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Bottom ash utilization: A review on engineering applications and environmental aspects

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Abstract. Bottom ash produced from coal-fired power plants has been utilized in engineering applications for the purpose of recycling and solving disposal issue of bottom ash. This study reviews various applications of bottom ash in engineering fields. The engineering properties exhibited by bottom ash in terms of free draining, granular, lightweight and interlocking nanostructures allow them to be used for different functions. The bottom ash used is not limited to its raw state, but can be mixed and modified for advanced applications without neglecting the impacts on the environmental. The presence of metals in bottom ash are well known and being discussed whether they are harmful to the environment. Many countries have their own threshold limit of maximum contaminants, hence TCLP result will determine the hazardous status of bottom ash. This review helps in promoting the solution and potential usage of bottom ash, since coal is one of the dominant source of energy in power generation sector.

Keywords: bottom ash; engineering applications; environment

1. Introduction

The rapid growth of global population boosted the economic growth, especially in energy sectors. China, India and USA account for the top three countries in the world with the highest demand of fossil fuels and rapidly increasing every year [1]. Table 1 present the production of bottom ash from different countries. Among the fossil fuel resources, coal is the most demanded compare to oil and gas because it is the cheapest and most abundant in the world [2].

However, rising demand for coal lead to new challenges. The consumption of coal in the boiler produce two main waste product bottom ash and fly ash in the range of 10-30 and 70-90 % respectively [3], [4] and [5].

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Table 1. Bottom ash production.

Reference/Year	Bottom ash (tonnes) / year
USA [6]	10 million
Europe [7]	18 million
China [8]	~ 60 million
India [9]	100 million
Tanjung Bin (Malaysia), [10]	96 thousand
Catalonia (Spain), [11]	200 thousand

This huge amount of waste has become a global issue and required serious attention from those countries that consume coal for their energy resources. Since the amount of bottom ash accumulated keep on increasing, the cost for opening new landfill area, transporting to a disposal site and maintaining the reclamation facilities will increase significantly. Therefore, plant operators started to collaborate with researchers and industries in order to fully utilize the vast amount of accumulated bottom ash.

Bottom ash generally disposed of in slurry condition by mixing with water and being discharged into ash ponds [12] and [13]. Researchers commonly collect samples from ash pond and ensure that they are in compliance with local authority standard.

In recent years, the utilization of bottom ash in engineering field has received considerable attention due to its potential application including aggregate replacement, concrete products, embankment fill, road construction and reclamation work [14] and [15]. In order to utilize bottom ash, the physical, chemical properties as well as the method of application must be studied. This paper aims to review the engineering application use of bottom ash and its environmental impact through literature finding.

2. Engineering Application of Bottom Ash

Generally, the bottom ash particles have dark, angular shapes with porous textures and rough surface. The particle size ranging from gravel of 40 mm to fine sand of 0.075 mm [14]. Most researchers believed that the properties of bottom ash are similar to natural sand material [13,16-18].

Bottom ash has been utilized in civil engineering field, agriculture and manufacturing soil products industry [19]. According to [14], bottom ash is mainly used in civil engineering field. It is reported that the European Union and United States used about 50% and 35% of the produced bottom ash respectively in this field. Such waste materials are widely used as replacement materials in construction including natural silt, clay, sand and gravel. Hence, bottom ash has the potential application in road construction, concrete, various cement products and reclamation fills.

2.1 Road construction

Bottom ash is listed as one of waste materials suitable for recycling in road construction [20] and by far is the most popular outlet for the material. Bottom ash is targeted to substitute sand or fine aggregates in road construction either as partially or full replacement due to its similar properties to natural sand.

Coal Combustion Products Utilization Handbook [19], conducted a study on the performance of bottom ash in subgrade using plate load bearing tests. After one season, the road pavement was found to be in good condition indicating that the subgrade performed satisfactorily. In order to enhance the performance of the pavement, a recommendation has been made to use bottom ash in a 2 to 1 thickness ratio compared to normal base course material.

[5] summarized the uses of bottom ash as subbase, road-base materials and as bituminous mixes for binder layer. From the report, it is found that bottom ash provides adequate bearing capacity for lower strength application such as subbase materials and embankment fills [5]. On the other hand, the utilization of bottom ash in road base materials depends on the percentage content because the compressive strength is said to be reduced with an increase of bottom ash replacement percentage [5,12]. Besides that, low content of bottom ash in bituminous mixes is found practical as the ash not modify the

mechanical characteristics of the mixture. Conversely higher content of bottom ash in the mix requires higher amount of bitumen in order to satisfy Marshall Mix design limit [5, 21].

In addition, replacement material formulated with bottom ash and fly ash in subbase and road-base was found suitable for road embankment construction. The limitation is that low bottom ash to high fly ash ratio (ranging from 50 to 100% of fly ash content) was suggested for better performance and stability [22-23]. In four season country, a field study to identify the potential of bottom ash as insulation layer also has been conducted by [24]. The results indicate that bottom ash performed well as heat insulator and was effective in reducing frost penetration into the subgrade.

2.2 Aggregate Replacement in concrete

The potential of bottom ash to be used as replacement material in concrete has been explored by numerous researchers. The ash either can use as fine aggregate or coarse aggregate replacement. The replacement will cause some changes on the properties of concrete such as the workability, compressive strength and durability.

[16] found that the workability of concrete reduces with the use of bottom ash as fine aggregate replacement due to physical properties of bottom ash (irregular shape, rough texture and high porosity) increased the inter particles friction and thereby hinders the flow characteristics of fresh concrete. Other than that, the higher water absorption capability of bottom ash itself reduced the workability. This finding has confirmed by [25] which has stated that the increased of bottom ash percentage by weight in concrete has decreased the workability by 4% to 9%. Meanwhile, [26] examined the effect of slump flow values of fresh concrete with bottom ash as the replacement and found the slump value decreases with increasing percentage of bottom ash. This indicate the fact that as water absorbed internally by the porous bottom ash particles increased, huge amount of water was required in order to mix the concrete.

In term of compressive strength, [26] studied the effect of bottom ash as fine and coarse aggregate in concrete mix at 7 days and 28 days curing age. Based on observation, the compressive strengths were found not significantly affected by the replacements of fine bottom ash. However, for the 7-day curing period, the compressive strength of concrete mixes containing 50% and 100% bottom ash decreased about 9% and 15.16% compared to the strength of the control samples, respectively [27]. The lower compressive strength is related to the strength of replacement material in concrete mix. Studies show that bottom ash are more porous and weak than natural sand. As mentioned before, the higher water absorption by bottom ash has increased amount of mixing water, which contribute to more volume of pores left by water. These pores prevented the strong bonding of cement paste with the aggregate. As a result, the transition zone between the aggregate and cement paste becomes weak and porous which eventually reduces the strength of bottom ash concrete mix [13].

Nevertheless, [28] found that with long-term duration of curing age, up to 60 days, the compressive strength increased up to 10%. Similar finding was observed by [29], where 30% sand replacement is used in the concrete mix and the compressive strength recorded the highest value at the curing ages up to 60 days. Therefore, it can be concluded that concrete with bottom ash content will reach its optimum strength beyond 28 days.

3. Environmental Aspects

From environmental point of view, utilization of bottom ash in engineering field is a potential solution for the disposal issue of the material. However, [30] stated that bottom ash disposal must be properly managed to prevent or minimize any environmental impacts since utilization of bottom ash is still lacking and at low percentage. In contrast, fly ash has been used by cement industries and some plants has made agreement with power plant operators to collect their fly ash regularly. Therefore, study on the chemical composition of bottom ash is important to investigate the risk and behavior that it may impact the environment. Table 2 tabulates the chemical compositions of bottom ash samples obtained from different sources.

Table 2. Chemical composition of bottom ash from various sources (%).

Component	Thailand [15]	Indonesia [31]	India [18]	USA [19]	Cyprus [32]	USA [33]	Morocco [34]	Malaysia [35]	India [25]
SiO_2	36.84	50.03	56.00	82.73	61.00	46.60	55.10	43.1	45.64
Al_2O_3	18.28	3.68	26.7	1.89	25.40	26.10	28.10	19.89	18.2
Fe_2O_3	15.46	32.88	5.80	5.10	6.60	12.40	8.30	9.57	8.74
CaO	18.43	3.80	0.80	2.17	1.50	8.31	1.10	16.38	8.18
MgO	2.62	4.01	0.60	1.10	1.00	1.26	0.30	3.83	3.80
SO_3	0.74	-	0.10	1.51	-	0.30	0.30	0.44	-
K_2O	2.29	0.32	2.60	-	0.20	1.34	1.50	0.42	2.01
Na_2O	0.75	-	0.20	-	0.90	0.62	-	0.25	-
TiO_2	0.9	-	1.30	-	-	1.84	-	1.51	0.98
P_2O_5	0.17	-	-	-	-	0.62	-	0.45	0.98
SiO_2, Al_2O_3, Fe_2O_3	70.58	86.59	88.5	89.72	93.0	85.1	91.5	72.56	72.58
LOI (Loss on Ignition)	2.02	3.99	4.60	1.80	-	-	3.90	-	-

The chemical composition of bottom ash samples was investigated using XRF and XRD analysis by various researchers. In general, the major contents of bottom ash were silica, alumina, iron and calcium oxide. Others were magnesium, kalium, barium, potassium, sodium and titanium oxides in smaller percentage less than 4%. Referring to Table 2, it shows that bottom ash classified as ASTM C 618 as Class F ash with the percentage combination of SiO_2, Al_2O_3 and Fe_2O_3 ranging from 70 to 93% which exceeds 70% [19, 25, 31 and 36]. Loss on ignition (LOI) of bottom ash range from 1.8 to 3.99 due to the amount of carbon to measures the quantity of CO_2 [37]. Variability of coal ash sources, processing of coal ash (combustion temperature, residence time, turbulence) and ignition temperatures contribute to the variation in LOI results [5]. For example, LOI threshold of 5% has been set by the French Ministry and Netherlands to promote full utilization of bottom ash.

With respect to utilization of bottom ash, the amount of heavy metals must be considered because bottom ash is often considered as not harmful. The reactivity and potential of heavy metal release by reaction of bottom ash with CO_2 and water will further reduce as time pass by through aging and weathering process which result in more stable complex compounds in bottom ash [38-39]. Therefore, the quality of bottom ash can eventually improve due to aging and weathering making its recycling a viable option.

For the beneficial utilization of bottom ash, many countries had implemented their own policies and regulations with regard to ash management. In order for bottom ash to be considered as non-hazardous waste, it required to pass the Toxicity Characteristic Leaching Procedure (TCLP) [40, 41]. An effort was made to compile limitation values among different country standards as summarized in Table 3.

Table 3. Maximum concentration of contaminations TCLP in various countries (mg/L).

Element	USA [42]	USA Drinking Water Standard [43]	Malaysia [41]	Singapore [44]	China [45]	Australia [46]
Antimony (Sb)	-	0.006	15.0	-	-	-
Arsenic (As)	5.0	0	5.0	5.0	5.0	5.0
Barium (Ba)	100.0	2.0	100.0	100.0	-	-
Berylium (Be)	-	0.004	0.75	-	-	1.0
Cadmium (Cd)	1.0	0.005	1.0	1.0	1.0	1.0
Chlorine (Cl)	-	4.0	-	-	-	-
Chromium (Cr)	5.0	0.1	5.0	5.0	5.0	-
Chromium-VI (CrVI)	-	-	5.0	-	-	5.0
Cobalt (Co)	-	-	80.0	-	-	-
Copper (Cu)	-	1.3	25.0	100.0	100.0	
Fluorine (F)	-	4.0		150.0	-	-
Lead (Pb)	5.0	0	5.0	5.0	5.0	5.0
Manganese (Mn)	-	0.05	-	50.0	-	-
Mercury (Hg)	0.2	0.002	0.2	0.2	0.1	0.2
Molybdenum (Mo)	-	-	350.0	-	-	5.0
Nickel (Ni)	-	-	20.0	5.0	5.0	2.0
Selenium (Se)	1.0	0.05	1.0	1.0	-	1.0
Silver (Ag)	5.0	0.1	5.0	-	-	5.0
Thallium (TI)	-	0.0005	7.0	-	-	-
Vanadium (V)	-	-	24.0	-	--	-
Zinc (Zn)	-	5.0	250.0	100.0	100.0	-

According to [12-13, 47-48], bottom ash contains heavy metals, i.e. Manganese (Mn), Copper (Cu), Zinc (Zn), Arsenic (As), Lead (Pb), Cadmium (Cd), Cobalt (Co), Chromium (Cr) and Nickel (Ni). The presence of these elements can be harmful to the environment as it can be leached out to surrounding soil and groundwater. However, TCLP test conducted on bottom ash shows that the amount of heavy metals does not exceed the maximum concentration in their respective country regulations [47-48]. Traces of Mercury (Hg) also found in bottom ash, but [49] reported that during the combustion process, a large portion of Hg is vaporized and remaining Hg is tightly bound and not easily released into the environment.

Heavy metal contents in bottom ash from three sources of coal power plants with different capacities S1 (750 MW), S2 (840 MW) and S3 (2,100 MW) were studied by [50]. It is observed that the concentration of heavy metals in three different sources of bottom ash is highest from lower capacity boiler (source 1>source 2>source 3).

Although bottom ash has passed toxicity test, there are risks of heavy metals release to the environment. In order to reduce the risk, [47] suggest that utilization of bottom ash in the topmost exposed layer must not be practiced. In recent years, many research focused on treatments for leaching of bottom ash. Contaminants are extracted and pre-leach before being utilized or transport to landfill. For instance, in USA, USEPA has supported research projects on ash utilization, indicating no adverse environmental or health impacts using bottom ash in pavement works since 1995 [51]. Moreover,

utilization of bottom ash in roads construction in some countries was successful and gain support from the local authorities as the leaching of metals during service life comply with standards [52-55].

Another effective technique to completely stabilize heavy metals is by waste vitrification [56]. Vitrification process destroys hazardous organic compound that presents in bottom ash and yields a highly homogeneous glass to be used in many applications [16]. The transformation into more valuable products with glassy nature can compensate for the high energy demand of the process.

4. Conclusions

Utilization of bottom ash in engineering and their impact on the environment are reviewed in this paper. Recycling of bottom ash able to conserve usage of natural resources (sand, gravel, limestone) needed for cement production or road constructions. Recently, some countries reported that natural sources for aggregates from viable quarries are decreasing. Thus, similarities properties shown by bottom ash with fine aggregates allow them to be partially replaced. In term of economic benefits, it helps plant operator to save cost in terms of opening new landfill, land acquisition and ash management.

Many countries like Malaysia has a very low percentage of bottom ash utilization due to environmental issue as the ash contains heavy metals that may leach into the environment. Bottom ash composition of heavy metals that poses environmental hazards which can leach into the environment. Based on this review, bottom ash can be categorized as non-hazardous and safe to be utilized and recycled as long as the contaminant levels do not exceed the permissible limits set by the respective regulatory bodies.

Nowadays, majority researchers focus on advanced technology to reduce the contaminants. Hence, allow bottom ash to be fully utilized and less concern on their impact to the environment. Political support is strongly needed. Some government imposed strict regulations on hazardous materials and their potential used as recycled materials in civil engineering applications. The implementation will require the government to revise their current environmental act which is a very long process. While, one government should consider to make some exclusion to certain act by detailed monitoring of specific cases for the beneficial use of bottom ash.

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