International Journal of Integrated Engineering: Special Issue 2018:
Innovations in Civil Engineering, Vol. 10 No. 9 (2018) p. 28-36

DOI: https://doi.org/10.30880/ijie.2018.10.09.006

A Review on Potential Use of Coal Bottom Ash as a Supplementary Cementing Material in Sustainable Concrete Construction

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Received 9 April 2018; accepted 11 December 2018, available online 31 December 2018

Abstract: The demand of concrete is increased rapidly due to worldwide growth in infrastructural development. Consequently, consumption of concrete also raises the demand for Portland cement, because it is the fundamental material in concrete construction. The increasing demand for Portland cement is expected to be encountered by introducing new supplementary cementing materials. Considering the sustainability of construction, it is imperative to develop supplementary cementing materials from the industrial waste by-products; one of such waste is the coal bottom ash, produced by coal-based thermal power plants. Previously several studies have been conducted on the utilization of coal bottom ash in its original form as natural sand replacement, but limited research has been reported on the coal bottom ash as replacement of cement. It was observed through the literature review that the original coal bottom ash is porous in nature, and cannot be used as a replacement of cement, but after the proper grinding, it possesses the good pozzolanic property and could be utilized as replacement of cement in concrete. The result of this review has indicated that ground coal bottom ash has a good potential to be utilized as supplementary cementing materials in concrete construction. The aim of this review is to summarize the previous findings on the utilization of coal bottom ash as supplementary cementing materials in concrete construction. Hence, this article will deliver the key information and valuable material for the researchers looking for the supplementary cementing materials in the field of advanced concrete technology.

Keywords: Coal bottom ash, pozzolanic material, physical properties, compressive strength, and durability.

1. Introduction

Concrete is an important material in construction. Globally around 2.7 billion cubic meters of concrete was produced in 2002, which is about 0.4 cubic meters of concrete produced per capita annually. It is expected that the concrete demand will be increased more than 7.5 billion cubic meters (about 18 billion tons) a year by 2050 [1] Such massive application of concrete raises the demand for cement which is the main constituent material in the generation of concrete. In addition to that, it was also noted by Scrivener [2] that every year more than one cubic meter of concrete is produced per capita globally with Portland cement being the key ingredient, but it produces huge environmental load. Currently, about 3 billion tons of OPC are consumed worldwide and to produce every 600 kg of cement, around 400 kilograms of carbon dioxide (CO_2) gas is released in the environment. Beside the consumption of energy during the manufacturing of cement, the greenhouse gas emissions are an imperative matter for sustainable concrete construction [3]. Considering the sustainability of construction materials, it is important to utilize industrial waste products as a partial cement replacement, one of such waste is the coal bottom ash (CBA), produced through coal-based thermal power plants.

Coal based thermal power plants produces two type of waste: one is fly ash and other is bottom ash. In the furnace, coal is placed for burning and it many contains non-combustible materials also which consequences in the production of coal ash. The ash which is collected at lower part of the furnace is known as bottom ash and its quantity is almost 25% of the total waste generated by the coal power plant [4]. Since long, CBA is being known as a material of construction. But the application of CBA as replacement of cement is very limited, because of its larger particles. It has a high porosity as compared to fly ash, The CBA particle size is same as to the normal sand, therefore, numerous researches has been conducted on CBA as sand replacement in concrete [5]. It was found from the review of literature that CBA has been used in concrete as a sand replacement with a significant proportion around 20 to 30% [6].

Furthermore, electric power research institute [7] reported in 2009 that coal based power plants in the USA produces annually larger than 92 million tons of coal ash and about 40% is beneficially used in different applications, and about 60% is managed in storage and disposal sites. Therefore, it is necessary to utilize CBA in the field of construction engineering as new supplementary cementing materials because, CBA has well pozzolanic property and can be utilized as cement replacement material in concrete by reducing its particle size. It was observed by Okoye [8] that the concrete structures made from Portland cement, when exposed to aggressive environments; tend to deteriorate much faster than their projected service life. Therefore, it is important to introduce new materials for concrete construction to enhance durability performances.

Utilization CBA as a SCM in concrete construction, have two foremost environmental benefits; considerable reduction in greenhouse gasses emissions and solid waste production through coal-fired thermal power plants. Moreover, it was also observed by the researchers that the strength of concrete can be improved by utilizing fine ground supplementary cementing materials in the concrete [9] [10]. However, strength development is very slow due to low hydration activity and large particle size of SCMs. Therefore, the selection of proper proportion of SCM in concrete construction is also a challenging for the engineers. Whereas, previous also indicated that, smaller the particle sizes higher the hydration rate [11]. This paper summarizes the advanced findings on the CBA as a cement replacement material by previous researchers. The basic motive behind the utilization of CBA is the reduction in the environmental burden in terms of reduction of CO_2 emissions and identifying the potentiality of CBA as SCM for the sustainable concrete construction.

2. Alternative Materials

The selection of appropriate cement replacement material for the concrete construction is very challenging job for engineers and researchers. It was commonly assumed that supplementary cementing materials plays very important role in the development of concrete inherent properties due to pozzolanic activity. The pozzolanic activity means a material containing the reactive silica and/or alumina, because, once mixed with lime in presence of water, will act as cement. Furthermore, fly ash, slag cement (ground, granulated blast-furnace slag), and silica fume, were extensively used with cement with varying proportions. In concrete, the supplementary cementing materials are frequently mixed to achieve more economical, less permeable, higher strength, and influence other concrete properties [7 - 9]. In addition to that SCMs also saves the energy and has environmental welfares, because it's utilization in concrete could reduce the substantial amount of carbon dioxide produced through cement manufacturing process [9].

Based on extensive literature review, the list of waste products commonly used as partial cement replacement material is provided in the Table 1.

Table 1 List of cement replacement materials

Industrial / Agricultural Waste	Ref.
Coal Bottom Ash (CBA)	[1] [4] [6] [12]
Coal Fly Ash (CFA)	[1] [8] [13]
Sawdust Ash (SDA)	[14] [15]
Palm Oil Fuel Ash (POFA)	[16] [17]
Sugarcane Bagasse Ash (SCBA)	[18] [19]
Rice Husk Ash (RHA)	[10] [20][21]

3. Discussion on Previous Findings

3.1 Physical Properties

CBA contains large size, porous particles, irregular in shape, rough surface, lighter in weight and brittle in nature [1] as shown in Fig. 1, which shows three varying scopes of CBA; coarse, fine and micro fine CBA.

Fig. 1 Typical particle sizes of coal bottom ash [1]

Jaturapitakkul, and Cheerarot [27] utilized original bottom (OB) ash and ground bottom (GB) ash in concrete and they declared that OBA particle size around forty times greater than that of the ground BA. Comparing the particles sizes of ordinary Portland cement (OPC), original CBA, and ground CBA were noted as 13, 290, and 7 mm respectively [27]. Therefore, original CBA must be ground before using as a cement replacement [27]. For the instant, the grain size distributions of OPC, ground CBA and original CBA has been shown in Fig. 2 and physical properties of CBA are presented in Table 2.

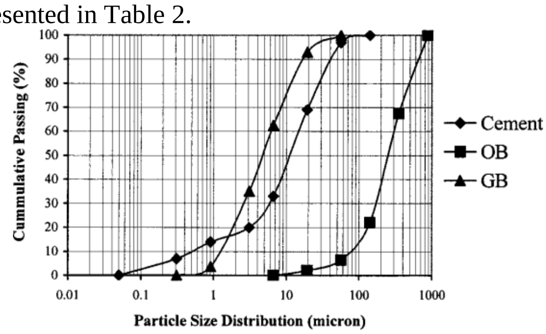

Fig. 2 Typical particle sizes of CBA [27]

Table 2 Physical properties of CBA

Ref.	Sp. gravity	LOI	FM	Application
[1]	1.88	< 0.1	3.44	Sand replacement
[22]	1.39	0.89	1.37	
[23]	2.22	-	2.71	
[24]	2.65	3.80	-	Cement replacement
[25]	2.39	4.65	-	

Specific gravity of the CBA was found from 1.39 to 2.65, it's dependents on source of coal and chemical configuration. Whereas loss of ignition (LOI) in all cases were observed lower than 6 as accepted by ASTM C618 [26]. It was also detected that original CBA has less specific gravity as compared with the ground CBA, because ground CBA contains finer particles. However, ordinary Portland cement have specific gravity of 3.10 [24]. Beside that loss of ignition for original CBA is lower as compared to the grinded CBA, this happens due to unburned corban present in CBA. Overall, it was agreed that grinding process is necessary for CBA to make it pozzolanic material and to achieve similar characteristics as to OPC.

3.2 Pozzolanic Property and Chemical Characteristics

Pozzolanic activity is the most significant characteristics of SCM. It is a capability to consume calcium hydroxide (portlandite, CH) and form calcium silicate hydrate (C–S–H). There are numerous approaches are available to measure the pozzolanic property of the material, but the chemical composition of material can help to understand the pozzolanic potentiality of that material. The chemical composition requirement for pozzolanic material in accordance with the ASTM C618 [26] is approximately 70 % contains silicon dioxide, aluminum oxide and iron oxide. While ignition loss is required to max 10%, detail is provided in Table 3.

Table 3 Chemical Characteristics of OPC and CBA

Chemical contain	[1] [26]	[27]	[28]	[1]	ASTM C618 [26]
	OPC (%)	Coal Bottom Ash (%)			
SiO_2	20.40 - 20.62	48.12	42.7	45.3	SiO_2 + Al_2O_3 + Fe_2O_3 > 70 Class 'F'
A_2lO_3	5.20 - 5.22	23.47	23.0	18.10	
Fe_2O_3	3.10 - 4.19	10.55	17.0	19.84	
SiO_2+Al_2O_3+Fe_2O_3		82.14	82.7	83.24	
CaO	62.39 - 64.99	11.65	9.8	8.70	-
MgO	0.91 - 1.55	3.45	1.54	0.969	Max 5.0
NaO2	0.50	0.07	0.29	-	Max 15.0
SO3	2.11 - 2.70	1.76	1.22	0.352	Max 5.0
LOI	1.13 - 2.36	4.02	-	-	Max 6.0

From the above table 4, it was perceived that chemical characteristics CBA is mainly composed of silica, ferric oxide and alumina, with minor quantities of calcium oxide, sodium oxide, magnesium oxide and sulfur trioxide. It was also endorsed by Jaturapitakkul and Cheerarot [27] that the CBA holds well pozzolanic properties.

Furthermore, it was also observed that once pozzolanic materials are added with the cement, calcium hydroxide $Ca(OH)_2$ is transformed into secondary calcium silicate hydrate (C-S-H) gel [29] transforming the larger pores into finer ones as a result of pozzolanic reaction of the mineral admixtures [30]. The formation of C-S-H is a good sign pozzolanic activity, which could enhance the strength and durability performances of concrete.

3.3 Mineralogical Properties

Kurama and Kaya [25] investigated on the mineralogical analysis for CBA. The crystalline mineral phases were recorded by X-Ray Diffraction (XRD), model S5000 diffractometer, with a nickel-filtered. Results indicated that CBA had a relatively simple mineralogy comprising of alumina, glass and flexible number of crystalline phases of quartz, ferrite spinel, and calcite as shown in Fig. 3.

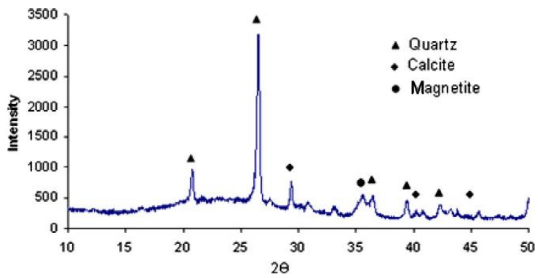

Fig. 3 XRD of the bottom ash (CBA) [23]

The scanning electron micrograph image as shown in Fig. 4, it classified the CBA particles into three kinds: fine portions of crushed BA, large spherical like fly ash particles, and groups of attached particles of fly ash. Though, the common particles are looked like the first type. The certain portion of BA looked like the joint with FA particles, in which they are noticed to be unevenly on exterior surface of the greater particles [28].

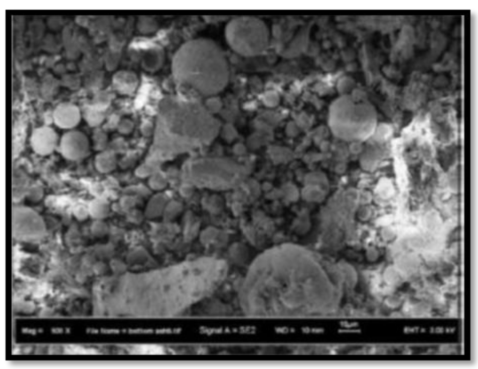

Fig. 4 SEM photomicrographs of Tanjung Bin CBA Malaysia [28]

3.4 Workability

The demand of water for workability of concrete is governed by particle fineness and its characteristics [4]. With constant water to blinder ratio, the workability reduces with the use of CBA as sand / cement replacement in concrete. The previous research also indicated that to achieve desired slump vales, demand of water increases with the use of CBA as partial sand / cement replacement in concrete. The following examples are the presented as an evidence of decrease in workability of concrete containing CBA.

Rafieizonooz et al. [1] investigated the influence fly ash (FA) and coal bottom ash (CBA) as cement and sand replacement in concrete and they found lower workability in concrete mix due to FA and CBA. They highlighted this performance due to rough surface and irregular particles size of CBA which significantly changes the texture of concrete mix. Therefore, it increases the internal friction of particles which is liable for low flow of fresh concrete.

Jaturapitakkul, and Cheerarot [27], investigated original CBA and ground CBA, declared that water requirement for the concrete is increased due to addition of CBA. However, workability could be affected due to the reduction in the water content in the concrete mix.

Similarly, Singh and Siddique [31] examined the effect of CBA as partial sand replacement on workability of concrete, a fixed water-cement ration the workability was found to be decrease. The low workability because of ball bearing effect of the spherical shape of BA particles as compared to irregular natural sand particle [4]. This behavior indicated the internal particle friction and more water absorbed during mixing of concrete, which caused reduction in slump value [31].

It was observed that the utilization of CBA as sand or cement replacement in concrete could significantly reduce the workability performances of concrete, due to higher water absorption. Therefore, care should be taken while adopting water to blinder ratio in concrete mix design.

3.5 Compressive Strength

The CBA has largely contained silica, alumina, and iron with some portion of calcium, magnesium, sulfate, etc. which indicates the potentiality act as a pozzolanic material and it can be utilized as a supplementary cement material [5]. The mechanical performance in terms of compressive strength of concrete containing CBA as SCM in the cement mortar (CM) are provided in Figure 6 which show the compressive strength performances of original and grounded CBA at different curing periods, this has been reflected in the research findings of Jaturapitakkul and Cheerarot [27]. Furthermore, it was found in the mortar with original bottom ash having less compressive strengths than that of the OPC mortar at all curing periods. But the considerable increment in compressive strength was noted when the ground CBA has incorporated in the mortar. Almost 60% compressive strength was noticed to be increased with ground CBA as compared with the original CBA [27]. The results of compressive strengths are provided in Fig.5.

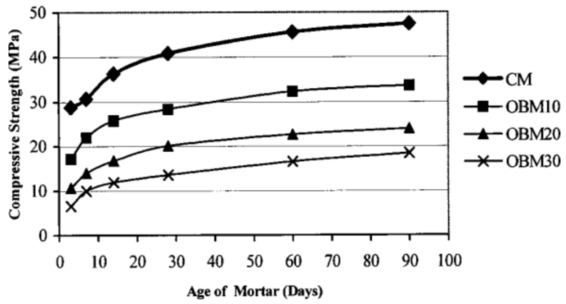

Fig. 5 Compressive strength of original CBA mortar at different curing ages [27]

The utilization of CBA as SCM without modifying quality, bring low compressive strength of the concrete at all curing periods. This is just because of the bigger unit size of CBA [27]. It was experiential perceived that the significant increment in compressive strength concrete/mortar was noted once increasing the fineness of the CBA. Obviously, lower increment at early days and considerable increment in strength were observed after 28days [27]. Whereas, curing time play a vital role in the development of concrete strength. Water curing has so far been widely practiced for curing of hydrated cemented concrete. Due to the addition of SCMs, it was generally perceived that the hydration process takes more time as compared to the normal mix concrete because of the chemical imbalance within the mix.

Khan and Ganesh [32] conducted an experimental study on effects of origional and grinded CBA in concrete. They were focused on the compressive strength performances of concrete cubes (150mm x 150mm x 150mm) containing original bottom ash (OBA) and ground bottom ash (GBA) at 10, 20 and 30% replacement of cement for the curing period of 7, 14, 28, 56 and 90 days. Whereas M1 represent the control specimen, M2, M3 & M4 represents the concrete cube containing OCBA and M5, M6 & M7 represents the GBA at 10, 20 and 30% replacement of cement respectively. The compressive strength of concrete containing CBA as compare with control specimen has been provided in Fig. 6.

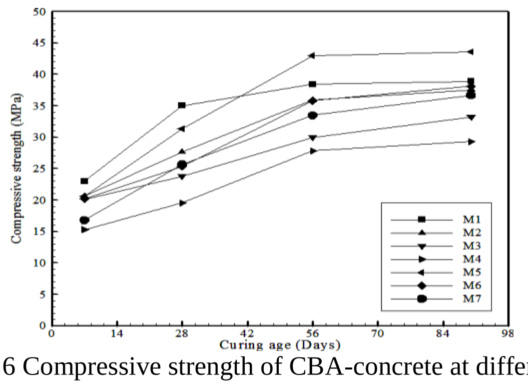

Fig. 6 Compressive strength of CBA-concrete at different curing time [32]

It was observed that compressive strength of the CBA concrete is lower compared to control specimen at 28 days, which indicated that at early ages the pozzolanic reaction doesn't start so premature strength is due to the cement in the concrete mix. GBA concrete density was recorded higher as compared to concrete containing OBA, due to that compressive strength of GBA concrete was more than that of OBA concrete. The strength of the GBA concrete at 10% replacement is more than the control mix at 56 days, due to pozzolanic activity. It was previously agreed by Mangi et al. [14], the usage of supplementary cementing material in concrete could enhance strength with increasing curing ages.

Hence, in the light of previous inputs it can be perceived that the mechanical performance of concrete / mortar containing ground CBA is suitable as compared to the original CBA. It was also decided that the compressive strength of CBA-concrete/mortar at initial or later ages depends on the particle fineness of CBA.

3.6 Durability Performances

The durability of concrete structure is the significant aspect while erecting the prominent structures. According to the ACI committee 201 [33] the durability of hydraulic-cement concrete is described as the ability of concrete to resist chemical attack, weathering attack, abrasion, or other process of deterioration. The durable concrete will retain in its original form, event exposed to aggressive environment.

Okoye et al. [8] define the durability of concrete as; its capability to resist weathering action, chemical attack and abrasion. Currently, durability of concrete structure is an important subject in the field of construction engineering, since cement is the one of the major sources for greenhouse gas emissions. It was noticed by Pyo and Kim, [34] that considering the environmental concerns, the selection of sustainable construction material is stimulating aspect. The selection of construction material should be such that it has high durability and adequate strength properties and it can be conceivable through utilizing industrial by-products.

The durability of concrete structures is affected by exposure conditions due to exchanges between aggressive agents present in environment and the cement constituents. Deterioration of concrete in terms of salt attack can happen either due to the decomposition of cement paste. It was mentioned by Siddique and Khan [35] deleterious chemicals can react with $Ca(OH)_2$ to form water soluble salts that can be leached out of the concrete over the time, thus increasing the permeability of concrete and annoying the damage by increased and faster access of harmful chemicals. Considering the aggressive environment, previous research has been conducted on concrete exposed to the different exposure conditions such as sulphate and chloride attack and combined attack because seawater holds high concentrations of chloride and sulfate salts [36].

It was perceived by the Gutierrez [37] that the selection of supplementary materials is depends upon the availability of the material, which will affects the performance of the concrete structure as well as the cost saving, development of mechanical properties, reduction of permeability in concrete, prolong the service life of structure under selected exposure conditions. The application of supplementary cementing materials (SCMs) has been raised in the cement and concrete production. The concern of the producers has focused on the cost reduction and benefits for obtaining high resistant cement-concrete and in general, an addition of SCMs will increase the strength of concrete [37]. However, SCMs are under attentions about durability, volume stability and performance in aggressive environments have gained great consideration. Hence, SCMs have tendency to reduce or break the expansion in concrete due to alkali silica reaction (ASR) with reactive aggregates.

Madandoust et al. [21] investigated the effect of rice husk ash (15 to 25%) on the chloride penetration in concrete and perceived that, higher the amount of RHA lower is the chloride permeability, and the chloride penetration as shown in Fig. 7.

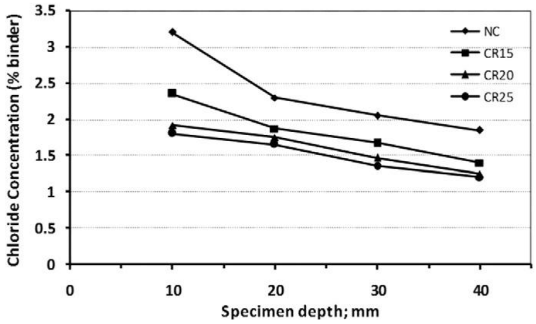

Fig. 7 Chloride concentrations for different specimens after 360 days [23]

Recently, Argiz, et .al. [24] Carried out research on the utilization of ground CBA as a new supplementary cementing material in concrete. They found ground CBA as an alternative material of cement, with good durability performance, especially in chloride ingress and they also declared a linear relationship between the chloride diffusion coefficient and chloride migration coefficient with 10% of CBA. Furthermore, it was also formerly investigated that the SCMs protect against alkali silica reaction (ASR) has been improved by aluminum presence in SCM, it decreases the solubility of silica in alkaline solutions, restricting ASR expansions This phenomena could lead towards more effective utilization of SCMs for ASR mitigation [11] [38] [39].

3.7 Summary of Key Findings

The summary of key research findings has been prepared from the extensive literature review. It indicates the key findings on the application of CBA as supplementary cementing materials (SCM) in the concrete production. It was explored by the researchers that the CBA has great tendency to perform as a Pozzolanic material, it can be considered to produce normal as well as high strength concrete. Through the adoption of these practices could reduce the environmental burden and creates a solution to the sustainable construction material to build economic structures. The summary of key findings is presented in Table 4.

The application of CBA in concrete also has some advantages and disadvantages, which also summarized in this paper and presented in Fig. 8. It was well recognized that CBA can be utilized in two forms either in original or in powdered form (after proper grinding). The original CBA was broadly used as natural sand replacement in concrete construction. But CBA in powdered form is very limited. Since, systematic grinding process is required for the conversion of original CBA in to ground CBA.

Therefore, few studies have been reported on ground CBA as partial cement replacement. Hence, it can be summarized based on available literature, that ground CBA has great advantages as compared with the original CBA. Among the advantages the chief benefit is that application of ground CBA in concrete could significantly reduce the chloride penetration and reduces the environmental burden. Beside that it has also some minor disadvantages for example, it reduces the early strength and absorbed more water during preparation on concrete mixture.

Table 4 Summary of key research findings

Ref.	**Particle size / grinding period**	**Key research findings**		**Observations**
		Recommend level	Benefits	
[24]	3% residues on 45 µm sieve	10%	Reduces chloride migration in concrete	Ground CBA was observed as a new durable supplementary cementing material in concrete construction.
[25]	25 % residues on 38 µm sieve	10%	Compressive and flexural strength increased 10% at 56days	Pozzolanic reaction not initiated at early ages due to that strength was not increased at the ages of 7 and 28days.
[27]	2.8% retained on Sieve #325 (45 µm)	20%	Good compressive strength performances	Grinding is necessary to convert original CBA in to a pozzolanic material. Strength not increased at initial ages, but it was observed 8% and 11% increased at 60 and 90days respectively.
[28]	Particle size of original CBA is almost similar as natural sand	-	Material of low specific gravity, ease in compaction	CBA recommended as pozzolanic material for concrete construction, it was also suggested for geotechnical application.
[32]	CBA grinded for 30 minutes to get particle size between 0.1mm-1mm	10%	14% compressive strength increased at 56days. Whereas, 10% cost saving and reduction in CO_2 emissions	Pozzolanic reaction not started at first 28days. Afterward, strength was significantly raised at 56 and 90days. Ground CBA also improves durability performances of concrete in terms of resistance to acid (H_2SO_4) attack.
[34]	Mean particle size 5.88 µm	20%	Compressive strength increases	Application of CBA with silica fume gives good compressive strength after curing period of 28 days
[40]	Ground CBA for 6 h to obtain a similar size close to that of OPC	10 to 30% with 10% (Ca (OH)2)	20% greater strength performances and reduced thermal conductivity	CBA can be used as partial cement replacement after proper grinding. Ground CBA with combination of calcium hydroxide (Ca (OH)2) was found good strength performances
[41]	Ground CBA for 6 h to obtain a similar size to OPC	20%CBA+5 %SF	13% compressive strength increased at 28days	Without silica fume, lower strength performances but ground CBA with silica fume having good strength performances even at early ages.

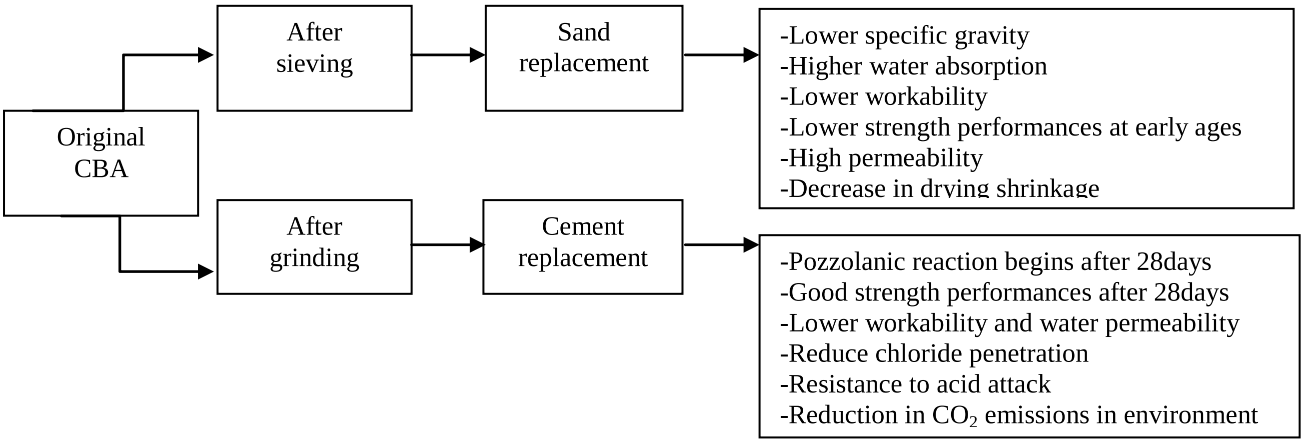

Fig. 8 Advantages and disadvantages of CBA application in concrete

4. Observation and Conclusion

Recently published literature has been critically reviewed in this paper on the utilization CBA for sustainable concrete construction. Several new understandings have been perceived through the review process, which could have significant inputs for future works. It was observed that original CBA is porous in nature, so it cannot be used as a cement replacement, but after the grinding, it possesses the good pozzolanic property and could be utilized as SCM. Whereas, the cement hydration and mechanical property like compressive strength could be improved by incorporating ground CBA in the concrete. From the previous research, it can be concluded that:

- CBA application in concrete construction as supplementary cementing material could enhance the long-term strength performances and reduces the permeability.
- CBA can be used as a pozzolanic material in the powdered form and could be used as partial replacement of cement in durable and sustainable concrete construction.
- Its application as cement replacement material will significantly reduce the environmental problems.
- Its application will also resolve the problem of CBA handling and dumping in the open fields.

The review of literature on ground CBA starting from the early days till now suggest that detailed research on workability, tensile strength and drying shrinkage performances of concrete containing ground CBA need to be considered for the future studies.

Acknowledgment

The authors gratefully acknowledge the financial support of Research Management Centre (RMC), Universiti Tun Hussein Onn Malaysia, through grant Tier-1 Vot No. U838 and support of Mehran University of Engineering and Technology, Jamshoro, Pakistan in terms of FDP scholarship is also acknowledged.

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