggregate material in place, thus increasing the freshness and strength of the concrete. This is often referred to as the technique of packing aggregates closely [10]. This means that SCC should use a minimum coarse aggregate amount volume, an increased paste volume, an increased powder volume, a lowering water-to-powder ratio, a higher superplasticizer dose, and an infrequently necessary viscosity modifying agent [96]. Recent studies have summarized the SCC mixture design [97] and, in 2015, it was found that the SCC mixture design is determined by five factors. These include 1) an empirical design method, 2) a close aggregate packing technique, 3) paste rheology, 4) a method of compressive strength, and 5) a statistical factorial approach [95]. Previous research has shown that the SCC compressive strength ranged between 20 and 100 MPa at 28 curing days, with 40 MPa as a mean compressive strength [98–100]. SCC has a high resilience degree. Also, no extraordinary mix design is required if it achieves real applicability, economy, practicability, and high quality in both its fresh and hardened states. General exhibits are determined as a part by the basic materials used in the mix design [101].

5 Fresh properties of self-compacting concrete incorporating CBA

As displayed in Table 5, previous studies reported the results of fresh properties tests of CBA in the SCC, showing the range of fresh properties and the impact of adding varying ratios of CBA substitution in SCC.

5.1 Slump flow test

The slump flow test involves an average diameter of a concrete volume after releasing the conventional slump cone. It can be assessed on a couple of perpendicular sides [95]. As shown in Fig. 4, previous research identified the CBA quantity impact on the SCC passing ability. Siddique et al. [38] studied the SCC fresh properties with the use of CBA at 10%, 20%, 30%, and this superplasticizer amount (1.88–2.0%). The results showed that slump flow increased for all the replacement percentages, excluding the one containing 20% CBA and 1.90% of superplasticizer (591mm) [38], as per the guidelines outlined by the standard EFNARC, ranging between (650–800 mm) of SCC [95]. Increases in the superplasticizer amount resulted in a higher flow, while increases in the CBA amount resulted in a reduction of slump flow [38]. In their study, Ibrahim et al. [42] studied the slump flow for SCC and the results revealed a 740–540 mm range and reported a relative difference between various mixes because the flow characteristics of self SCC mixtures contain CBA, which have a higher viscosity than control specimens [42]. Another study by Keerio et al. [102] produced various SCC mixes using CBA (10–40%) as a fine aggregate substitute and found that CBA content increased and the slump flow decreased due to the CBA porosity, which, compared with fine aggregate, absorbed more water. The findings of another study, conducted by Hamzah et al. [103] revealed that the time of slump flow increased with an increase in the CBA replacement content in SCC. Mixtures containing 0–30% CBA content showed slump flow time, ranging between 2 and 5 s, i.e., in line with the range outlined by EFNARC [95]. The reason is that the CBA's irregular shape lowered inter-particle friction with the addition of CBA, which decreased the SCC mixes' viscosity.

5.2 L-Box test

The percentage of L-box elevation can be used in tandem with the H2/H1 ratio to define the self-compacting concrete's passing abilities [95]. Several previous studies examined the effect of CBA quantity on the SCC L-box test, as shown in Fig. 5. Kasemchaisiri et al. [104] reported that the L-box passage ratio was between 0.83 and 0.05 and that the value decreased in all mixtures as the CBA percentage in SCC increased. A reduction in the L-box ratio due to the presence of aggregate blockage in a mixture of self-compacting concrete, containing CBA, was detected and a greater level of inter-particle friction was produced by the CBA particles [104]. Similarly, another study by Jamaluddin et al. [37] reported a decrease in the L-box test results with increasing the replacement proportion of CBA incorporated into the SCC mixture. Nevertheless, when the w/b proportion increases, the value of the L-box decreases. The results varied between 0.9 and 0.66, indicating that the concrete mixture without CBA had a higher passing ability [37]. This is due to the aggregate clogging up in front of apertures, which made it difficult for particles to flow freely without occlusion [37].

Hamzah et al. [103] observed that the L-box flow results improved with increasing the CBA proportion in concrete. The range is between 0.7 and 0.95 [103]. According to Singh et al. [35], an increase was observed in the L-box ratio, thereby increasing the replacement proportion of CBA in the SCC mixture. The value reached up to 1.0 in a 30% of CBA, with a greater value, which showed an improved passing ability [35]. EFNARC standard guideline [95] categorized L-box passing ratios as (passing ability1(PA1) with

Table 5 Summary of CBA Fresh properties in the SCC mixtures

References	CBA replacement (%)	w/b	Superplasticizer (%)	Fresh concrete properties			
				Slump flow (mm)	L-box (H2/H1)	V-funnel (s)	J-ring (h2–h1 mm)
[95]	–	–	–	650–800	0.8–1	–	–
[42]	0	0.4	0.16–0.36	730	0.94	–	–
	10			710	0.859	–	–
	20			640	0.80	–	–
	30			570	0.74	–	–
[103]	0	0.35, 0.40 0.45	0.16–0.30	730	0.70	–	–
	10			710	0.8	–	–
	15			690	0.82	–	–
	20			640	0.85	–	–
	25			600	0.9	–	–
	30			560	0.95	–	–
.[102]	0	0.38	2.0–17.0	740	0.83	7.4	2.5
	10			735	0.85	11.2	4.5
	20			760	0.92	11.89	7.4
	30			755	0.87	10.22	8.7
	40			750	0.89	12	6.8
. [37]	0	0.35, 0.40, 0.45	0.16–0.32	745	0.90	–	–
	10			725	0.81	–	–
	15			708	0.80	–	–
	20			685	0.77	–	–
	25			648	0.70	–	–
	30			625	0.66	–	–
[104]	0	0.31	1200 cc/m^3	700	0.83	–	–
	10			680	0.80	–	–
	20			670	0.60	–	–
	30			560	0.50	–	–
[38]	0	0.41–0.55	1.88–2.0	673	0.89	7.50	2.3
	10			673	0.80	6.60	4.6
	20			591	0.95	6.20	4.7
	30			627	0.82	4.0	11.6
[41]	0	0.68	5.16	702	0.99	8	–
	5			696	0.97	8	–
	10			676	0.96	10	–
	15			670	0.9	11	–
	20			660	0.89	12	–
	30			640	0.88	12	–
[40]	0	0.4	0.20	715	0.92	–	–
	5			705	0.89	–	–
	10			700	0.84	–	–
	15			615	0.79	–	–
	20			560	0.75	–	–
	30			550	0.65	–	–

two rebars) or (passing ability 2 (PA2) with three rebars). The findings provided by each researcher indicated that the L-box passing ratio is within the acceptable range [95].

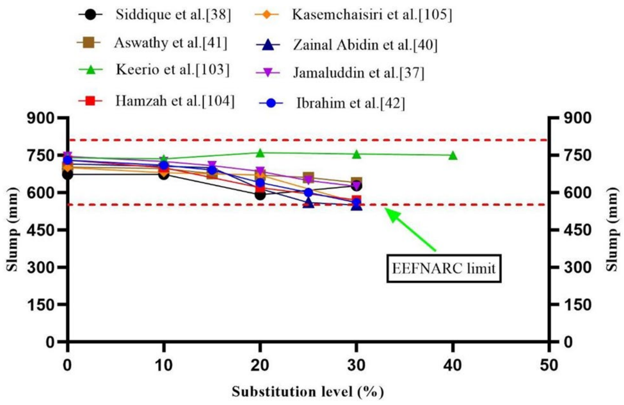


Fig. 4 Variation of slump values in SCC with varying CBA substitution ratios

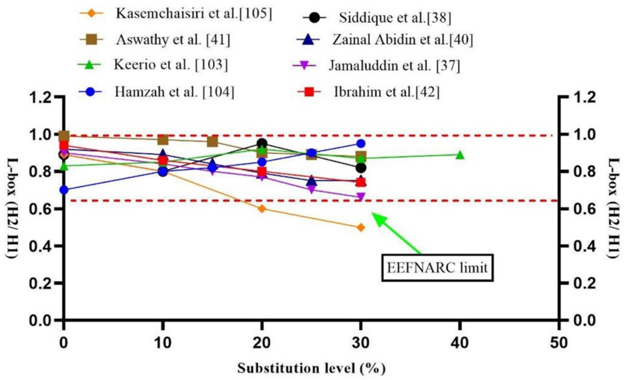


Fig. 5 L-box values' variation in SCC using varying CBA replacement ratios

5.3 V-funnel test

This conducted test verifies the SCC mixtures' viscosity and flowability. A mixture's better flowability denotes a very short flow time and, as per EFNARC, the V-funnel test's duration ranges between 6 and 12 s [95]. It was established in another previous study that the V-funnel flow time for several types of SCC ranged between 2.5 and 4.6 s according to Keerio et al. [102]. They found that the V-funnel flow time of SCC increases as the replacement ratio of CBA increases. They also confirmed that a high quantity of superplasticizer is required for producing SCC when CBA is combined with metakaolin, as compared to SCC made without any replacement materials [102]. Likewise, Aswathy et al. [41] observed an increment in the V-funnel value as the percentage content of CBA increased. The finding of V-funnel value between 8 and 12 s, signifying an enhanced passing ability [41]. The EFNARC standard guideline [95] categorized V-funnel flow time into two categories: VF1 (8 s) and VS2 (9–25 s) [95]. According to the findings obtained by each researcher, the V-funnel flow time of certain results falls into the VF1 category, while others fall into the VF2 category [95].

5.4 J-ring test

The J-ring test, in parallel to the L-box test, can be applied in conjunction with the test of slump flow to ascertain that concrete can pass-through bars, as per EFNARC [95]. According to ASTM C1621 [105], J-ring can be defined as a method of testing concrete's capacity of passing through under its weight, thereby filling spaces, and getting a blocking evaluation [105]. The J-ring flow results were reported by Siddique et al. [38] which ranged between 2.3 and 11.6 mm for various self-compacting concrete. The results of the J-ring flow of SCC containing CBA rose as the CBA amount increased for all the mixtures [38]. Also, based on another study by Keerio et al. [102] the values of the J-ring ranged between 2.5 and 8.7 mm. As observed, the values increased with an increase in the CBA replacement ratios in the SCC mixture [102].

6 Discussion of finding from fresh properties

Existing research indicates that the ideal content of CBA is between 10 and 20% to meet the criteria of "filling and passing ability" and "segregation resistance". The dependence of the result depends on the water-binder ratio and the amount of superplasticizer used. An increase in the CBA content has been observed to have a negative effect on processability and segregation. CBA has the potential to be used at 10% to 20% in SCC, meeting standards set by the European Federation of National Associations Representative for Concrete (EFNARC). Based on the above-mentioned previous studies, it was observed that the key properties of CBA in SCC, namely slump and L-box ratio, show a decrease, while J-ring and V-funnel values increase with increasing substitution ratio of CBA in the concrete mix. The reduction in the freshness properties of the mixture can be attributed to the absorption of moisture content by the CBA particles, resulting in increased friction between the aggregate particles generated by the CBA particles. The conclusions from all of the previous studies support the criteria and limitations established in the SCC standards and recommendations, including the requirements of EFNARC, 2002, and ACI 237R-07.

7 Mechanical properties of self-compacting concrete incorporating CBA

The next sub-sections discuss the mechanical properties of self-compacting concrete (SCC) incorporating CBA. The discussion includes compressive strength, flexural tensile

Table 6 Summary of mechanical properties of CBA on SCC mixes

References	CBA replacement ratio (%)	Finding		
		Compressive strength	Flexural strength	Split tensile strength
[44]	0, 10%, 20%, 30%	Decreased for all replacement percentages	–	Decreased for all replacement percentages
[39]	0, 10%, 20%, 30%	Reduction for all replacement percentages	–	Decreased for all replacement percentages
[63]	0, 10% CBA mixed with 25%, 50%, 75% and 100% recycled coarse aggregate	Decreased for all mixes and all replacement percentages for early age for long term increased in each percentage	–	Decreased for all mixes and all replacement percentages for early age for long term increased in each percentage
[35]	0, 10% of CBA mixed with 20% and 30% of FA, and 10% of MK	Increased in all percentages of CBA replacement with RCA up to 50 after that drop in higher percentages	–	A drop in all percentages of replacement expect at 50% of RCA
[38]	0, 10%, 20, 30%	Decreased in all replacement percentages at all curing ages	–	Decreased in all replacement percentages at all curing ages
[37]	0, 10%, 15%, 20%, 25%, 30%	–	Increased by 10% replacement other percentages was decreased as CBA increased	–
[40]	0, 10%, 15%, 20%, 25%, 30%	Increased by up to 15% CBA and other percentages was decreased as CBA increased	–	–
[104]	0%, 10%, 20% and 30%	increased by 10% CBA and other percentages were decreased as CBA increased	–	–
[47]	10%, 15%, 20%, 25% and 30%	Reduction for all replacement percentages	–	–
[41]	5%, 10%, 15%, 20%, 25% and 30%	Increased by 5% and 10%, while other percentages were decreased as CBA increased	Increased by 5% and 10%, while the other percentages were decreased as CBA increased	Increased by 5% and other percentages were decreased as CBA increased
[109]	0, 10%, 15%, 20%, 25%, 30%	Increased by up to 10% CBA and other percentages was decreased as CBA increased	Increased by up to 10% CBA and other percentages were decreased as CBA increased	Increased by up to 10% CBA and other percentages were decreased as CBA increased
[90]	0, 10%, 15%, 20%, 25%, 30%	Increased by up to 15%, and other percentages were decreased as CBA increased	Increased by up to 15%, and other percentages were decreased as CBA increased	Increased by up to 15%, and other percentages were decreased as CBA increased
[102]	0.10%, 20%, 30%, 40%	Increased in all replacement percentages	Increased in all replacement percentages	Increased in all replacement percentages
[110]	10% CBA, 30% FA and 25% to 100% RCA	Increased by 10% CBA with RCA up 50%, and other percentages of RCA with CBA were decreased	–	–
[107]	0, 10%, 15%, 20%, 25%, 30%	Increased by 10% and other replacement percentages were decreased as CBA increased	–	–

strength, and splitting tensile strength. Table 6 presents a summary of the CBA effect on the SCC mechanical properties based on previous studies.

7.1 Compressive strength

Compressive strength along with fresh characteristics are regarded as the significant valuable features of self-compacting concrete (SCC), providing a complete picture of the condition of concrete as they are closely associated with the cement paste structure [6]. Furthermore, the concrete's compressive strength at room temperature is influenced by ambient curing, water-to-cement ratio, aggregate particles size and category, aggregate-paste interface transition zone, categories of admixture, and stress applied [106]. Previous researchers [47, 104, 107] confirmed the CBA suitable percentages of use in the SCC mix, i.e., 10–20%; such a percentage improved compressive strength properties. Siddique et al. [44] examined how the compressive strength of the SCC containing CBA and coal fly ash can be affected by the utilized water-to-powder ratio. The results showed a comparable behavior with regular SCC when strength was increased by lowering the w/p ratio. Self-compacting concrete showed enhanced strength properties as the w/p ratio decreased, i.e., 0.439–0.414 for the 0% CBA, a decrease from 0.50 to 0.47 for the 10% CBA, with a decrease from 0.58 to 0.51 for the 20% CBA, and from 0.620 to 0.546 for the 30% CBA. Self-compacting concrete can, therefore, be produced at 40–50 MPa compressive strength using various percentages of CBA merged with coal fly ash between 15 and 30%.

As reported by Kasemchaisiri [104] the SCC compressive strength with CBA is 10–30%, compared with the control samples without CBA. It was found that 10% of CBA obtained higher values of compressive strength. Other percentages were decreased, which can be attributed to delayed pozzolanic reaction, which dominated over the raised porosity. Similar observations were also made by [107], whereby increasing replacement amounts of CBA ranging from 10 to 30% decreased the compressive strength. The decrease was between 54 and 42 MPa at 180 curing days, as demonstrated in Fig. 6. Another study by Zainal Abidin et al. [40] recorded an increased compressive strength up to 15% CBA in the SCC mix. These increased properties of strength revealed that there was a pozzolanic reactivity in SCC containing CBA particles. Compressive strength obtained these increases: 44.30MPa, 50.33MPa, 54.05MPa, 37.90MPa, 36.65MPa for CBA0%, CBA10%, CBA15%, and CBA20%, CBA25%, respectively.

A reduction in concrete strength was obtained by Siddique et al. [38] throughout the curing initial stages due to CBA's delayed pozzolanic reactivity. However, the concrete strength improved significantly during the long period of curing. The compressive strength in SCC decreased with increasing the water-to-binder ratio and the proportion of CBA replacement. According to the conducted review of previous studies, the behavior of SCC containing CBA can be affected by the percentages of CBA, the superplasticizer inclusion, and the utilized w/c ratio. Therefore, adding a finer size of CBA using appropriate proportions encourages the formation of pozzolanic reactions.

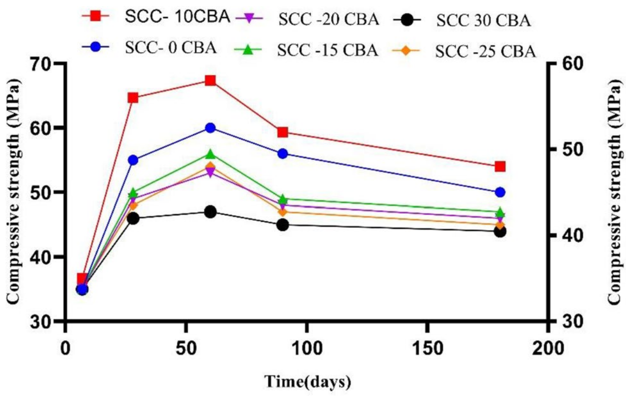


Fig. 6 The samples' compressive strength with varying replacement percentages in SCC [107]

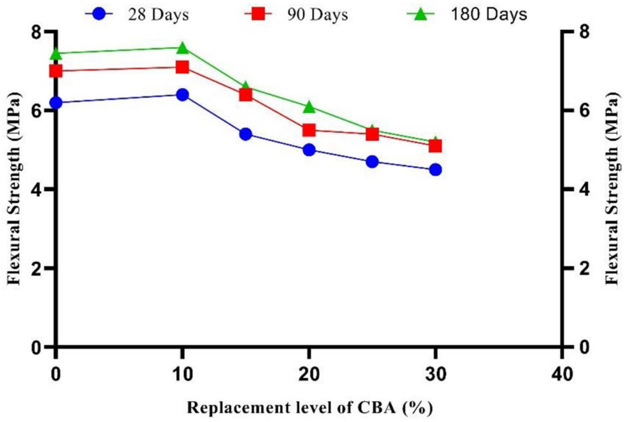


Fig. 7 Flexural strength of samples with various replacement ratios in SCC at different curing ages [37]

7.2 Flexural strength

According to Jamaluddin et al. [37], a reduced flexural strength for SCC incorporating CBA was observed at different ages, as exhibited in Fig. 7. Fine aggregate was substituted with CBA at varying ratios of replacement up to 30%. Furthermore, the optimal percentage of 10% CBA is higher when compared with control samples. The authors reported an increased flexural strength with a higher value of 8.2 MPa with 0.35 w/c during the lengthy time of curing ages. Conversely, the flexural strength was decreased for all water-cement ratios when 15%, 20%, 25%, and 30% alternative of CBA is utilized in SCC [37]. Another study by Zainal Abidin et al. [90] reported that CBA's flexural strength in self-compacting concrete with 10% and 15% alternative of CBA is greater compared to SCC without the addition of CBA at 7–28 ages of curing. Furthermore, flexural strength for other replacement percentages was decreased.

Another study by Siddique et al. [44] reported that the flexural strength of SCC was decreased as CBA increased. They showed that when the CBA replacement ratio increases, flexural strength drops because of a weaker contact between the cement paste and ashes. As per Keerio et al. [102], the SCC mixes' flexural strength with CBA from (10% to 30%) decreased as the replacement percentages increased at various ages starting from 3 to 180 days of curing in contrast to regular concrete without CBA. The reduction occurred due to low inter-particle abrasion between the aggregate particles, as the CBA particles have spheres formed.

7.3 Splitting tensile strength

Various mechanical characteristics of concrete can be assessed using one of the fundamental and significant characteristics [42]. The splitting tensile strength of the concrete structures significantly affects the cracking development and size [42]. Concrete is weak under tension and, therefore, it is essential to conduct a preliminary assessment of the concrete's splitting tensile strength [42]. Another study by Siddique et al. [38] examined the splitting tensile strength of self-compacting concrete containing 10%, 15%, 20%, 25%, 30% of CBA as a partial replacement for fine aggregate in concrete. There was a decrease in the concrete's splitting tensile strength with increased amounts of CBA at the entire ages of curing due to insufficient interlocking of the fine aggregate particles replacing the fine aggregate with CBA. Similar trend observations were also made by Sandhya et al. [108], who reported a decrease in the SCC splitting tensile strength with increased CBA replacement percentages, while strength increased with curing ages.

Another study by Zainal Abidin et al. [90] recorded splitting tensile strengths of 3.6, 3.75, 3.9, 3.5, 3.4, and 3.1 MPa at 28 days, in the examined SCC mixture containing CBA 0,10%, 15%, 20%, 25%, 30%, respectively. An increase was reported in the splitting tensile strength of the samples as the CBA replacement ratio reached 15%, as shown in Fig. 8. Similarly, another study by Aswathy et al. [41] reported an increase in the splitting tensile strength as the replacement ratio of CBA reached 10% using a fixed 0.45 w/c ratio. This increased CBA replacement resulted in more porous concrete, having larger pores, which were scattered across the CBA aggregate surface, thereby decreasing its tensile strength [41].

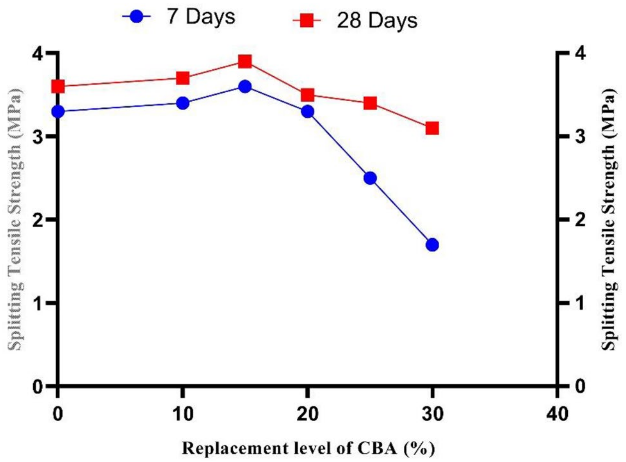


Fig. 8 CBA samples' splitting tensile strength with varying replacement percentages in SCC at different curing ages [90]

8 Discussion of finding from mechanical properties

The investigation of the influence of the CBA volume in SCC on its strength characteristics revealed that the incorporation of CBA as a replacement material at levels of up to 10% yielded a significant improvement relative to traditional concrete. Previous research has shown that the incorporation of a modest amount of CBA in SCC has resulted in notable improvements in mechanical parameters, including compressive strength, split tensile strength, and flexural strength. These enhancements have been seen that reach up to 10% in the majority of the results. The increase in strength may be ascribed to the pore refinement effect resulting from the pozzolanic activity of CBA. The use of CBA as a replacement material leads to an enhanced level of porosity. However, it is worth noting that the presence of silica in CBA particles plays a crucial role in facilitating the synthesis of calcium-silicate-hydrate (C-S–H), a gel-like substance that significantly contributes to the development of strength in materials. The observed increase in strength may be attributed to the higher concentration of calcium silicate hydrate (C-S–H) in the SCC samples mixed with CBA. This increase in C-S–H is a consequence of the reaction between the calcium hydroxide produced during cement hydration and the reactive silica present in the CBA.

9 Conclusion

The aim of this research was to provide a comprehensive review regarding the use of CBA in SCC. Based on the conducted review the following conclusions were drawn:

- CBA can be used to replace up to 20% of the fine aggregate in SCC without negatively affecting its fresh properties and up10% without reducing its mechanical properties considerably.
- Extending the age of curing for samples with CBA can significantly enhance the properties of SCC due to the delayed pozzolanic reaction of CBA.
- The CBA's physical and chemical characteristics are suitable to be effectively utilized in producing self-compacting concrete.
- The CBA inclusion affects fresh properties like (L-box, V-funnel, slump flow, J-ring) in the SCC mixture. The L-box height ratio ranged from (0.8 to 1.0), which is in the range of the EFNARC standard for all SCC mixtures as mentioned by several researchers. For other fresh properties like (V-funnel, slump flow, J-ring) in self-compacting concrete, they were decreased as the substitution ratio of CBA increased.

10 Future recommendations

The utilization of SCC in the building industry has been growing steadily and according to previous studies, SCC has several appealing features. It contributes to enhancing fresh and hardened characteristics, which makes it perfect for effective use in the construction sector. By adding CBA and chemical admixtures, as well as a variety of aggregate percentages, improved fresh and hardened characteristics were obtained. The evaluation has been conducted in line with this review and sufficient materials were provided. However, many gaps remain in this field of research, which should be explored further. To concentrate on the construction industry's use of SCC, it is, therefore, recommended to examine the effect of CBA inclusion on the durability characteristics, such as bond strength, impact resistance, and abrasion resistance. Apart from these mechanical characteristics, time-dependent mechanical characteristics of SCC, such as creep and shrinkage are suggested topics for further studies to narrow the scope of research. The inclusion of CBA as a pozzolanic material and chemical admixtures (superplasticizers) increases the capacity of SCC to pass through and flow. Additionally, limited research has been conducted on the rheological and thixotropic behavior of SCC. Therefore, to obtain a better understanding of workability, such behaviors should be investigated by incorporating CBA into SCC.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval We confirm the ethic approval.

Consent to participate All the authors and contributors have consent for this article.

Consent for publication All authors and contributors have consent to publish in this journal.

Human and animal rights and informed consent This article does not contain any studies involving animals or human participants performed by any of the authors.

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