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Coal Bottom Ash as Sustainable Material in Concrete – A Review

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Abstract

Objective: This paper reviews the literature available on coal bottom ash (CBA) and its applications in building industry. **Methods:** The current trends on the reuse of CBA have been reviewed and the various properties of CBA are presented and discussed. Different percentage of CBA replacement in concrete was used. **Findings:** CBA were found thermally stable within the temperature range considered. Workability of fresh concrete containing CBA show a lower value due to the higher amount of replacement which required huge amount of water which effect the workability. Compressive strength of the concrete shows that it's reached optimum strength beyond 28 days and no leachate of toxic elements in CBA was present. **Application/Improvements:** The review of the literature showed that the CBA was successfully recycle and applied for replacement as fine aggregate as well as coarse aggregate. It is concluded that the recycling of CBA as cement replacement material and also processing of CBA to develop nano-material are the future of CBA research.

Keywords: Coal Bottom Ash, Compressive Strength, Power Plant, Sustainable Material, Workability

1. Introduction

Coal is a main source to produce electricity and heat through combustion process[1]. Coal ash is residue resulting from combustion of pulverized coal or lignite in thermal power plant[2]. The burnt coal produces smoke which goes into air which is captured as fly ash[3]. The burnt coal that is at the bottom of the burning chamber is cooled and that is bottom ash[4]. Bottom ash forms up to 25% - 90% of total ash generated while the remaining are fly ash[5]. The percentage of bottom ash depends on the type of coal and the temperature they are subjected to[6].

Malaysia is a fast developing country with thriving economies and hence the demand of electricity is increasing. There are six thermal power plants operated in Malaysia with annual coal consumption of 24.7 million tonnes[7]. Due to the high demand of coal consumption, the production of coal and waste was increased. Tenaga Nasional Berhad (TNB) consumed 1.5 million tonnes of coal each year[8] it was reported that coal consumption is projected to steadily increase due to new coal-fired generating units[9]. The annual coal consumption of power sector in peninsular Malaysia for 2016 was recorded as 29 million tonnes[10]. Electricity generation by coal-fired plants generate waste by product such as coal bottom ash which are normally sent to landfills[11,12]. As reported by American Coal Ash Association (ACAA) 12 million tonnes of coal bottom ash was produce during 2015 which represent 40.13% of production rate[13]. Hence there is a necessity to reuse the bottom ash for sustainability[14]. The reuse of CBA in construction applications such as asphalt concrete aggregate, road base material, embankment or backfill material and structural fill was 49% in year 2014 and 40% in year 2015. Bottom ash was also being widely

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used as replacement of fine and coarse aggregates to produce control low-strength material[15].

Few studies have been carried out by use bottom ash as aggregate replacement[16]. It is concluded that the addition of in concrete gives advantage in terms of light weight, economical, and environmental friendly opportunities leading in the direction of sustainable production chain[17]. The research on potential use of CBA to be used as cement replacement materials is still limited and need to be explored further.

1.1 Environmental Sustainability Assessment

The environmental sustainability of a product can be ensured periodically by carrying out Environmental Impact Assessment (EIA) over its life cycle. During such assessments, several factors are critically measured including efficient design of products and processes, selection of raw or natural materials (resources), recycling and reuse of the products, evaluation and assessment processes for waste material usage and waste generation, development in energy efficiency of the system etc[18]. The EIA is a systematic method for identifying, evaluating, and analyzing the major environmental effects of a production process throughout the life cycle of the product[19]. The Life Cycle Assessment (LCA) is an important tool in EIA system that can be used to identify, evaluate and analyze the major environmental issues of the production process throughout the life cycle of the product[20]. The detailed framework of the LCA for any individual project depends on three most important steps as shown in Figure 1[21].

The main research content includes recognizing and quantifying the whole life cycle of clean coal including coal and the other raw material collection, washing and selecting, transportation, transformation, handling and emitting waste and all of the raw material and energy input and output also as pollute emission concerned as reported[22].

1.2 Recycling of Coal Bottom Ash

CBA is a waste of product by the thermal-power plants, the characteristic of CBA fit to make it as an alternative material in construction[23] and a research was reported, and CBA was being tested to substitute the common noise barrier in order to reduce the sound reflection towards noise sensitive areas nearby the highway[24]. Therefore, CBA was reported to have a good absorption characteristic with potential to be used commercially rather than being disposed at ash pond[25].

It is originated from agglomerated ash particles that are not finer and lighter to be found in the flue gases. CBA were reported to have angular particle and a porous surface texture[26]. CBA particle was range in size from fine gravel to fine sand with low percentages of silt-clay sized particle. In general, CBA has 50 to 90% of particles of size smaller than 4.75m41m size while 0 to 10% passing through 75μm size. Particles of size 19 mm to 38 mm have also been reported though it is negligible. Moreover, CBA is significantly a well-graded material with variations in the size of particle distribution[27].

2. Physical properties of Coal bottom ash

Physical properties of coal bottom ash have been assessed by various tests such as specific gravity, shape, surface texture, sieve analysis, and water absorption, and setting time. The specific gravity of CBA is presented in Table 1. The lower value indicates a high carbon content that caused the CBA to absorb more water. Furthermore, the lower specific gravity value is due to a very porous texture, therefore will also absorb water[26].

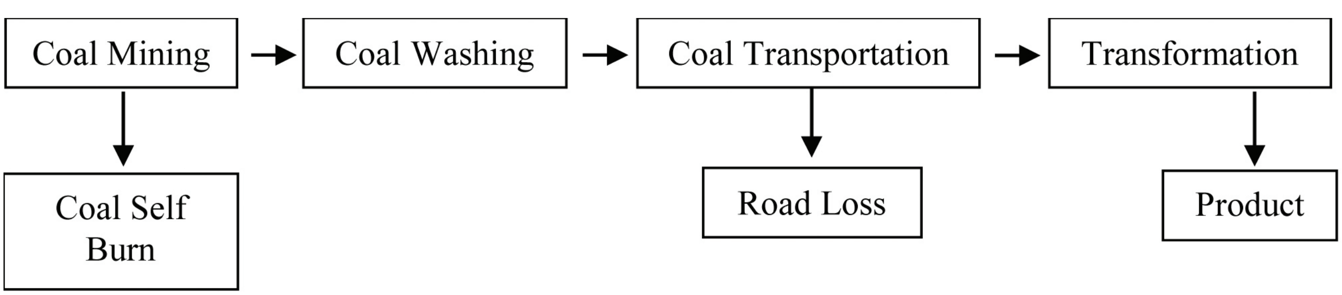

Figure 1. Life cycle margin of clean coal power generation.

Table 1. Specific gravity of CBA from various sources

Source	[5]	[15]	[17]	[24]	[26]	[31]	[51]	[52]
Specific Gravity	1.39-2.33	1.8	1.93	1.674	2.00 - 2.39	2.65	1.87	2.98

2.1 Chemical properties of Coal bottom ash

By referring to Table 2, CBA were classified as ASTM Class F ash in which the percentage composition of SiO_{2+} Al_2O_{3+} Fe_2O_3 exceeds 70%[28]. Pozzolanic reactivity of CBA were determined by the amorphous state of CBA particles and the percentage content of SiO[29]. Due to CBA chemical carbonated nature containing CO_2, by adding the right admixtures it can gain the paste glue state to work as a cementitious material[30]. Loss of ignition (LOI) of CBA was range between 2.4 to 7.24 was due to the amount of carbon that present in CBA, which measure the quantity of CO_2[15].

3. Potential of Coal bottom ash to be used as replacement material in concrete.

3.1 Coal bottom ash as Fine Aggregate Replacement

Normal concrete mixes consist of certain amount of cement, which were determined by the strength of the concrete itself. Due to the modification of concrete for various performance characteristics, researchers prefer for different trial of mixtures with varying cement and CBA ratios. A study was conducted by replacing natural sand with CBA in range of 20% to 50% by weight. It was reported that, increase in CBA decreased the workability by how much 4 to 9% from the control mix, as well as compressive strength by meanwhile the 28-day compressive strength decreased by range of 8 to 20%[1] while other study used the same material with different percentage and reported a 28-day compressive strength range of 8.6 to 32.6 MPa with dry density between 1869 to 2238 kg/m[31]. A study was carried out by replacing sand with CBA with increments of 10% to 40%. The compressive strength of CBA was reported slightly lower with range of 19.99 to 24.65MPa compared to that of the control mix of 39.52 MPa[8]. It was found that the CBA replacement has increment in strength with long-term duration of curing day up to 60 days with increment of up to 10%[31]. The pattern of strength development of concrete with certain percentage of CBA for sands replacement to be likely similar to control sample[32]. For 7 days of curing age it is reported the compressive strength consist of 50% and 100% of CBA

Table 2. Chemical composition of CBA from various sources

Component	[3]	[8]	[15]	[16]	[17]	[24]	[25]	[31]	[32]	[34]
SiO_2	44.01	54.8	56	68.90	57.76	56	55.95	47.53	38.64	57.9
Al_2O_3	9.31	28.5	26.7	18.67	21.58	26.7	16.65	20.69	21.15	22.6
Fe_2O_3	25.03	8.49	5.8	6.50	8.56	5.8	9.69	5.99	11.96	6.5
CaO	13.01	4.2	0.8	1.61	1.58	0.8	4.39	4.17	13.8	2
MgO	1.88	0.35	0.6	0.53	1.19	0.6	-	0.82	2.75	3.2
SO_3	-	-	-	-	0.02	0.1	0.7	1	0.61	-
K_2O	1.25	0.45	2.6	1.52	1.08	2.6	1.44	0.76	2.06	0.604
Na_2O	-	0.08	0.2	0.24	0.14	0.2	-	0.084	0.9	0.086
TiO_2	-	2.71	1.3	1.33	-	1.3	-	-	-	-
P_2O_5	-	0.28	-	-	-	-	-	-	-	-
SiO_{2+} Al_2O_{3+} Fe_2O_3	78.35	91.79	88.5	94.07	87.9	88.5	82.29	74.21	71.75	87
LOI	-	2.46	4.6	2.68	5.8	4.6	3.96	4.65	7.24	2.4

Concrete													
Mix	Mix Proportions	CBA Replacement	OPC (kg /m^3)	Aggregate		Slump (mm)	Strength (MPa)						Ref
				Fine (kg/ m^3)	Coarse (kg/m^3)		3 days	7 days	28 days	56/ 60 days	90 days	180 days	
Control Mixture	OPC+ Fly Ash + Aggregate	-	51.7	94	100	190	57.3	61.8	66.7	76.7	-	-	15
Mix 2	OPC + Fly Ash + 12.5% CBA + Aggregate	11.75	51.7	82.25		220	48.2	59.5	69.5	79.4			
Mix 4	OPC + Fly Ash + 25% CBA + Aggregate	23.5	51.7	70.5		220	41.5	47.3	68.7	72.8			
Control Mixture	OPC + Aggregate	-	479	479	1175	-	-	7.37	6.99	-	7.57	7.38	33
A20	OPC + 20%CBA + Aggregate	51.22		383.2				7.72	7.45		7.45	7.32	
A30	OPC + 30%CBA + Aggregate	76.82		334.6				8.48	7.92		7.25	7.26	
A40	OPC + 40%CBA + Aggregate	102.4		287.4				7.85	7.65		7.57	7.07	
A50	OPC + CBA + Aggregate	128		239.5				8.82	7.96		7.59	7.6	
A75	OPC + CBA + Aggregate	192.1		119.75				8.93	7.76		7.72	7.52	
A100	OPC + CBA + Aggregate	256.1		0				9.02	7.94		7.77	7.96	
Control Mix	OPC + Aggregate	-	28.62	48.64	79.37	-	28.1	34.2	39.5	43.5	-	-	8
M10	OPC + 10%CBA + Aggregate	4.86		43.78			17.6	16.5	21.4	23.7			
M20	OPC + 20%CBA + Aggregate	9.73		38.91			19	20	23.8	23.9			
M30	OPC + 30%CBA + Aggregate	14.6		34.04			18.8	20.8	24.7	27.4			
M40	OPC + 40%CBA + Aggregate	19.46		29.18			15.8	17.9	20	23.4			
M50	OPC + 50%CBA + Aggregate	24.32		24.32			14.4	17.3	21.2	22.4			

M1	OPC + Aggregate	0		532.7				24.7	33.3	35.4	37.2		
M2	OPC + CBA + Aggregate	106		426.7				23.3	30.4	32.2	36.1		
M3	OPC + CBA + Aggregate	160	426.7	372.7	1225	-	-	22.5	29.6	31.8	36.7	-	31
M4	OPC + CBA + Aggregate	213		319.7				21.7	28	30.6	35.3		
M5	OPC + CBA + Aggregate	266.4		426.7				20.2	26.4	30.4	35.2		

Appendix A. Summary of fresh properties and compressive strength for concrete mix of CBA as fine aggregate replacement

Appendix B. Summary of fresh properties and compressive strength for concrete mix of CBA as cement replacement material

Concrete												
Mix	Mix Proportions	CBA Replacement	OPC (kg/m^3)	Aggregate		Slump (mm)	Strength (N/mm^2)					Ref.
				Fine (kg/m^3)	Coarse (kg/m^3)		3 days	7 days	28 days	56/60 days	90 days	
M1	OPC + Aggregate	-	438			107			38.9			
M2	OPC + 10% OBA + Aggregate	43.8	394.2			101			37.55			
M3	OPC + 20% OBA + Aggregate	87.6	350.4			96			33.25			
M4	OPC + 30% OBA + Aggregate	131.4	306.6	630.89	1099.3	91	-	-	29.3	-	-	41
M5	OPC + 10% GBA + Aggregate	43.8	394.2			99			43.6			
M6	OPC + 20% GBA + Aggregate	87.6	350.4			93			38.1			
M7	OPC + 30% GBA + Aggregate	131.4	306.6			88			36.7			

NC (0%)	OPC + Aggregate	-	519	718		75		38.22	48.7	54.22		
Mix-1	OPC + 20% BA + Aggregate	143	376	575		71		34.88	45	53.54		
Mix-2	OPC + 30% BA + Aggregate	215	304	503	570	68	-	30.44	43.4	50.05	-	1
Mix-3	OPC + 40% BA + Aggregate	287	232	431		72		28.9	42.58	49.1		
Mix-4	OPC +50% BA + Aggregate	359	160	359		67		27.5	40.79	47.13		
0% CRT	OPC + Aggregate	-	304	912	806		15.9		28.4		32	
25% CRT3	OPC + 25% CBA + Aggregate	145	305	686	808		12.5		23.2		25.7	
50% CRT3	OPC + 50% CBA + Aggregate	287	301	452	798		9.9		18		23	
75% CRT3	OPC + 75% CBA + Aggregate	422	295	221	782		6.3		11.5		14.9	
100% CRT3	OPC + 100% CBA + Aggregate	570	299	0	792	-	4.2	-	8.6	-	12.5	24
25% CRT4	OPC + 25% CBA + Aggregate	103	323	727	856		19.5		27.2		32.1	
50% CRT4	OPC + 50% CBA + Aggregate	212	334	501	885		17		28.5		35.9	
75% CRT4	OPC + 75% CBA + Aggregate	340	356	267	943		16.1		26.1		32.7	
100% CRT4	OPC + 100% CBA + Aggregate	441	386	0	1023		21.2		32.6		38.4	
STD	OPC + Aggregate	-	450					27.8	40.9	42.65		
BC5	OPC + 5%CBA + Aggregate	22	428					28.09	40.38	44.08		
BC10	OPC + 10%CBA + Aggregate	45	405	1350	-	-	-	28.22	40.24	45.1	-	23
BC15	OPC + 15%CBA + Aggregate	67	383					26.47	33.57	43.45		
BC25	OPC + 25%CBA + Aggregate	112	338					19.79	29.13	41.33		

decreased by 9% and 15.16% respectively when compared to the control sample. The compressive strength of 28 days has reported decreased from 38.21 MPa to 37.25 MPa[38].

It has concluded that as the replacement level increases and huge amount of water was required in order to mix the concrete. This condition was affected by the extra finest of the CBA and the compressive strength of concrete mixes made with various percentage of CBA[33]. The pattern of strength development of concrete with certain percentage of CBA for sands replacement to be likely similar to control sample[34]. The factor responsible for lower compressive strength of CBA was due to the replacement of stronger material with the weaker material with the absence of pozzolanic activity of CBA and causes the porosity of the concrete increased[35]. Development of concrete strength was influenced by the porosity of hydrated paste[36]. Porosity of hydrated paste was controlled by water and cement ratio. The strength of replacement material in concrete other than conventional concrete also has effect the strength of concrete mix. The higher water cement ratio results in low density of bottom ash concrete mix. There is transition zone between the aggregate and cement paste become weaker and porous and cause reduction in strength of bottom ash mix[37]. By the use of CBA, weak microstructure was obtained and hence the decrease in compressive strength[38].

3.2 Coal bottom ash as Coarse Aggregate Replacement

Use of CBA as partial replacement of coarse aggregate has also been investigated by few researchers with range of replacement of 25% to 100%. The CBA was found to reduce the early age strength whereas it increases the long-term strength by 56-65%[26]. The CBA concrete were reported to gain strength at a slower rate in initial period with optimum strength at faster rate beyond 28 days due to the effect of pozzolanic action of CBA[39].

3.3 Coal bottom ash as Cement Replacement

Investigation of CBA effect on mechanical and durability characteristics of concrete as cement replacement material has carried out. Original bottom ash and Grinded Bottom Ash were used. By replacing OPC to CBA with percentage of 10 to 30%, during the mix, a slump test was conducted in order to investigate the workability of the concrete[41]. It has discovered that, as the replacement of cement to CBA increase, the workability of concrete mix was decrease compared to control mix[40]. It has shown that by adding original CBA the workability becomes decrease more compared to grind CBA. It may due to the grind CBA have finer properties compared to original CBA which it absorbs more water therefore it reducing the workability of the mix. By increasing amount of CBA replacement as cement replacement material up to 10% the compressive strength of 56 days age of concrete was increased approximately 5% compared to control specimen and the higher percentage of the replacement will lead to a decrease of compressive strength due to the shorter curing period; 7 and 28 days[23]. Meanwhile, concrete with 56 days of age is stated to be more higher compared with control specimen. The various literatures on the assessment of performance of CBA have been compiled in Appendix A and B.

3.4 Nano-material in concrete

Nano-material is the understanding and control matter at dimension between approximately 1 and 100 nanometers[42], where unique phenomena enable novel application[43,44]. The basic concept of using nano-material in construction applications are having large surface area in order to improve the compressive and flexural strength during the early ages[45], enhance hydration and reduce the porosity and water absorption when compared with conventional cementitious materials[46].

Application of nano-material in construction will reduce the volume of cement needed which can lower the usage of material and labor cost and resulting in reduction of greenhouse emissions[47]. Most commonly used nano-material is nano silica, a study of the effect of nano-silica on compressive strength of high volume fly ash concrete as cement replacement material has discovered nano-silica was enhancing the strength properties of high volume fly ash concrete with higher compressive strength and it can be an effective solution for sustainable concrete[48,49]. It also reported microstructure of cement mortar containin nano-material are denser than plain mortar and increase rates of compressive strength for 3 and 28 days[50]. It has been reported earlier that grinding the CBA increases its finest and hence enhances the performance of CBA[33]. Hence it is the opinion of the authors that processing the CBA and grinding the same to get nanoparticle which can be used in development of materials may be possible and needs to be explored.

4. Leach ability

Toxicity Characteristic Leaching Procedure (TCLP), Synthetic Precipitation Leaching and Procedure (SPLP), Static Leaching Test (SLT) can investigate the leach ability of heavy metals in CBA. Leaching test was carried out to measure the concentration of toxicity in the raw bottom ash. The result shows that there is no leachate of toxic elements in CBA excluding Arsenic 0.00035 mg/L; yet, the level is quiet outlying below the limit of 1.5 mg/L. Therefore, it is reported that CBA is a material that is acceptable to be used in construction[12, 51, 52].

5. Conclusion

This paper reviewed the existing literature on the use of bottom ash in various applications. The conclusion is as given below:

1. CBA was significantly a well-graded material with variations size of particle distribution.
2. The specific gravity of CBA ranges between 1.39-2.98 and its depends on the chemical composition which controlled by the source of coal and combustion temperature.
3. CBA were found thermally stable within the temperature range considered and loss of ignition (LOI) was to be recorded up to 2% to 8% due to the evaporation of water and it has gradual weight loss and it was the effect of evaporation of physio-chemically bonded water molecules with the CBA particles.
4. Due to the decreasing of slump result by increasing the amount of CBA it can conclude that as the replacement level increases and huge amount of water was required in order to mix the concrete. This condition was affected by the extra finest of the CBA.
5. For compressive strength it shows that the early strength of the concrete was at low level due to the higher percentage of the replacement with the effects of the shorter curing period; 7 days.
6. It also can be concluding that, concrete with CBA content will reach its optimum strength beyond 28 days due to the effect of pozzolanic action of CBA. It can conclude there is no leachate of toxic elements in CBA and it is acceptable to be used in construction.

6. Future research direction

After the literature research done on the use of bottom ash, we feel that the research on CBA may be oriented more towards its use as cement replacement material or cement substitute and also its use in developing nanomaterial. This is because the effect of the presence of carbon in the CBA is found to be minimized when we grind the CBA. Following are some recommendations for future investigation and research.

1. CBA can be used as a cement replacement material.
2. CBA can undergo a few physical treatments such grinding and sieving process in order to study the finest effect to the CBA concrete and to be compared with ground CBA.
3. CBA has good potential of nano-material in construction application as sustainable materials.

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