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Sustainable application of coal bottom ash as fine aggregates in concrete: A comprehensive review

Hussein Hamada [a,*], Alyaa Alattar [b], Bassam Tayeh [c], Fadzil Yahaya [a], Adeyemi Adesina [d]

[a] *Faculty of civil engineering and technology, University Malaysia Pahang, Malaysia*
[b] *Northern technical university, Mosul, Iraq*
[c] *Civil engineering department, Faculty of engineering, Islamic University of Gaza, Gaza Strip, Palestine*
[d] *Department of civil and environmental engineering, University of Windsor, Windsor, Canada*

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ABSTRACT

The significant sustainability awareness in the construction industry coupled with the need for the industry to reduce its negative environmental impacts has resulted in the use of various ↱industrial wastes in construction ↱applications such as in the production of concrete. Various industrial wastes can be utilized as ↱partial or total replacements for some components in concrete. Such industrial waste that ↱can be utilized as fine aggregate in the production of concrete is coal bottom ash (CBA). Various studies have utilized CBA as fine aggregate in various types of concrete including high-strength concrete and there has been significant interest in the continuous use of CBA in concrete. To propel more application of CBA in various concrete types and to increase the understanding of the effect of the CBA on the properties of concrete, this comprehensive review was carried out. The properties explored are fresh, mechanical, durability and microstructural properties of concrete incorporating varying proportions of CBA. Findings from the existing studies indicate there exists a significant variation in the impact of CBA on the properties of various concretes. Nonetheless, numerous studies showed that CBA can be utilized as a sustainable alternative to the conventional natural fine aggregates to produce normal and high-strength concrete. Hence, this study recommends carrying out additional studies in this area to evaluate the effect of the physical and chemical properties of CBA on the resulting properties of concrete.↱

1. Introduction

Sustainable and economical concrete has been widely utilized in the construction of various infrastructures worldwide ranging from structural infrastructures to non-structural infrastructures [1,2]. The extensive utilization of concrete as a preferred construction material is due to the local availability of its components alongside its performance and ability to form it into various shapes [3]. However, depending on the environmental and structural conditions to which concrete structures are subjected, they can also undergo various deterioration processes [4,5]. Such deterioration may occur due to external or internal factors [6]. The properties of the materials (i.e. physical and chemical) which made up the concrete have a direct influence on the corresponding performance of the

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* Corresponding author.
E-mail address: enghu76@gmail.com (H. Hamada).

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concrete [7]. Thus, it is critical that there exists a comprehensive understanding of how various materials used as a component in concrete influence its performance especially when materials such as industrial wastes are utilized [8–10].

Over the years, various types of industrial and agriculture wastes have been utilized in different types of concrete to reduce their detrimental environmental impact and cost [11]. These wastes can be utilized as either binder and/or aggregate in concrete mixtures [12,13]. Of such promising industrial wastes available in large quantities in different parts of the world and can be utilized as fine aggregate in concrete mixtures is coal bottom ash (CBA). CBA is one of the wastes generated from the power generation from coal plants as shown in Error! Reference source not found. [3,14]. To produce electricity in coal power plants, a considerable amount of coal is burnt in specific boilers which results in the generation of a high amount of different types of ashes. The coarser particles, which are removed from the furnace bottom are referred to as CBA. CBA makes up about 10–20% of coal ash produced as waste during the generation of power from coal plants ↱[15] and it is composed of a complex mix of oxides↱ and metal carbonates [16].

Conversely, the finer ashes generated are scrubber ash and fly ash (FA) which are collected at different stages of the burning process [17–19]. Due to the use of coal plants in the generation of electricity in various parts of the world, there is a corresponding higher quantity of CBA generated as by-products. To produce 1 Mega Watt (mW) of electricity, about 20 tons of coal is used and about 15–20% of CBA is generated as a by-product by the thermal plants [20]. The high generation of CBA alongside other ashes during the coal power generation poses a threat to the environment due to the possible contamination of the environment if it is improperly disposed. The disposal of CBA in landfills and/or openly in the environment could result in the consumption of valuable land spaces and consequential contamination of the ground water and air. Hence, it is critical that these high amounts of CBA are properly managed and its corresponding use as fine aggregate in various concrete mixtures opens a pathway to effectively manage these wastes.

The sustainability benefits of CBA when used as an alternative to the conventional natural fine aggregates can be linked to the elimination of the need to dispose the CBA wastes in landfills coupled with serving as an alternative source for natural raw materials. Thus, the detrimental environmental impacts associated with the mining and processing of natural fine aggregates are eliminated. Moreover, the sourcing of natural fine aggregates has been found to also alter the aesthetic of the environment. The sustainable advantage of CBA utilization in the construction industry has also been extensively explored in its use in soil stabilization [21].↱The use of CBA in concrete mixtures as a sustainable alternative to the conventional natural fine aggregate is gaining significant momentum and it is critical that there exists a good understanding of the properties of CBA and its impact on the properties of different types of concrete. Thus, this study aims to provide a comprehensive review of recent studies that have utilized CBA as aggregate in various types of concrete including high-strength concrete. The effect of CBA used as fine aggregate on the properties of concrete was discussed in terms of the fresh, mechanical, durability and microstructural properties. The fresh properties explored are the setting time, bleeding, and workability while mechanical properties were explored in terms of the compressive strength, split tensile strength, and flexural strength was also discussed. The influence of CBA on the durability properties was discussed in terms of water and chloride permeability in addition to the resistance to acid and sulphate attacks, abrasion resistance, water-absorption capacity and drying shrinkage were discussed. It is anticipated that this comprehensive review open a pathway for more research and application in the utilization of CBA and other industrial wastes as raw materials in the production of various types of concrete.

2. Coal bottom ash

2.1. Environmental and health problems of CBA

CBA is mostly disposed of in areas such as landfills and ponds because it is regarded as a waste material that should be discarded [15]. However, the improper disposal of CBA from coal power plants may cause serious health problems and hazardous environmental pollution, especially when disposed of in open-air areas or water [22]. Singh et al. [23] described that the existence of CBA in the open-air areas and water is one of the main reasons behind the ever-increasing health problems such as lung, skin, and bladder cancer in areas surrounding the disposal sites. According to the standards provided by the European Community for the recognition of wastes at landfills and open areas, CBA can be classified as one of the dangerous wastes due to comprising high contents of toxic elements, such as chromium (24.25 mg L−1) and nickel (175.3 mg L−1) [21,24].

2.2. Treatment of CBA

In order to utilize CBA as aggregate in concrete mixtures, there is a need for the CBA to undergo some form of treatment or the treatments applied to the concrete incorporating the raw CBA. Raw CBA is normally inappropriate to be used as concrete materials due to their physical characteristics that reduce the mechanical properties in concrete mixtures. Treatment processes which could be in terms of the addition of chemical additives or processing physically can be carried out to improve the properties of the CBA and the corresponding concrete [25]. The chemical treatment includes inserting alkali-activators and other chemical additives into concrete mixtures to enhance the pozzolanic reaction of CBA. While, the physical treatment includes grinding, sieving, soaking, and burning of the CBA before incorporation as fine aggregate in concrete mixtures. Chemical and Physical treatments affect CBA in various ways; consequently, numerous researchers use both procedures of treatment to achieve desired properties. Sieving is commonly conducted together with grinding as a process to maximize fineness. Saturation and burning of CBA are usually utilized procedures to eliminate contaminations from CBA, such as water-soluble chlorides and unburnt carbon [26]. The existence of chloride ions on the CBA particles when utilized in concrete mixtures could result in corrosion of the steel reinforcements in concrete.

2.3. Applications of CBA

The recent increasing sustainability awareness in the construction industry has called for the need to source and utilize eco-friendly materials as sustainable alternatives for the conventional ones. CBA can be deemed a low-cost and eco-friendly material as it is a by-product and can be used to replace components in concrete [17,27]. The properties of CBA make it a suitable candidate to be used as fine aggregates in various types of concrete, asphalt, bricks, etc. [28]. CBA can be in various forms such as bituminous, sub-bituminous, anthracite, lignite, etc. CBA also possesses pozzolanic properties and its use in concrete would contribute positively to its performance [17]. Thus, CBA can be used as a sustainable and economical aggregate in concrete [29].

2.4. Properties of CBA

2.4.1. Physical properties of CBA

The physical characteristics of CBA are mainly influenced by the properties of the coal burnt for power generation. The degree of firing temperature and pulverization also contribute to the physical characteristics of CBA. Generally, CBA particles are larger than fly ash (FA) particles. The density of CBA ranges between 1200 kg/m^3 and 1620 kg/m^3, whereas that of FA ranges between 1900 kg/m^3 and 2800 kg/m^3 [30,31]. The specific gravity of CBA ranges between 2.36 and 3.1 [32]. The study by Bajare et al. [33] indicated that the specific surface area of CBA is in the range of 1164 m^2/g to 9849 m^2/g. Most CBA particles have an angular shape and dark gray color [31,34,35]. Table 1 presents some physical characteristics of the CBA used as aggregate in different types of concrete as evident in the existing literature. As a result of the size range of CBA, it can be utilized as fine aggregate in concrete mixtures. In contrast to natural fine aggregates, the water absorption of CBA has been found to be greater [36–39].

2.4.2. Chemical characteristics of CBA

The chemical composition of the CBA is presented in Table 2. As per ASTM C 618 [48], the summation of SiO_2, Al_2O_3, and Fe_2O_3 in a pozzolanic material greater than 70% indicate it is a 'class F'. Observing Table 2, it can be deduced that the sum of the SiO_2, Fe_2O_3, and Al_2O_3, in CBA is greater than 70%. Hence, CBA can be classified as a pozzolanic material belonging to class F. It can also be observed from Table 2 that the loss on ignition (LOI) of CBA is lower than 8% of the total composition. The existence of unburnt carbon in the CBA could result in an improvement in the properties of concrete [49].

As mentioned earlier, the variation in the chemical characteristics of CBA is due to various types of burnt coal, and various furnace conditions which influence directly or indirectly the performance of the concrete. CBA which is produced from lignite encompasses calcium and other alkaline components. On the other hand, CBA produced from anthracite is higher in iron and lower in calcium contents [66]. In terms of the chemical aspect, SiO_2 and Al_2O_3 in CBA particles are the main pozzolanic component similar to that of FA [67]. During the process of cement hydration, these composites can react with calcium hydroxide (i.e. $Ca(OH)_2$) to produce further Calcium aluminate hydrates (C-A-H) and calcium silicates hydrates (C-S-H) gels [67].

2.4.3. Microstructure properties and pozzolanic reactivity of CBA

The incineration process in terms of cooling rate and the combustion temperature has a considerable influence on the microstructure characteristics of the CBA. The pozzolanic capability of CBA embodies it with the ability to react with calcium hydroxide of the cement hydration [68]. Cheriaf et al., [69] examined the effect of $Ca(OH)_2$ and CBA on the microstructure characteristics of concrete. The findings from the study indicated that concrete mixtures composed of 50% $Ca(OH)_2$ and 50% CBA with a water to solid ratio of 0.42 yielded compressive strength ranging from 1.8 MPa to 17.3 MPa. Similarly, the depletion of Ca $(OH)_2$ for the aforementioned mixtures was in the range of recorded 5–60%. Figure shows the equivalent influence of $Ca(OH)_2$ and CBA. Fig. 1,2and3.

3. Properties of concrete incorporating CBA as fine aggregate

The influence of the use of CBA as fine aggregate in various types of concrete was explored and discussed in this section.

Table 1
Physical properties of CBA.

Source	Water Absorption (%)	Fineness Modulus	Specific Gravity (g\cm^3)
[40]	–	1.6	1.93
[41]	18	2.967	2.967
[12]	11.61	3.44	1.88
[42]	6.63	3.06	2.46
[43]	1.8	3.86	2.3
[44]	11.61	3.44	1.88
[45]	28.9	1.83	2.19
[46]	7.0	2.8	2.33
[38]	5.4	2.36	1.87
[22]	31.5	1.37	1.39
[47]	4.06	5.63	1.87

Table 2
Chemical characteristics of CBA (%).

Source	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	MgO	SO_3	TiO_2	LOI
[50]	52.02	23.23	9.11	1.14	0.49	6	2.17	0.65	1.23	–
[51]	48.71	29.23	4.29	0.55	1.16	7.44	1.7	3.96	1.88	–
[52]	56	26.7	5.8	2.6	0.2	0.8	0.6	0.1	1.3	4.6
[12]	45.3	18.1	19.84	2.48	–	8.7	0.969	0.352	3.27	–
[53]	65.3	25.94	4.76	0.67	1.38	2.48	1.1	–	0.86	–
[40]	57.76	21.58	8.56	1.08	0.14	1.58	1.19	–	–	5.8
[54]	68.9	18.7	6.5	1.52	0.24	1.61	0.53	–	1.33	2.68
[55]	38.64	21.15	11.96	2.06	0.9	13.8	2.75	0.61	–	7.24
[56]	41.70	17.10	6.63	0.40	1.38	22.50	4.91	0.42	3.83	1.13
[57]	61.80	17.80	6.97	2.00	0.95	3.19	1.34	0.79	0.88	3.61
[58]	57.90	22.60	6.50	0.60	0.08	2.00	3.20	–	–	2.40
[45]	60.70	18.30	6.56	2.12	0.89	3.25	1.28	0.82	0.95	4.13
[59]	54.80	28.50	8.49	0.45	0.08	4.20	0.35	–	2.71	2.46
[40]	57.76	21.58	8.56	1.08	0.14	1.58	1.19	0.02	–	–
[60]	47.53	20.69	5.99	0.76	0.33	4.17	0.82	1.00	–	–
[61]	52.10	18.34	11.99	1.57	2.43	6.61	4.85	–	0.87	4.13
[62]	62.32	27.21	3.57	2.58	0.70	0.50	0.95	–	2.15	–
[63]	55.10	28.10	8.30	1.50	–	1.10	0.30	0.30	–	3.90
[64]	58.7	20.1	6.2	1.0	0.1	9.5	1.6	0.4	–	0.8
[65]	52.2	27.5	6.0	0.6	01.3	5.9	1.7	–	1.53	1.8

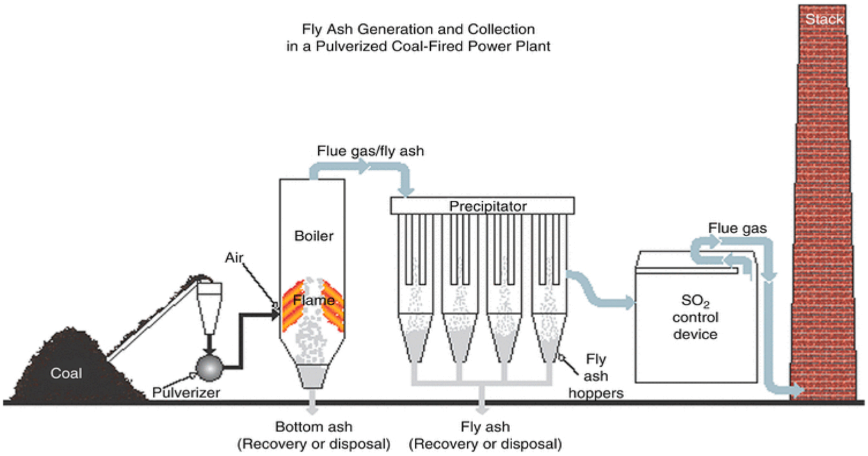

Fig. 1. Producing coal bottom ash in thermal power plants [14].

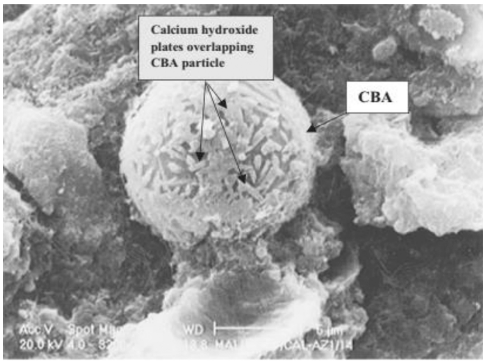

Fig. 2. The start of a reaction between $Ca(OH)_2$ and CBA [69].

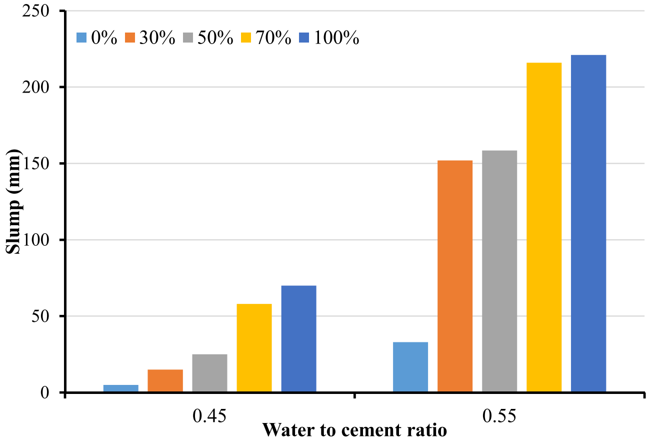

Fig. 3. Slump values of fresh concrete containing CBA at different replacement levels [57].

3.1. *Fresh properties*

3.1.1. *Workability*

The water to cement ratio (w/c) and the aggregate's nature play important roles in the properties of concrete. ↱Many studies have examined the effect of CBA on the workability of concrete in terms of the compaction factor or slump. In general, increasing the content of CBA particles in the concrete mixtures has been found to result in a decrease in slump [70–72]. Similar observations have been reported in terms of compaction factor as a reduction in compaction factor occurs with higher CBA content in concrete [43]. Table 3 shows the effect of CBA on the workability of concrete. Observing Table 3, it is evident that there exist some contradictions in the effect of CBA on the workability of concrete as few studies have reported an increase in a slump with higher CBA content. This could possibly be a result of the size of the CBA used. The use of fly ash which is finer in concrete has been found to yield higher workability.

Bai et al., [57] stated that using CBA as fine aggregate in the concrete mixtures with a fixed water-cement ratio and cement content resulted in an increase in the slump when the content of CBA was increased as shown in Figure. An increase in the slump was also observed in the study by Yuksel and Genç [58] where concrete was produced using CBA in the range of 10–40% to substitute the natural fine aggregate. Similar findings were reported when CBA was used as aggregate in high-strength concrete, and an improvement in the workability was observed [73]. However, when silica powder was used to replace CBA in the high-strength concrete, no significant improvement in the workability was observed. Thus, it is critical that additional extensive studies are carried out to correlate the physical and chemical properties of the CBA to the corresponding slump of concrete.

3.1.2. *Bleeding*

Bleeding is the amount of water loss in the concrete mix which is primarily dependent on the cement properties, water-cement ratio, and the physical properties of fine aggregate especially when the fine aggregate has a particle size lower than 150 μm. Based on the previous results, water-reducing chemical admixtures has a significant impact on the quantity of bleeding shown by the CBA concrete. After the production and shaping of concrete, the segregation process starts owing to the various weights of the compound materials. Andrade et al. [84] used CBA as the fine aggregate replacement and evaluated its corresponding effects on the bleeding. They used a glass mold with a surface area of 140 mm by 190 mm. The reduction of water quantity by bleeding was calculated in terms of time. The total water loss was found to be close regarding the two types of concrete, including CRT3 and CRT4. Table 4 shows the influence of CBA on the bleeding of cement paste/concrete.

There are three significant factors, which play a key role in the effect of bleeding on ↱concrete performance: (1) The lost water amount by bleeding and evaporated water to the ↱environment surrounding. The increase in water leaving from the concrete mixture

Table 3
Influence of CBA on the workability.

Source	Replacement Level	Effect of CBA on Workability
[74]	0%, 5%, 10%, 15%, 20%, 25%, and 30%	Increasing CBA content in the concrete mix resulted in reducing the slump value from 140 to 60 mm.
[57]	0%, 30%, 50%, 70%, and 100%	The slump increased with increasing CBA and fixed w/c in the concrete mix.
[58]	10%, 20%, 30%, 40%, and 50%	The use of 50% CBA as a replacement for fine aggregate resulted in decreasing workability more slightly than that of the reference concrete.
[45]	0%, 25%, 50%, 75% and 100%	The slump increased with a higher content of CBA.
[38]	25%, 50%, 75%, and 100%	The slump did not change as the replacement ratio of fine bottom ash increased
[22]	0%, 20%, 30%, 40%, 50%, 75%, and 100%	The lower slump of the CBA concrete was approximately similar to the higher CBA content in the concrete mixtures.

Table 4
Influence of CBA on the bleeding.

Source	Replacement Level	Effect of CBA on concrete bleeding
[80]	0, 25%, 50%, 75%, and 100%	Water bleeding increased due to an increase in the CBA amount.
[46]	0%, 10%, 20%, 30%, and 40%	The CBA mixtures displayed a higher amount of bleeding compared to the control
[22]	0%, 20%, 30%, 40%, 50%, 75%, and 100%	The control concrete showed a higher loss of water as a result of bleeding. The concrete mixtures made with 100% CBA showed bleeding in the range between1.66% to 1.68%.
[52]	0, 25%, 50%, 75%, and 100%	Increasing CBA content with water resulted in increasing the water loss by bleeding.

results in increasing durability problems (permeability, capillarity) related to the transport of sulphates and mineral materials, which, in turn, results in the corrosion of concrete and reduces its strength against environmental conditions. (2) The overall time of water bleeding occurrence; long-term bleeding results in reducing the importance of the capillary pressure resulting in the drying of the pores. (3) The rate of bleeding, which can be measured by the loss of water mass per open area by/versus/with time [75,76]. The bleeding rate provides a significant value, which can be associated with the surface evaporation ↱since a reduced bleeding rate value associated with the evaporation rate leads to the ↱continuity or start of the plastic shrinkage process [75,77–79].

3.1.3. Setting time

Some researchers examined the influence of CBA on the initial setting time and they reported that using CBA resulted in increasing both the initial and final setting time compared to that of the control concrete↱ [25,81,82]. This phenomenon occurred owing to the existing water with CBA in the concrete mixture and cement paste needed in making the cement hydration products. Also, decreasing the pH value resulted in decreasing or delaying the hydration actions of the cement paste [56]. Table 5 displays the outcomes of the setting time of the cement paste/concrete made with CBA. Overall, a large amount of free water in the cement paste/concrete mix resulted in increasing the setting time. Table 5 illustrates the influence of CBA on the setting time of cement paste/concrete in previous studies. Pyo and Kim [73] used CBA, fly ash, and slag as construction materials to produce high-strength concrete. The results showed that there was no significant effect on the setting times because of the fact that CBA has a pozzolanic reaction.

3.1.4. Density

Density is an important property to find out the total weight of concrete produced. CBA may be classified as a lightweight granular aggregate due to a bulk density ranging between 0.7 and 0.9 g/cm^3. Its incorporation into the mixtures with appropriate hydraulic binders can offer the opportunity of gaining heat-resistant lightweight concretes between 1.0 and 1.2 g/cm^3 density [85]. Table 6 displays the results of several studies that investigated the influence of CBA content on the density of concrete.

The findings from previous studies revealed that there is a significant decline in density when natural fine aggregate is replaced by CBA. The decrease in the density of concrete containing CBA can be ascribed to the porous structure and lower unit weight of CBA compared to fine aggregate. Andrade et al., [80] confirmed that the utilization of CBA with a fineness modulus of 1.55 and a specific gravity of 1.67 g/cm^3 as fine aggregate replacement in concrete resulted in reducing the unit weight of the concrete mixture by 25%. Pyo et al., [88,89] used CBA as a fine aggregate to produce high-strength concrete, the same results were achieved by Pyo and Kim [73], whereas the high-strength was achieved high density due to adopting a lower water binder ratio of less than 0.3 and reinforced by steel fiber.

Kim and Lee, [38] examined the influence of coarse and fine CBA on the density. The proportions of the used concrete mix included 607 kg/m^3 of cement, 143 kg/m^3 of silica fume, 187 kg/m^3 of water, and 14 kg/m^3 of superplasticizer. The findings from the study as shown in Fig. 4 revealed that the densities of hardened concrete were reduced linearly due to increasing the replacement level of coarse and fine CBA. Topçu and Bilir, [37] examined the impact of CBA at the age of 7 and 28 days masses of mortars having materials of fixed amounts of 500 kg/m^3 cement, different replacement levels of CBA as natural fine aggregate, and 3 kg/m^3 high range water reducing admixtures. They observed that the density of samples reduced due to higher CBA content. Ghafoori and Bucholc [46] observed that the CBA concretes showed a lower density than that of the reference specimen. This observation is consistent with that of [37] where it was noted that the density of concrete was reduced due to increasing CBA content.

Table 5
Effect of CBA on setting time.

Source	Replacement Level	Effect of CBA on setting time
[83]	0%, 4%, 7%, 10%, 13%, and 16%	Setting times (i.e. initial and final) increased due to an increase in CBA content in the concrete mix.
[84]	0%, 5%, 10%, 15%, 20%, 25%, and 30%	Incorporation of CBA with bentonite enhanced initial setting time, having an insignificant effect on the final setting time.
[46]	0%, 10%, 20%, 30%, and 40%	Average initial and final setting times for concrete made with CBA are 6.3% and 9.5%, higher compared to the control mixture.
[52]	0, 25%, 50%, 75%, and 100%	Concrete made with CBA exhibited extended setting times.

Table 6
Influence of CBA on the density of concrete.

Source	Replacement Level	Influence of CBA on the density
[86]	0, 25%, 50%, 75%, and 100%	Increasing the CBA level replacement led to decreasing the density gradually.
[22]	0%, 20%, 30%, 40%, 50%, 75%, and 100%	The dry density of the CBA concrete mixtures generally decreased equally when using CBA.
[62]	0, 10%, 20%, 30%, 40%, 50%, 75%, and 100%	Increasing the CBA level replacement led to decreasing the density of concrete.
[12]	0%, 20%, 50%, 75% and 100%	Increased CBA content led to decreasing density.
[87]	0–100%	The use of CBA as aggregate produced lower-density concrete compared to natural aggregate.

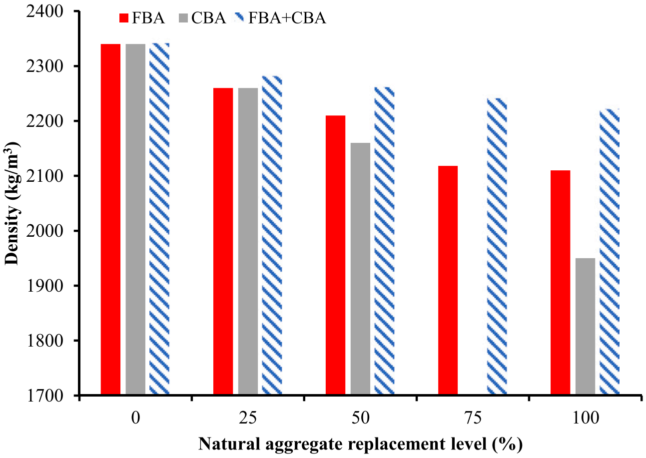

Fig. 4. The effect of CBA on the density [38].

3.2. Mechanical properties

3.2.1. Compressive strength

Existing studies have confirmed that using CBA as a concrete material can influence the compressive strength of concrete [36,52, 90–94]. The lower substitution level of fine aggregate by the CBA particles led to an increase in the compressive strength in the concrete mix in some cases, whereas adding large quantities of CBA resulted in decreasing the compressive strength of concrete. The compressive strength was reduced slightly with a replacement level of fine aggregate by CBA up to 20%, while a significant reduction in compressive strength was observed at a replacement level up to 50% in the concrete samples [51].↱ Wongkeo et al. [95] evaluated the properties of lightweight concrete containing CBA at different replacement levels. It was observed that the compressive strength increased with increasing CBA content to 10.6 and 11.7 MPa for the concrete mixtures containing 20% and 30% CBA, respectively as shown in Fig. 5.

Similarly, another study used CBA as fine aggregate at a 100% replacement level; it was observed that compressive strength

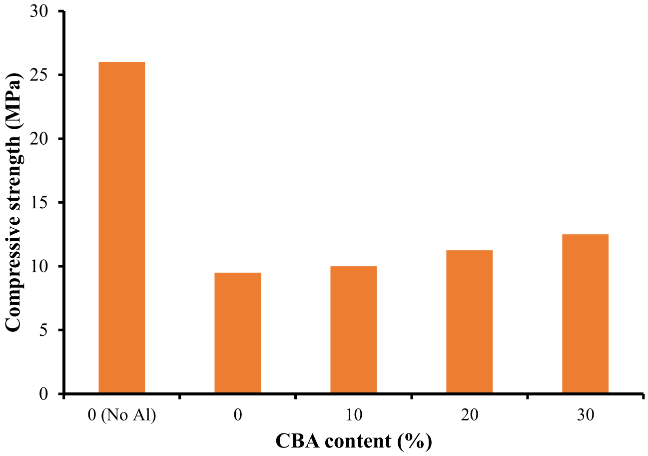

Fig. 5. Compressive strength of concrete mixes comprising CBA [95].

decreased significantly at ↱28 curing ↱days [22]. Moreover, it was observed that the low compressive strength of concrete samples (less than 15 MPa) is a gradual decrease in the compressive strength rate due to the higher replacement level of fine aggregate [53]. In some cases, the addition of CBA up to ↱20% as fine aggregate replacement resulted in an increase in the compressive strength up to 10%. However, several studies have indicated that the accepted compressive strength for various structural applications can be achieved when CBA is utilized as replacement of natural fine aggregate up to 30% [38,51,92]. The influence of different proportion of CBA used as replacement of the natural fine aggregates on the compressive strength of various types of concrete is presented in Table 7.

Furthermore, a slight enhancement was observed in compressive strength in the concrete mixtures containing CBA at different replacement levels alongside the inclusion of different types of ↱additives such as metakaolin, sugarcane molasses, micro-silica, and non-ground granulated blast ↱furnace slag [36,70,96,97]. The compressive strength of normal concrete made of CBA and sugar molasses increased ↱up to 8% when using 20% CBA as a normal fine aggregate replacement [96]. Also, the use of CBA with 8% of Micro-Silica has exerted a positive effect on the concrete mixtures in terms of increasing the 28-day compressive strength up to 10% ↱with 10% CBA as fine aggregate replacement level [70].

3.2.2. *Ultrasonic pulse velocity*

Ultrasonic pulse velocity (UPV) is one of the ways to assess the quality in a non-destructive way. The UPV measures the velocity of pulse waves passing through the concrete. The higher the presence of deformities such as cracks in concrete, the longer it takes the pulse to pass through the concrete. It was observed that the UPV values of concrete containing CBA ↱increased with the increase of curing age. Accepted values of UPV were acquired at a lower replacement level of CBA than that of a higher replacement level of CBA. The values of UPV were reduced by about 5% for the higher fineness ↱modulus values of CBA based on concrete mixtures compared with that of the control concrete. Generally, it was concluded that utilizing CBA as natural fine aggregates replacement yielded a more uniform and homogenous concrete ↱[22]. A study [74] investigated the influence of CBA on two groups of concrete mixtures. The first group was made without fly ash and the second group used fly ash as a cement replacement at different replacement levels. Findings from the study indicated that UPV values decreased for all concrete mixtures and curing ages except for the concrete mix with 10% CBA as fine aggregate and 10% fly ash as a cement replacement as shown in Fig. 6.

The mechanical properties of concrete comprising a low substitution level of CBA as fine aggregate increased in most outcomes. However, the incorporation of cement additives has been found to increase the UPV and the corresponding compressive strength of concrete made with CBA as a replacement for natural fine aggregate. Moreover, the durability properties such as surface abrasion, water absorption, and rapid ↱chloride penetration have shown an enhancement with CBA at a lower replacement level ↱as fine aggregate. Table 8 illustrates the effect of CBA on the UPV in several previous studies.

3.2.3. *Tensile strength*

Existing studies have revealed that the use of CBA as the fine aggregate replacement has exerted a positive impact on the splitting tensile strength at various curing times [51,91]. Adding further CBA as fine aggregate in the concrete mixtures resulted in producing further ↱pozzolanic reactions, which led to enhancing the interfacial transition zones and quality of cement ↱paste [70,99]. Many studies proved that the splitting tensile strength increased by 5–15% more than the control concrete at 28 curing days with a replacement ↱level of CBA not more than 20% [23,51]. Another study by Purushothaman and Senthamarai [100] concluded that there is a significant development in the tensile and flexural strength of UHPC due to the use of CBA and silica fume. Yang et al., [93] conducted a study to assess the HPC by using CBA as a fine aggregate replacement. The CBA used a considerable affected on the splitting tensile strength of the high-strength concrete, especially after 56 curing days. Table 9 illustrates the influence of CBA on tensile strength. The findings presented indicate that there is no consensus on the impact of the incorporation of CBA as fine aggregate in concrete mixtures. Some studies concluded that CBA decreased tensile strength more slightly than that of the control while others observed an increase in the tensile strength of concrete with higher content of CBA. Hence, additional studies is imminent in order to accurately understand how the properties of CBA influences its corresponding impact on the tensile properties.

Remarkable differences have been found in concrete containing 100% CBA as a full substitution level of fine aggregate; equivalent values of splitting tensile strength at 28 curing days were observed [12]. However, the splitting tensile strength in other studies increased due to the utilization of CBA as fine aggregate with full replacement levels [60]. Aggarwal et al., [103] observed that the flexural strength of concrete samples containing CBA was lower than that of the control samples on the same curing days as illustrated in Fig. 7. According to existing studies, tensile strength has not been substantially influenced by the addition of the CBA in the concrete mixtures. ↱ Fig. 8 shows the correlation between split tensile strength and compressive strength in comparison with the volume of CBA.

Table 7
Influence of CBA on the compressive strength of concrete.

Source	Replacement Level	The influence on compressive strength
[86]	0, 25%, 50%, 75%, and 100%	Increasing the replacement levels of CBA led to a decrease in the compressive strength gradually.
[74]	0%, 5%, 10%, 15%, 20%, 25%, and 30%	The combination of 10% CBA with fly ash led to an increase in the 90 day-compressive strength compared to the control concrete.
[44]	0, 25%, 50%, 75%, and 100%	Increasing the replacement level CBA led to reducing the 7-day compressive strength but increased to 36.6 MPa at 180 days.
[83]	0%, 4%, 7%, 10%, 13%, and 16%	The compressive strength increased due to higher CBA content because of the pozzolanic activity of CBA.
[95]	0%, 10%, 20%, and 30%	The compressive strength increased due to increasing CBA content by up to 30%.
[54]	0%, 20%, 30%, 40%, and 50%	The compressive strength decreased for all CBA replacement levels.

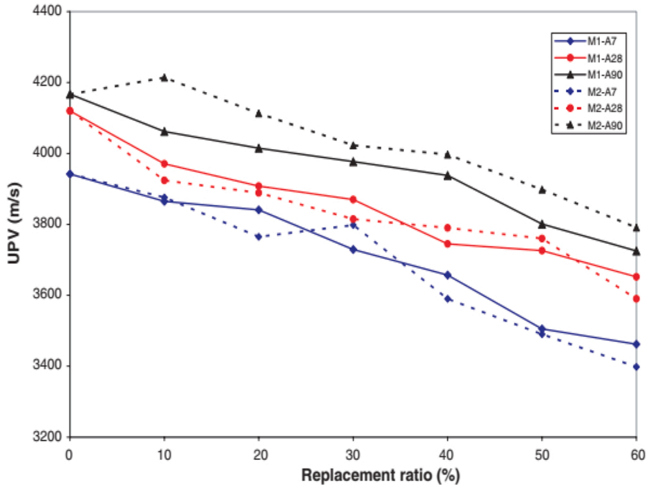

Fig. 6. UPV of concrete mixtures at different curing ages [74].

Table 8
Effect of CBA on the UPV.

Source	Replacement Level	The effect of CBA on UPV
[74]	0%, 5%, 10%, 15%, 20%, 25%, and 30%	The combination of 10% CBA with 10% FA increased the 90-day UPV compared to the control
[22]	0%, 20%, 30%, 40%, 50%, 75%, and 100%	UPV of concrete made with CBA increased with age but decreased with higher CBA content.
[98]	0, 25%, 50%, 75%, and 100%	The UPV values reduced from 4393 m/s to 4337 m/s due to the combination of 100% CBA as a replacement for fine aggregate in the concrete mix.
[12]	0%, 20%, 50%, 75% and 100%	The increased CBA content decreased the UPV similarly to the compressive strength case.
[87]	0–100%	The UPV value decreased due to higher CBA content.

Table 9
Influence of CBA on the tensile strength.

Source	Replacement level	Influence of CBA on the tensile strength
[58]	10%, 20%, 30%, 40%, and 50%	There is no change in tensile strength due to the use of 10% CBA as a fine aggregate replacement, but reduced considerably due to an increase in the CBA content
[46]	0%, 10%, 20%, 30%, and 40%	The splitting tensile strength of concrete increased by 12% compared to the control
[101]	10%, 20%, 30%, 40%, and 50%	The splitting tensile strength was reduced with higher CBA content.
[102]	0, 25%, 50%, 75%, and 100%	The split tensile strength of concrete comprising 20% CBA was higher than the control
[103]	0%, 20%, 30%, 40%, and 50%	The 28-day tensile strength ranged between 121% and 126% of the tensile strength of the control

The relationship equation is shown in Fig. 8.

3.2.4. Flexural strength

The flexural strength of concrete is affected considerably by the ↱replacement levels of natural fine aggregate with CBA up to 30%. Several studies have investigated the flexural strength of concrete when CBA is used as fine aggregate [53,90,91]. It has been observed that the incorporation of CBA in conventional concrete as fine aggregate at a low ↱replacement level (i.e. less than 10%) resulted in an increase in the 28-day flexural strength. Nevertheless, an increase in the flexural strength has also been observed when CBA was used for up to 20% as a replacement for natural fine aggregate in concrete [39]. The enhancement in the flexural strength was ascribed to the combined use of CBA as fine aggregate and various supplementary cementitious materials as partial replacement of the Portland cement [96].

Extensive studies have also revealed there is a significant decrease in the flexural strength when the content of CBA used as the replacement of natural fine aggregates is greater than 30% [53]. Moreover, at higher replacement levels up to 50% of CBA as replacement of natural fine aggregates; the flexural strength can decrease up to 30% [90,104]. This observation was also observed for concrete cured at various ages [91]. However, similar to the mechanical properties; the combined use of CBA as the natural fine

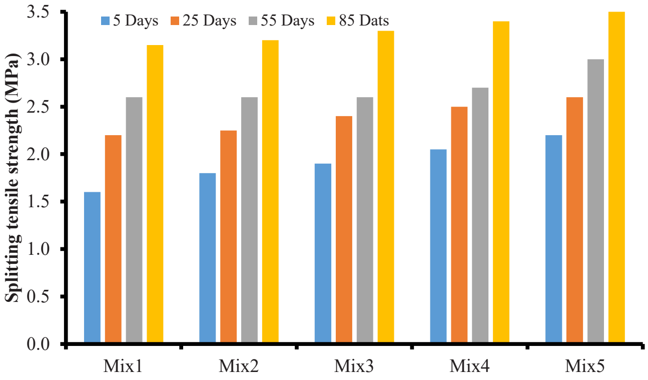

Fig. 7. Influence of CBA on Splitting tensile strength [103].

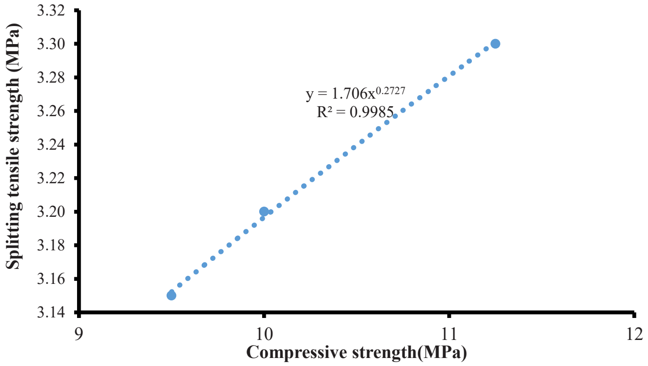

Fig. 8. Correlation between split tensile strength and compressive strength.

aggregate replacement and the use of supplementary cementitious materials to replace Portland cement has been found to enhance the flexural strength. The influence of CBA content on the flexural strength of concrete is presented in Table 10.

3.2.5. Modulus of elasticity

The modulus of elasticity (MOE) of concrete is an important parameter that is required for structural design and analysis. The MOE of concrete is influenced by the elastic modulus of hardened cement paste and aggregate volume. Yüksel et al., [105] investigated the MOE of concrete containing CBA as fine aggregate under high temperatures in two groups. The first group C includes GBFS as a different substitution of fine aggregate from 0% to 50%, whereas the second group K includes CBA as the fine aggregate replacement from 0% to 50%. Findings from the study showed that the MOE of concrete incorporating alternative aggregates (i.e. slag or CBA) was reduced compared to the control concrete as shown in Fig. 9. This reduction in the flexural strength was ascribed to the exposure of the samples to elevated temperatures (800 °C) and the instability of the alternative aggregates (i.e. slag and CBA) at elevated temperatures. Table 11 presents some findings on the influence of the utilization of CBA as a replacement of different proportions of natural fine aggregates on the MOE.

3.3. Durability properties

3.3.1. Water absorption

The water absorption of concrete is a good indication of its overall durability. It has been shown that the replacement of natural fine aggregates with CBA in concrete at replacement levels of 25%, 50% and 75% resulted in an increase in the water absorption by 2%, 4% and 6%, respectively [107]. However, the use of supplementary cementitious materials as a replacement for Portland cement in concrete incorporating CBA as fine aggregate reduces the water absorption. Up to a 20% reduction in the water absorption has been observed when supplementary cementitious materials are used in concrete made with CBA [22]. Singh and Siddique, [108] investigated the effect of CBA content on the water absorption of concrete. The findings from the study presented in Fig. 10 revealed that the incorporation of CBA as aggregate resulted in higher water absorption at early ages (i.e. 28 days). However, in the long-term, the water absorption of concrete incorporating CBA as aggregate is similar to that of the control concrete without any CBA.

Table 10
Influence of CBA on the flexural strength.

Source	Replacement level	Influence of CBA on the flexural strength
[63]	0%, 70%, and 100%	Flexural strength tended to reduce with higher CBA content at 7 and 28 curing age.
[84]	0,10%, 15%, and 20%	Flexural strength decreased with higher CBA content at 90 curing age.
[29]	0,10%, 15%, and 25%	Flexural strength increased for different replacement levels of CBA at later ages (28 and 56 days).
[95]	0,10%, 15%, and 30%	Flexural strength decreased for a higher replacement of CBA in concrete mixes compared to the control mix.

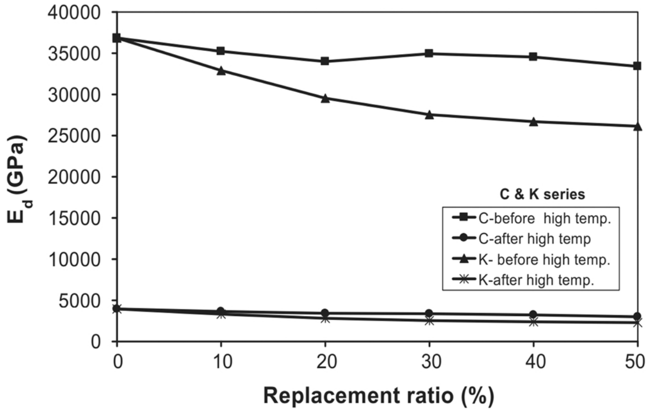

Fig. 9. MOE of the concrete specimen before and after exposure to high temperatures [105].

Table 11
Effect of CBA on the MOE of concrete.

Source	Replacement Level	Effect CBA on MOE
[86]	0, 25%, 50%, 75%, and 100%	Increasing the replacement levels of CBA led to a decrease in MOE regularly.
[105]	0, 10%, 20%, 30%, 40%, and 50%	The MOE of concrete containing CBA decreased compared with other concrete types.
[22]	0%, 20%, 30%, 40%, 50%, 75%, and 100%	50% substitution of sand by CBA, the MOE of CBA concrete mixtures was approximately 98% compared to the control concrete mixture and for replacement, more than 50%, the MOE of CBA concrete mixtures decreased significantly.
[106]	15%, 25%, 35%, and 45%	The modulus of elasticity of all concretes decreased with higher CBA content

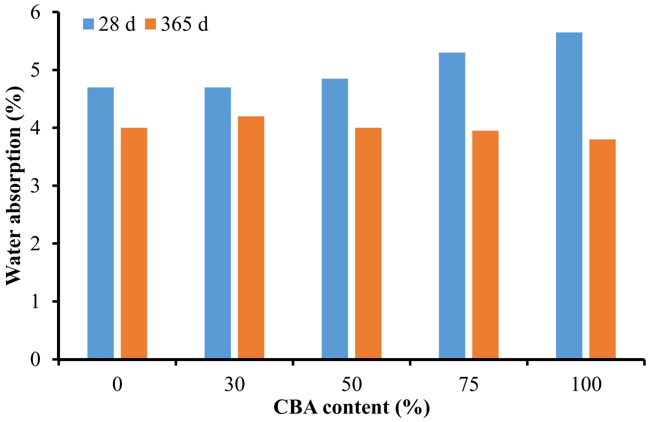

Fig. 10. Influence of CBA content on water absorption [108].

3.3.2. Chloride ion permeability

The evaluation of chloride ion permeability of concrete containing CBA has been conducted by evaluating the whole chloride diffusion coefficient at 28 curing days ↱[109]. Some studies have been carried out on the chloride ion permeability properties ↱of concrete containing CBA as fine aggregate replacement along with some types of cement additives [110,111]. Also, the study compared the chloride ion penetration of concrete containing CBA as fine aggregate with a concrete mixture containing a constant ↱quantity of fly ash at fixed water content. The findings from the study revealed that concrete made with CBA as aggregate and no additives exhibited an increase up to 17% in chloride diffusion coefficient [112]. However, the use of slag as partial replacement of Portland cement alongside CBA as replacement of the natural fine aggregate resulted in an enhancement in the chloride ion resistance compared with that of ↱the concrete mixture made without CBA and additives. The enhancement in the chloride ion resistance of the concrete containing slag can be linked to the pozzolanic reactions of the slag which resulted in more product formation and a corresponding reduction in ↱permeability↱ [109].

3.3.3. Abrasion resistance

Few studies were conducted on the influence of CBA as fine aggregate on the abrasion resistance of concrete [113,114]. The use of CBA at different replacement levels has been evaluated in terms of the effect on the abrasion resistance (decrease/increase) compared to the normal control concrete. The loss in mass was gained after conducting the test of Laos Angeles Abrasion of concrete containing CBA as fine aggregate [36]. The wear depth was reduced initially at ↱a lower CBA replacement level (20% of total weight), while the high replacement level was not affected as in the low CBA content in the concrete mix. The concrete behavior in this case can be attributed to ↱the lower replacement levels of CBA↱. The porosity increased at high replacement levels of CBA (more than 50%) and the strength of crushing ↱aggregate has overrun the concrete containing CBA as fine aggregate. Similarly, excellent outcomes were obtained for concrete containing NGGBFS and CBA compared with concrete containing only CBA [36]. Hashemi et al. [98] investigated the effect of CBA content on the abrasion resistance of concrete. The outcome of the study presented in Fig. 11 showed that the increase in the CBA content is beneficial in improving the resistance of the concrete to abrasion.

3.3.4. Acid resistance

Acid resistance is one of the important tests, which is used to evaluate the long-term durability of cement paste/concrete mixtures. The resistance of acid attack can be used for the concrete cube specimens after being exposed to an external acid solution. All concrete specimens should be weighed after the initial curing period of curing days in water. After that, the specimens were exposed to a certain acid solution. The change in mass reduction and compressive strength of the concrete specimens has been evaluated after different curing days of the submersion period in a certain acid solution. The proportion loss in mass of all concrete specimens after submersion in a certain acid solution can be calculated to determine the percentage loss. Khan and Ganesh [115] investigated the acid resistance property in some concrete mixtures containing grounded CBA at various replacement levels of cement from 0% to 30% as shown in Fig. 12. It was observed that the loss in unit weight was due to the deterioration of the concrete samples for the immersion time between 28 and 90 days.

3.3.5. Shrinkage

As observed in previous studies, the incorporation of CBA as a fine aggregate replacement with a low w/c ratio led to a decrease in the shrinkage rate [99,113,116,117]. At a low water-cement ratio, initially, water is quickly drawn into the hydration process. ↱Moreover, the water demand for the completion of the hydration process at later age ↱increases, which leads to the production of quite fine capillaries. The tension in the concrete surface leads to ‘autogenous shrinkage’, which results in further concrete cracks [118]. The autogenous shrinkage values were observed in various studies. The decrease in the shrinkage values of concrete containing CBA as fine aggregate can be attributed ↱to reducing the water-cement ratio. The fine particles of CBA probably absorbed some of the water amounts ↱during the mixing process internally. However, the high porosity of ↱CBA led to an increase in the gradual flow of water, which resulted in decreasing the dry shrinkage of concrete [116]. Rodríguez-Álvaro et al., [119] reported that all the concrete mixtures, including the mixtures with CBA content, had preserved their relative position of the shrinkage. On the other hand, autogenously shrinkage is higher for normal concrete samples compared to the concrete samples, which contain BCM in their components as shown in Fig. 13.

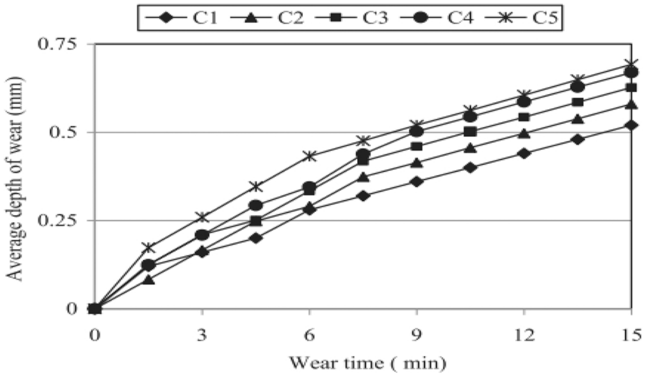

Fig. 11. Depth of wear with CBA content in concrete at 365 curing days [98].

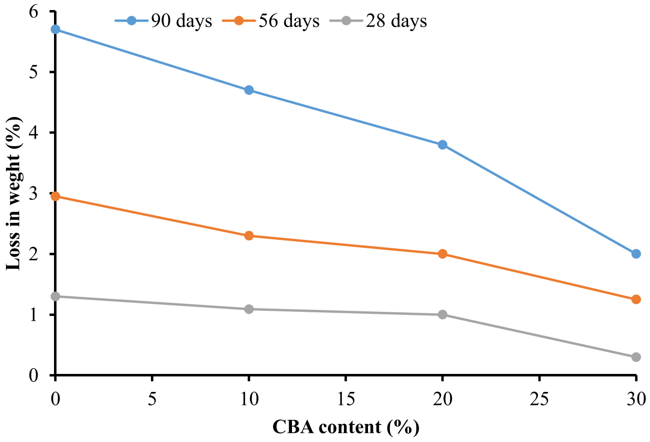

Fig. 12. The loss in unit weight (density) of concrete at various curing ages [115].

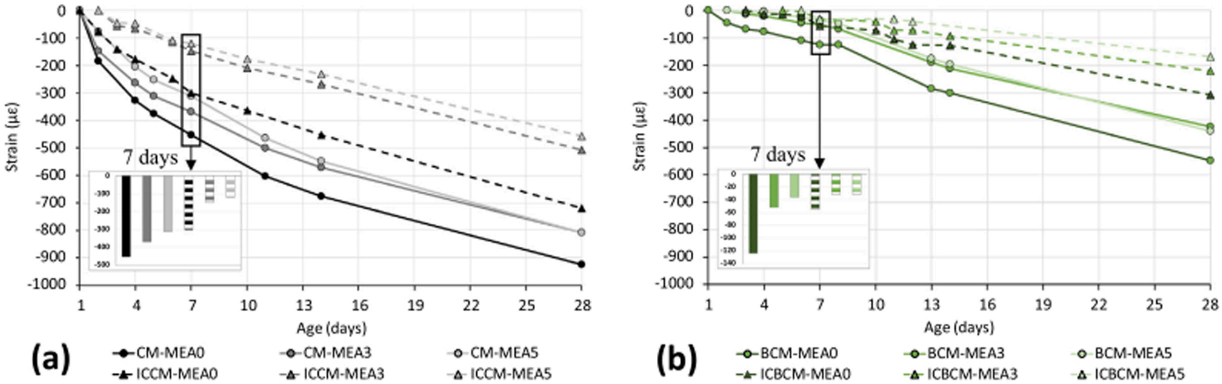

Fig. 13. (a) CM and (b) BCM autogenous shrinkage [119].

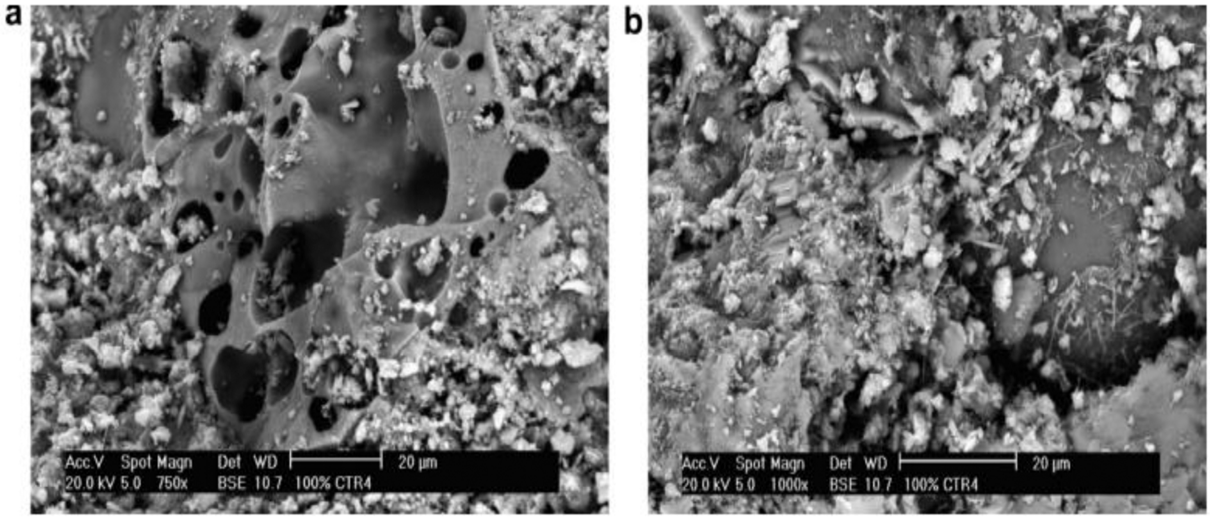

Fig. 14. SEM image of CBA in concrete samples in (a) 760x and (b) 1000x [86].

3.4. Microstructural properties

The confirmation that the CBA particles may be measured as small water reservoirs since they have a substantial porosity, affecting the outcomes of the moisture transport tests in concrete, has been established in Fig. 14. The results showed that the CBA particles suffered a scission, almost certainly during the mixing process, representing a porous surface slice. This particle is enclosed by fine particles of the material itself and cement paste. The pozzolanic influence, low but present nevertheless, has been confirmed as being existent in the CBA concrete, which presents a spherical particle almost surrounded totally by a calcium hydroxide layer [86].

4. Conclusions

This paper reviewed the latest studies, which examined the performance of concrete when CBA is incorporated as fine ↱aggregate at different replacement levels. The performance of ↱concrete containing CBA at various curing ages has been described based on the results of previous studies. These conclusions are drawn based on the results of previous studies about the CBA-incorporated concrete and its effect on the behavior of concrete. ↱.

- Normal concrete, which contains CBA as fine aggregate, achieved accepted workability compared with the control concrete. A general decreasing pattern in the slump values ↱carried out in concrete has been observed compared with the control.
- The compressive strength of concrete has been decreased due to the incorporation of a high quantity of CBA as fine aggregate. Moreover, in some cases, a slight improvement in compressive strength was achieved for a less quantity of CBA as fine aggregate replacement. The utilization of cement additives has assisted in increasing the compressive strength at 28 curing days. The compressive strength has been considerably affected by increasing CBA content in the concrete mix.
- A decrease in the tensile strength of concrete containing CBA as fine aggregate was observed in most cases. The tensile ↱strength has been reduced up to 30% due to the incorporation of CBA as fine aggregate in the concrete mix.
- The flexural strength of concrete containing CBA as fine aggregate has been enhanced for lower replacement levels of CBA. The use of some cement additives assisted in improving the flexural strength values at different curing ages. The flexural ↱strength has been ↱decreased considerably due to the use of CBA instead of the normal fine aggregate by 25% compared to normal concrete without CBA↱. ↱
- Most researchers reported that the water absorption rate was negatively affected by using CBA as a fine aggregate replacement. The water absorption of concrete increased because of the porous nature of CBA. However, using some cement additives has improved the water absorption rate.

5. Limitation of the study

It is worth mentioning that the results presented in this paper are based on various experimental investigations where a controlled environment was used to produce the concrete samples. Thus, it is expected that a variation in the environmental conditions used in the production of concrete incorporating CBA in the lab or the production of concrete made with CBA in the lab would yield varying performance. Similarly, it is known that the properties such as tensile and flexural properties are influenced by the sample geometry. Thus, a variation in the geometry of concrete incorporating CBA as fine aggregates could also vary. The authors would also like to emphasize that the chemical and physical properties of the CBA in various studies explored are different. Thus, a comprehensive comparison of these findings might not be ideal without a proper connection to the properties of the CBA. Nonetheless, the findings presented in this study are a good reference to understanding how the use of CBA as aggregate in different types of concrete can influence its corresponding properties.

6. Recommendations for future studies

The possibility of incorporating coal bottom ash (CBA) into concrete has been established in the published literature. However, this paper aims to advance suggestions and recommendations for further studies. These include: 1) further studies should carefully examine the effects of CBA in the regular concrete mixture and SCC, 2) the environmental effects and the economic aspects of using CBA should be investigated, 3) more properties and tests such as Shrinkage, Curing Tests, and Toughness Tests should be investigated, 4) the long-term behavior of CBA needs to be examined, 5) the effect of adding other materials with CBA needs to be studied, 6) the effects of exposing CBA concrete to fire and thermal tests need a thorough analysis, and 7) the effects of CBA in the high strength concrete mixture should be examined.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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