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Review

A Review of the Utilization of Coal Bottom Ash (CBA) in the Construction Industry

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Abstract: One effective method to minimize the increasing cost in the construction industry is by using coal bottom ash waste as a substitute material. The high volume of coal bottom ash waste generated each year and the improper disposal methods have raised a grave pollution concern because of the harmful impact of the waste on the environment and human health. Recycling coal bottom ash is an effective way to reduce the problems associated with its disposal. This paper reviews the current physical and chemical and utilization of coal bottom ash as a substitute material in the construction industry. The main objective of this review is to highlight the potential of recycling bottom ash in the field of civil construction. This review encourages and promotes effective recycling of coal bottom ash and identifies the vast range of coal bottom ash applications in the construction industry.

Keywords: coal bottom ash; waste material; recycle; construction industry; civil engineering

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1. Introduction

The increasing price of oil and natural gas has made coal-fired power generation more economical, especially in countries with vast coal resources such as India, the United States of America (US), and China [1]. China consumes 50.2% of the coal in 2012, followed by US and India (11.7%), Japan (8.0%), Russia (3.3%), South Africa (2.5%), South Korea (2.4%), Germany (2.2%), Poland (2.1%), and Indonesia (1.4%) [2]. India, China, and Australia are projected to contribute 64% of the world coal production in 2040, a growth of about 4% compared to the 2012 coal production [3].

The increasing trend in coal consumption will continue mainly due to the high demand for electricity. Coal is rapidly gaining favor as an energy source for generating electricity, after gas [4]. The 0.9% increase in world coal consumption in 2019 was driven by Asia (1.8%). The utilization of coal as a global source of electricity generation is expected to increase to 47% by 2030 [2,5].

The high demand for coal production has resulted in the generation of a higher amount of industrial waste. Fly ash makes up 70–80% of the total coal ash wastes, and the remaining 10–20% is bottom ash [2,3,6]. Of the millions of tons of coal ash waste generated annually, 100 million metric tons (Mt) is bottom ash, and the remainder is fly ash [7]. The World of Coal Ash (WOCA) estimated that coal thermal power plants generate 780 million metric tons of coal bottom ash (CBA), of which 66% is by Asian countries, followed by Europe and the United States [8]. China produces the highest amount of coal ash of 395 million metric tons (Mt), followed by the US (118 Mt), India (105 Mt), Europe (52.6 Mt), and Africa (31.1 Mt). The Middle East and other countries contributed a small amount to the global coal ash generation [9]. Of the 105 million metric tons of coal produced in India [9], about 35 million metric tons is coal bottom ash produced by the power plants that generate electricity [10].

The wastes produced in electricity generation are boiler slag, fly ash, clinker, and bottom ash [11,12]. The physical properties and the chemical composition of bottom ash and fly ash differ because fly ash is lighter than the bottom ash collected in a hopper after falling through the bottom furnace. The bottom ash could be wet or dry bottom ash, depending on the type of boiler.

Bottom ash has a porous texture and angular particles; the size of the bottom ash generally ranges between sand and gravel particles and a small amount of slit–clay particles [11,12]. A large proportion of the bottom ash is fine particles that comprise 50–90% of bottom ash. The specific gravity of bottom ash is dependent on its chemical properties and ranges between 1.39 and 2.41 [13–15]. Coal bottom ash falls into the A-1-a class and well-graded sand groups of the AASHTO and USCS classification systems [16].

The disposal of bottom ash landfills has raised a grave environmental concern [16,17]. The high composition of heavy metal in bottom ash, relative to fly ash, increases the risk of groundwater pollution [18,19]. One way to deal with the increasing amount of CBA generated and the scarcity of land is by recycling and reusing CBA [20].

The large amount of coal bottom ash produced by the thermal power plants is one of the primary industrial wastes. Therefore, using CBA in the construction industry will save time and reduce landfill use, cost, and energy. The two key benefits of recycling CBA in civil construction are a considerable reduction in greenhouse gas emissions and solid waste generation by coal-fired thermal power plants [15]. Moreover, this approach will protect the environment from the harmful impact of this waste material. This paper presents a review of the utilization of coal bottom ash in civil construction.

2. Properties of Coal Bottom Ash

The specific properties of coal bottom ash are dependent on factors such as the coal source and type of coal. There are four types of coal: anthracite, bituminous, sub-bituminous, and lignite [21]. The type of coal is dependent on the types and amounts of carbon, the amount of heat energy the coal can produce, the level of carbon moisture, and other chemical elements [22]. Anthracite has the highest carbon content, followed by bituminous, sub-bituminous, and lignite. Generally, the types of coal used in energy generation are bituminous, sub-bituminous, and lignite. The geological formation of the coal determines its chemical composition; the CBA from the different types of coal have varying silica oxide (SiO_2), alumina oxide (Al_2O_3), and ferric oxide (Fe_2O_3) contents and characteristics that influence the research finding [22,23].

Bottom ash is washed before use to remove unnecessary materials such as pyrite, which could degrade the bottom ash in the presence of water. The bottom ash should also be free of dust to ensure the correct grain size distribution. Finally, the bottom ash is dried to remove humidity and excessive moisture, which affect the mixture's reliability [24].

2.1. Physical Properties

Table 1 shows the physical properties of CBA from various sources. The specific gravity of CBA ranges between 1.39 and 2.41 and its water absorption is between 6.8 and 32%. CBA has a Los Angeles abrasion of 55% and a moisture content of 0.43%. Its fineness modulus ranges between 1.5 and 3.44, and its specific surface area ranges from 3835.7 to 10,500 (cm^2/g).

Table 1. Physical properties of CBA.

References	Specific Gravity (No Unit)	Water Absorption (%)	Los Angeles Abrasion, (%)	Moisture Content (%)	Fineness Modulus (No Unit)	Surface Area (cm^2/g)
[25]	2.21	-	-	-	2.79	-
[26]	2.41	32	-	-	-	3835.75
[27]	1.8	-	-	-	-	10,500
[28]	2.08	6.8	-	-	1.5	-
[14]	2.22	20.15	-	-	2.71	-
[3]	1.88	11.61	-	-	3.44	-
[17,29]	1.39	31.58	-	-	1.37	
[30]	2.00	-	-	-	-	-
[31]	2.21	11.17	-	-	-	-
[32]	1.87	5.4	-	-	2.36	-
[33]	1.39	12.10	-	-	-	-
[24]	-	-	55	-	-	-
[34]	2.10	6.18	-	0.43	2.10	-
[25]	2.21	-	-	-	-	-

2.2. Chemical Properties

Table 2 presents the chemical composition of CBA from various power plants, where the percentages of the chemical composition are expressed by mass. Silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and calcium oxide (CaO) are the primary mineral compounds in coal rock [35]. The chemical composition of CBA comprises the major and minor components. The total percentages of the chemical composition for the CBA from different sources varies and is less 100%. The minor components cannot be traced due to their small amounts. Table 2 shows that coal bottom ash contains high amount of SiO_2, Al_2O_3, and Fe_2O_3 that improve pozzolanic effects, mixture interlock, and properties such as the strength [28].

Table 2. Chemical composition of CBA.

References	Chemical Composition (%)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3
[36]	62.33	25.52	4.16	1.00	0.94	0.08	3.25	0.84	0.12	-
[6]	65.02	19.18	6.86	1.76	2.00	0.85	-	0.93	0.04	-
[26]	52.5	17.65	8.30	4.72	0.58	-	-	2.17	-	0.84
[27]	50.49	27.56	10.93	4.19	1.24	0.57	0.82	2.23	0.24	0.10
[37]	47.1	23.1	5.7	7.8	1.5	0.7	5.3	1.2	-	1.5
[38]	59.82	27.76	3.77	1.86	0.70	1.61	0.33	-	-	1.39
[39]	52.2	27.5	6.0	5.9	1.7	-	0.6	1.53	0.74	0.13
[40]	58.7	20.1	6.2	9.5	1.6	0.1	1.0	-	1.0	0.4
[14]	62.32	27.21	3.57	0.50	0.95	0.70	2.58	2.15	-	-
[3]	45.30	18.10	19.84	8.70	0.97	-	2.48	3.27	0.351	0.352
[17]	56.44	29.24	8.44	0.75	0.4	0.09	1.24	-	-	-
[30]	64.45	15.89	7.77	3.92	2.45	0.89	1.6	-	<0.01	<0.01
[41]	68.9	18.67	6.5	1.61	0.53	0.24	1.52	1.33	-	-
[31]	52.1	18.34	11.99	6.61	4.85	2.43	1.57	0.87	-	-
[29]	47.53	20.69	5.99	4.17	0.82	0.33	0.76	-	-	1.00
[42]	57.76	21.58	8.56	1.58	1.19	0.14	1.08	-	-	0.02
[43]	54.8	28.5	8.49	4.2	0.35	0.08	0.45	2.71	0.28	-

2.3. Comparison between CBA and Different Waste Used as Aggregate Replacement

Researchers have investigated steel slag, coconut waste, recycled asphalt, recycled concrete, mining waste, glass, crumb rubber, palm oil shell, and palm oil clinker as natural aggregate replacement. Table 3 summarizes the physical properties of the wastes used as aggregate replacement in asphalt pavements and concrete production.

Except for steel slag, the specific gravities of the wastes listed in Table 3 are similar to that of CBA. Steel slag has a higher specific gravity of between 3.01 and 3.67 [44–47], although coconut waste and palm oil shells have high absorption values of between 13.8 and 25% because of their porous structure [48–52]. The Los Angeles abrasion for the wastes ranges between 11.29 and 25.3% [44,45,53–60], which is lower than the 55% for CBA [24]. The lower Los Angeles abrasion values indicate that the materials are tougher and more resistant to abrasion than CBA. The moisture content of the waste is between 0.11 and 9.1% [46,61–63]. The fineness modulus values of 6.53–6.78% for the coconut waste, recycled concrete, and palm oil shell are similar to CBA and are comparable to the natural aggregates, making them suitable for aggregate replacement.

Table 3. The physical properties of the wastes used as aggregates in asphalt pavement and concrete production.

Waste	Physical Property Parameters					Used As		
	Specific Gravity (No Unit)	Water Absorption (%)	Los Angeles Abrasion (%)	Moisture Content (%)	Fineness Modulus (%)	Fine	Coarse	Reference
Steel slag	3.41	1.49	11.29				√	[44]
	3.01	-	14.2				√	[45]
	3.42 * 3.58 **	3.31 * 4.23 **	-	1.56 * 2.8 **	-	√	√	[46]
	3.67	1.4	-	-	-		√	[47]
Coconut waste	1.15	21	-		6.78		√	[48,49]
	1.16	13.8	-	-	-		√	[50]
Recycled asphalt	2.68	0.20	22.2			√	√	[53]
	2.55	0.23	20.25			√	√	[54]
Recycled concrete	2.41 * 2.42 **	4.80 * 7.40 **	18.7			√	√	[55]
	2.18 * 2.42 **	2.69 * 4.28 **	24			√	√	[56–58]
	2.35	8.01	-	9.1	-	√	√	[61]
	2.42–2.44 * 2.415 **	6.5–6.8 * 9 **	-	-	-	√	√	[64]
	2.53	3.04	-	-	-		√	[65]
	2.44	5.65	-	-	6.92		√	[28]
Mining waste	2.34	0.86	20.5				√	[59]
	2.87	0.23	25.3			√	√	[60]
Glass	2.3	20–25	-	-	-		√	[66]
	2.45	0.36	-	-	-	√		[65]
Crumb rubber	1.15	-	-			√		[67]
	1.25	-	-			√		[68]
Palm oil shell	1.37	12.47	-	-	6.53		√	[51]
	1.3	25	-	-	-		√	[52]
Palm oil clinker	2.08	-	-			√		[69,70]
	1.51	5.5	-	0.31	-		√	[71]
	1.78	5.7	-	0.38	-		√	[62]
	1.18 * 2.15 **	4.35 * 5.75 **	-	0.28 * 0.11 **		√	√	[63]

* Coarse aggregate, ** fine aggregate.

2.4. Sustainability

Researchers are looking for alternatives to the conventional CBA disposal method that has given rise to environmental problems. Recycling coal bottom ash is the best solution for the high cost of disposing of the coal bottom ash waste [72], the decreasing disposal area, and the harmful environmental impact [73]. CBA is physically similar to natural aggregates and resembles Portland cement (PC) when pulverized into finer particles [74]. Previous studies have shown that its pozzolanic reactivity makes CBA a promising alternative for cement replacement in concrete and can reduce up to 90% of the concrete carbon footprints [75]. Replacing PC with CBA in concrete production can reduce CO_2 emissions [74,76]. Previous studies have also proven the beneficial impacts of using CBA as PC replacement on the environment and the problems associated with conventional concrete [18,77,78]. CBA is a green material that could reduce harmful environmental impact and promote sustainability in concrete production [74].

Asphalt construction requires a large amount of natural aggregates, namely 100% aggregates for the base and subbase courses, 95% for bituminous, and 87% for concrete pavements. The natural aggregates used to construct one kilometer of a surface course using a bituminous mixture could exceed 15,000 tons [7]. In recent years, natural aggregate replacement with CBA has reduced construction costs and minimized the need to harvest aggregates from natural resources.

3. Applications of Coal Bottom Ash

3.1. Pavement Construction

Prior studies on the utilization of coal ash waste in the construction industry focused more on fly ash than bottom ash. However, recent studies reported that bottom ash has some desired engineering properties that make it a feasible construction material. The minimum strength, stability, durability, and other specifications of the products incorporated with CBA must be complied with [79]. CBA has been used as an aggregate replacement, cement replacement, additive in bitumen, and filler in asphalt pavement. Table 4 summarizes the effect of CBA in pavement construction.

Yoo et al. [80] investigated the performance of HMA mixture incorporated with bottom ash as a partial replacement for fine aggregates at the ratio of 10, 20, and 30%. The incorporation of bottom ash using the Marshall Mix Design increased the optimum asphalt content by 10%. Increasing the bottom ash content from 10 to 30% did not affect the optimum asphalt content [80]. The presence of bottom ash in asphalt mixtures did not affect the moisture susceptibility of the asphalt mixtures relative to the control mixture. The asphalt mixtures containing bottom ash exhibited higher resistance towards fatigue cracking when subjected to repeated indirect tensile stiffness modulus (IDT) testing under dynamic loading. The research performed the Synthetic Precipitation Leaching Procedure (SPLP) test on the raw bottom ash to determine its toxicity and found that the toxicity concentration in bottom ash is within the permissible range.

Colonna et al. [24] investigated the impact of utilizing bottom ash as a partial replacement for fine aggregates in asphalt mixtures. The percentage bottom ash as a partial replacement is 15, 20, and 25%, and the optimum binder content (OBC) is 4.5% of the 60/70 asphalt binder. However, the OBC percentage for 20% of the CBA replacement is 5% higher. The researchers observed enhanced stability and reduced wearing resistance with higher CBA contents. However, the mixtures have good wearing resistance with a Cantabro index of less than 30%. The researchers concluded that the optimum CBA content is 15%. The leaching test showed that the hazardous substances leached by all samples are below the limit of detection and the trace substances are below the allowable limit.

Ksaibati [81] examined the feasibility of using CBA as a complete aggregate replacement. The coarse CBA and fine CBA were used in HMA and tested in field and laboratory assessments. The three tested samples were prepared using bottom ash from three different resources. Results showed that the optimum asphalt content was higher in the mixture containing bottom ash with no difference in the performance of the bottom ash mixture and control mixture after being in service. The laboratory analysis showed that all tested HMA mixtures have different low- and high-temperature cracking characteristics, indicating that the varying properties of the bottom ash from the various power plants may affect the strength of the asphalt mixture.

Hesami et al. [82] assessed the potential of using bottom ash in rigid pavements. The coal waste ash, coal waste powder, and limestone powder were used as cement replacement in the roller-compacted concrete pavement (RCCP) in varying percentages of 5 to 20%. The researchers determined the elasticity modulus, splitting tensile strength, flexural strength, and compressive strength of the pavements between day 7 to day 90. The water/cement ratio increased when using the coal waste ash and coal waste powder. The mixtures containing 5% CWS and coal waste ash had similar strength to the control mixture. The strength of RCCP mixtures decreased with higher coal waste ash contents. In summary, coal waste ash enhanced the mechanical properties when combined with limestone.

Ameli et al. [83] examined the performance of asphalt mixture incorporated with varying percentages of coal waste ash of 0, 25, 50, 75, and 100%. The coal ash waste was used as a replacement for the conventional filler. The research measured the rutting resistance and fatigue resistance of the mastics, stability, resilient modulus, dynamic creep, and moisture susceptibility of the asphalt mixtures. The results indicate that the addition of coal waste ash improved the fatigue behavior of the mastics, and the fatigue behavior was further enhanced when the mastics were modified with SBS. The replacement with coal waste ash reduced the Marshall stability, resilient modulus, rutting properties, and tensile strength of the asphalt mixtures, but improved the moisture resistance.

Xu, Chen [84] investigated the effect of coal waste ash that has been retreated from coal waste by reheating, on the asphalt mastic and asphalt mixtures. The coal waste was used as a replacement in varying percentages of 20, 40, 60, and 80%. Compared to fine limestone powder, coal waste ash had a lower density, higher alkalinity, smaller particle size, and larger interior air voids. The bitumen incorporated with coal waste ash had a lower penetration value, higher softening point, and better temperature stability. The incorporation of coal waste ash reduced the Marshall stability and rutting resistance of the asphalt mixture. However, the moisture susceptibility of the asphalt mixture improved significantly with the addition of CBA.

Other studies assessed the potential of using CBA as a filler in bituminous mixtures [85,86]. The high porosity and high specific surface properties of hydrated lime and/or bottom ash increased the value for the optimum binder content. The higher absorption value is due to the high porosity of the ashes, indicating that the high specific density of the mixture relative to the control mixture is due to the low specific densities of the bottom ash and lime. A higher value indicates a longer lifespan and better performance of the pavement. The pavement containing 30% hydrated lime and 70% bottom ash had the highest density, which is the recommended density for the road surface and intermediate layers with small infrastructures and light traffic [86]. However, the results of this research are contrary to the findings of an earlier study [85], which showed that using bottom ash as a filler substitute resulted in a higher rutting potential and a lower dynamic modulus than the control mixture.

Modarres and Ayar [87] examined the effect of using coal waste ash and coal waste powder as additives in the cold recycled mixture, which contains 100% reclaimed asphalt pavement (RAP) materials, using the emulsified cold recycling technology, where the additives dimensions are below 0.075 mm. The addition of coal waste ash and coal waste powder in varying percentages of 3, 5, and 7% enhanced the mechanical properties of the pavement. The higher pozzolanic content in the coal waste powder enhanced the resilient modulus, tensile strength, and Marshall stability. Relative to coal waste powder, coal waste ash had a better impact on moisture sensitivity and enhanced moisture damage resistance.

Table 4. Summary of the utilization of CBA in pavements.

References	Function	Effect on Pavement Performance
[83]	Filler in SMA mixture	• Reduced Marshall stability, resilient modulus, tensile strength, and fatigue properties of the pavements. • Improved moisture resistance.
[84]	Filler replacement	• Reduced pavement stability and rutting resistance. • Improved moisture resistance.
[80]	Fine aggregate in HMA	• Higher OBC with 10% CBA replacement. However, there was no significant difference with a higher percentage of CBA replacement. • No significant change in moisture susceptibility. • Improved fatigue resistance.
[82]	Cement replacement in roller-compacted concrete pavement	• Increased the water/cement ratio. • The RCCP mixtures containing higher amounts of coal waste ash had a lower strength. • Coal waste ash produced better mechanical properties when used in combination with limestone.
[88]	Filler replacement in asphalt mixture	• The high specific surface area of the bottom ash particles resulted in a higher percentage of asphalt binder and better mastic quality. • Lower CO_2 emissions in the processing of bottom ash compared to a commercial filler.
[89]	Filler replacement in HMA mixture	• Improved stability, resilient modulus, moisture resistance, and tensile strength.
[87]	An additive in cold recycled mixture	• Enhanced stability, resilient modulus, and tensile strength.
[24]	Fine aggregate in HMA	• Enhanced stability and Cantabro index.
[81]	Fine and coarse aggregate replacement	• The difference in performance was not significant after a particular period of service. The varying properties of CBA from various coal sources influence the strength of the asphalt mixture.

3.2. *Aggregate Replacement in Concrete Production*

There has been an increase in literature on using bottom ash as an aggregate substitute in concrete production due to its porous texture and low particle densities. The literature reported the promising potential of bottom ash as an aggregate and cement substitute in concrete, particularly to enhance the concrete's strength and microstructural properties. During the past several decades, there has been extensive research on using alternative materials in concrete manufacturing. The benefits of lightweight concrete are reduced weight, good thermal and sound insulation, durability, strength, low expansibility, ease of use in construction, and low cost [90].

Rafieizonooz et al. [3] investigated the performance of concrete incorporated with CBA. Varying percentages of 0, 20, 50, 75, and 100% of coal bottom ash were used as fine aggregate replacement and 20% of coal fly ash (CFA) as cement replacement in concrete. After curing at 91 and 180 days, the compressive strength of CBA and control concrete increased significantly. Despite the enhanced strength after a long curing period, the compressive strength between CBA and control concrete had no significant difference; however, the flexural strength and splitting tensile strength of the 75% CBA was much higher than the control concrete. The concrete with 50, 75, and 100% CBA had a lower drying shrinkage than the control concrete. The late effect is due to the delayed hydration and slow pozzolanic activity of the CFA and CBA.

According to Singh and Siddique [17,29], adding CBA to concrete mix reduced the workability and bleeding of the concrete. The cement in 38 MPa and 34 MPa concrete grade was replaced with varying percentages of 20, 30, 40, 50, 75, and 100% CBA, and superplasticizer was used as an admixture in the 34 MPa concrete grade. The compressive strength and splitting tensile strength of CBA concrete was similar to the control concrete after 90 days of ageing. The modulus of elasticity and abrasion resistance decreased with higher CBA contents. However, the abrasion resistance improved significantly with ageing. Based on the workability and strength properties results, the researcher recommended the optimum use of CBA in concrete as up to 30% for concrete without superplasticizer and up to 50% with superplasticizer.

Zhang and Poon [31] studied the properties of lightweight concrete incorporated with 0, 25, 50, 75, and 100% of bottom ash as a fine aggregate replacement with a 0.39 w/c ratio. The results showed that 100% bottom ash replacement resulted in comparable workability and compressive strength relative to the regular concrete. Bottom ash concrete has a low density, and a replacement with less than 50% bottom ash resulted in a high fc/D ratio, making the lightweight concrete suitable for structural purposes. The durability test showed that the lightweight aggregate concrete containing bottom ash had a high chloride penetration. The heat insulation property test showed that the thermal conductivity decreased with higher bottom ash contents without a significant loss of strength, making the lightweight aggregate concrete suitable for use energy-saving building envelope materials.

Jang et al. [19] investigated the ecofriendly porous concrete fabricated using coal bottom ash. The coal bottom ash was used as a coarse aggregate replacement, and geopolymer was used as the binder. The combination of coal bottom ash and geopolymer produced porous concrete with a higher compressive strength relative to the porous concrete fabricated from recycled aggregate and cement paste. However, the concrete had a lower compressive strength than the regular porous concrete fabricated using gravel and cement paste. Concerning environmental impact, the concentration of heavy metals leached from the porous concrete did not exceed the maximum permissible concentration. The researchers concluded that the porous concrete could effectively immobilize the heavy metals as solidified/stabilized products.

Researchers have also investigated the effect of using coal bottom ash as fine aggregate in self-compacting concrete on the split tensile strength [41]. The fine aggregates were replaced with varying percentages of 0, 10, 20, and 30% coal bottom ash using different water–cement ratios of 0.35, 0.40, and 0.45. The split tensile strength and density of the self-compacting concrete decreased with higher CBA contents. The highest tensile strength of the concrete containing CBA was 3.28 MPa at 10% CBA replacement and 0.35 water–cement ratio. However, this value was lower than the control sample, which had the highest tensile strength of 4.25 MPa.

Kim and Lee [32] investigated the chemical composition and physical properties of bottom ash particles to determine the feasibility of using the bottom ash as fine and coarse aggregates in high-strength concrete with a compressive strength of 60–80 MPa. The fine and coarse bottom ashes were replaced in varying percentages of 25, 50, 75, and 100%. Unlike coarse bottom ash, fine bottom ash had no impact on the fresh concrete flow characteristics. The low slump value of the fresh concrete incorporated with coarse aggregate is due to the complex shape and rougher texture of the bottom ash relative to the normal aggregates. The density of the high strength concrete containing 100% fine bottom ash and 100% coarse bottom ash was less than 2000 kg/m^3. The incorporation of 100% fine and coarse bottom ash reduced the modulus of elasticity by 49% relative to the control concrete. The compressive strength was not affected by the incorporation of bottom ash in the concrete mix. However, the flexural strength and modulus of rupture decreased linearly with higher percentages of bottom ash in the concrete mix.

3.3. Cement Replacement in Concrete Production

Besides using CBA as an aggregate replacement, researchers and technocrats investigated using CBA as cement replacement. The chemical properties of CBA are similar to cement as both are class F materials. The SiO_2 content of CBA is greater than 25%, and the content of $SiO_2 + Al_2O_3 + Fe_2O_3$ is higher than 70%, which meets the requirement for the recycling bottom ash as cement [25,91]. Moreover, replacing cement with CBA can reduce CO_2 emissions and improved energy conservation.

Cement is the most widely used material in civil constructions. However, the high amount of carbon emitted in cement production has a harmful impact on the environment. An estimated 50% of the total CO_2 emissions are from cement production. The production of each ton of cement releases 0.55 tons of CO_2, and an additional 0.39 tons of CO_2 is emitted during the baking and grinding processes, which are the key contributors to global warming [73].

According to Singh and Bhardwaj [6], replacing a certain percentage of Portland cement with ground coal bottom ash enhanced the resistance towards carbonation, chloride penetration, acid attack, and sulphate attack. The sound absorption coefficient of the concrete improved with the incorporation of both fine and medium CBA. The concrete containing up to 30% of CBA had a lower drying shrinkage after short-term and long-term curing periods. The physical and chemical properties of ground CBA are similar to FA. The concrete containing CBA had a comparable compressive strength to the control concrete, and enhanced flexural strength.

Another study evaluated the performance of the concrete incorporating CBA when exposed to seawater [26]. The original CBA was ground in a ball mill for 20 and 30 h, and 10% of the ground CBA was used as supplementary cementitious material. The concrete containing CBA with a fineness of 3836 and 3895 cm^2/g had a higher strength than the control mix after 180 days of curing in water and seawater. The concrete containing finer CBA was lighter and had reduced salt permeability. Moreover, the concrete containing CBA had a lower chloride penetration than the control mix.

A researcher investigated the short-term impact of replacing cement with 10% coal bottom ash on sulphate and chloride attack [26]. The coal bottom ash was ground for two h in a Los Angeles machine and 20 h in a ball mill grinder to obtain a particle size similar to the ordinary Portland cement. After demolding, the concrete samples were immersed in water for 28 days, followed by immersion in 5% sodium sulphate (Na_2SO_4) and 5% sodium chloride (NaCl) solution for additional curing of 28, 56, and 90 days. The coal bottom ash concrete cured with 5% Na_2SO_4 solution was comparable to the control concrete for up to 90 days. The concrete containing CBA exposed to NaCl solution for a short period had a lower strength than the control concrete, but its strength increased with a longer curing period. This result indicates that the incorporation of CBA enhanced the concrete's resistance towards an aggressive environment.

Aydin [90] investigated the utilization of bottom ash as cement replacement to produce ecofriendly building material. The suitability of using bottom ash as cement replacement was assessed in term of its physical and mechanical properties. The CBA was used as cement replacement in varying percentages of 0, 70, 80, 85, and 100% with 5% hydrated calcium lime. The resulting lightweight composite was suitable for civil engineering applications. The slump, flow, and dry unit weight decreased with higher CBA contents. The concrete containing 70% CBA and 5% lime had a higher unconfined compressive strength and flexural strength than the composite containing only 70% CBA. The flexural strength of the final composite indicated that it is suitable for low- to medium-strength applications such as pavement, shotcrete lining, and base and subbase application.

3.4. Noise Barrier, Geotechnical Fill, Zeolite Composite, and Low-Cost Absorbent

Over the past four decades, extensive research has been conducted on noise barriers with different characteristics to protect the areas near roads, especially those with a high traffic volume [92]. Noise barrier wall, also known as the concrete wall, is one of the economic structures built to reduce noise pollution from transportation. Hannan et al. [25] investigated the production of concrete walls with varying CBA percentages that ranged from 0–100% fine aggregate replacement. The researchers reported that the values of fineness modulus of CBA were between 2.3 to 3.0, which is within the range as the fineness modulus of CBA was lower than the conventional fine aggregate specified in the BS 882:1992. The specific gravity of CBA was lower than the conventional fine aggregate due to the porous texture of CBA. The compressive strength of the concrete wall barriers did not increase linearly with higher CBA percentages, but increased with the concrete porosity, which is a good indicator for sound absorption structures. The sound absorption test to determine the acoustic performance showed that the walls containing 80–100% CBA were similar to the conventional wall and were class D absorbers; the remaining walls were class E absorbers. According to BS EN ISO 11,654:1997, the absorbers in class D absorb more than 30% of the sound, while class E absorbs between 15–25% of the sound [25].

Arenas et al. [30] studied the performance of road traffic noise reducing device prototypes from multilayer products composed of 80% bottom ash on a semi-industrial scale. The coarse bottom ash in this research had a Dp of >2.5 mm, and the Dp of the fine bottom ash was <2.5 mm. The measured acoustic performance parameters were the sound absorption coefficient and the airborne sound insulation in the reverberation room. The measured nonacoustic performance parameters were open void ratio, unit weight, compressive strength, Young's modulus, flexural strength, fracture energy, indirect tensile strength, characteristics length, impact strength, and fire resistance. The results showed that the bottom ash-based multilayer products were in the categories A2 and B3 of the sound absorption and assessment index, similar to other commercial products. The mechanical strength of the device containing bottom ash was lower than standard and porous concretes. The fire resistance of the coal bottom ash products remained unchanged after exposure to 47.8 min of fire, and only exhibited a slight discoloration.

Arenas et al. [93] evaluated the performance of highway noise barriers incorporated with bottom ash. Portland cement mixed with different sizes of coal bottom ash (coarse, medium, and fine) was used to produce mortar composite, and the results of the acoustic properties were compared with typical porous concrete. The CBA was separated into three particle size fractions, and a multilayer composite was fabricated using the fractions in three different layers. The wall incorporated with bottom ash had a density and compressive strength of 1470 kg/m^3 and 3.1 MPa. The acoustic properties of the composite containing CBA were comparable or better than the porous concrete. The wall fabricated using coarse CBA had the best sound absorption coefficient because of its porosity, while the wall fabricated with the finest CBA exhibited superior mechanical properties.

Researchers have assessed the potential of utilizing CBA in highway embankments. Theoretically, highway embankment materials must have high strength, density, and stability, good drainage properties, and low plasticity. Coal bottom ash has higher specific gravity than fly ash [94] because its high iron oxide content inhibits the transmission of dead load to the soil and supports the embankment. The application of high compaction resulted in low optimum water content and high maximum density. It also crushed the bottom ash particles and increased the density. Previous studies have shown that precautionary measures should be implemented when using bottom ash as an embankment material, especially upon including structural members and pipes in the ash [95], since mixtures of compacted ash can be corrosive.

A high bottom ash content could reduce hydraulic conductivity because of the significant effect of fine particles in bottom ash on permeability. The high permeability of kaolin mixed with CBA suits drainage application if used as backfill materials in embankments, particularly in areas with a high amount of annual rainfall [96]. The shear strength of the material or soil must be determined before beginning the construction because the ability to resist loading is a critical factor for an embankment. The friction angle of the bottom ash offers higher resistance to the rearrangement of the particles for sustained shearing due to the angular texture of bottom ash.

Researchers have investigated the conversion of coal bottom ash into zeolite X-carbon [97]. The Si and Al in CBA were the raw materials for zeolite, and the unburnt carbon was a source of activated carbon. NaOH and hydrothermal treatment at various times were used to alkali-fuse the CBA in the fabrication of zeolite X-carbon composite for hydrogen storage. The results showed that the optimum synthesis of zeolite X-carbon composite from CBA is by fusion through hydrothermal treatment at 90 °C for 15 h. The zeolite composite with the best crystallinity had a surface area of 185.824 m^2/gram, micropore diameter of 0.34 nm, mesopore diameter of 3 nm, and hydrogen uptake of up to 1.66% wt at 30 °C/20 psi. These results indicated that the composite is suitable for hydrogen storage.

Besides adsorption [98], reverse osmosis, flocculation, electroflotation, and precipitation techniques are also effective methods for eliminating pollutants from water [99]. Various low-cost adsorbents, such as clay materials [100,101], and agricultural wastes, such as apricot waste [102], soy meal hull [103], rice husk [104], sugar beet pulp [105], and wheat bran [106], have been reported as effective materials in eliminating hazardous chemicals from water. Jarusiripot [13] investigated the adsorption of dye using bottom ash as an absorbent. The International Union of Pure and Applied Chemistry (IUPAC) classifies bottom ash as mesopores with average pore diameter ranging between 3 and 7 nm. Before using it as an absorbent, the raw bottom ash was pretreated with chemical solutions, such as hydrochloric acid (HCl), nitric acid (HNO_3), and hydrogen peroxide (H_2O_2).

The results showed that bottom ash was an effective adsorbent for removing dye from wastewater even though it was not as efficient as the expensive commercially activated carbon. Because of the small surface area of the coal bottom ash, the dye absorption is dependent on the interaction between the charges of the dye molecules and the adsorbent surface. The superior absorption of the bottom ash with smaller particle sizes was due to the higher surface area of the absorbent. The adsorption capacity was also influenced by the chemical solutions used in the pretreatment process.

4. Critical Discussion

This review has shown that, at a higher percentage of CBA content, most of the CBA from various sources did not enhance the performance of the asphalt and concrete mixtures. Therefore, the CBA used as a replacement material in civil construction should be pretreated chemically or mechanically. The findings of previous research vary significantly, even at the same substitution ratio, because there was no control over the quality and constituents of the CBA. It is essential to perform a comprehensive assessment of the optimization of the materials used with the CBA because using CBA in combination with other materials, such as fly ash and superplasticizer, could enhance the mixture's performance. Despite its promising potential, there is a need to perform more comprehensive research to determine the cost–benefit and environmental impact of utilizing CBA and developing CBA as a green construction material. There is also a need to formulate a general guideline for using CBA as an alternative material in the construction industry.

5. Conclusions

The large volume of coal bottom offers a promising alternative for the aggregates used in the construction industry to prevent the depletion of natural aggregate resources. Previous studies have shown that coal bottom ash has a good potential as a substitute material, especially in the construction industry. However, further studies need to investigate turning bottom ash waste into applicable material. In summary, the use of coal bottom ash in the fields of construction, especially in civil engineering, can be commercialized through suitable design and appropriate construction procedures. A summary of this review is as follows.

1. CBA is a class F pozzolan that contains more than 70% of SiO_2, Al_2O_3, and Fe_2O_3.
2. The porous texture of CBA reduces the density of the pavement and concrete mixtures, making it a suitable lightweight aggregate in pavement and concrete production. Its porosity contributes to the ability of the CBA noise barrier wall to absorb more sound than the conventional wall.
3. The high-water absorption of the CBA particles increases the optimum binder content of the pavement mixture and the cement/water ratio in concrete production.
4. The pavement mixture incorporated with CBA exhibits enhanced moisture susceptibility. However, most research showed reduced Marshall stability, tensile strength, and resilient modulus. The low resilient modulus indicates that the mixture has a high elastic deformation, which increases its rutting resistance.
5. The optimum asphalt mixture performance is achieved with 10–30% CBA replacement. However, the performance can be enhanced by using CBA with other materials, such as fly ash, lime, and superplasticizer.
6. The concretes with higher CBA contents have reduced fresh concrete properties such as slump, bleeding, and flow because of the CBA's interlocking characteristics, rough texture, and irregular shape.
7. The properties of the concrete improved with the curing period, and after a certain curing period, the properties are superior to conventional concrete.
8. The utilization of CBA as cement replacement is beneficial to the environment because it reduces the CO_2 emissions in cement production. The heavy metals present in the raw CBA are below the permissible range.

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