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A comprehensive review on the applications of coal fly ash

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ABSTRACT

Coal fly ash, an industrial by-product, is derived from coal combustion in thermal power plants. It is one of the most complex anthropogenic materials, and its improper disposal has become an environmental concern and resulted in a waste of recoverable resources. There is a pressing and ongoing need to develop new recycling methods for coal fly ash. The present review first describes the generation, physicochemical properties and hazards of coal fly ash at the global level, and then focuses on its current and potential applications, including use in the soil amelioration, construction industry, ceramic industry, catalysis, depth separation, zeolite synthesis, etc. Finally, the advantages and disadvantages of these applications, the mode of fly ash utilization worldwide and directions for future research are considered.

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1. Introduction

Coal fly ash, a by-product of coal combustion in thermal power plants, is one of the most complex and abundant of anthropogenic materials. If not properly disposed of, it can cause water and soil pollution, disrupt ecological cycles and pose environmental hazards. More aggressive efforts have been undertaken recently to recycle fly ash (Temimi et al., 1995; Ilic et al., 2003). For example, about 20% of the fly ash generated is being used in concrete production. Other uses include road base construction, soil amendment, zeolite synthesis, and use as a filler in polymers (Cho et al., 2005). However, these applications are not sufficient for the complete utilization of the fly ash generated. The remainder is waste, and has to be discharged into ash ponds, lagoons or landfills. In the future, more stringent disposal siting restrictions, shrinking availability of landfill space and escalating disposal costs are anticipated, thereby it is imperative to develop new recycling techniques for coal fly ash. Recent review such as Ahmaruzzaman (2010) presented the details on properties of coal fly ash and its various possible applications. There are also other reviews on the fly ash utilizations from the perspectives of soil amelioration and mine reclaimation (Ram and Masto, 2010; Skousen et al., 2012; Ram and Masto, 2014), alumina and cenosphere recovery (Kolay and Bhusal, 2014; Yao et al., 2014), adsorbents for mercury removal, CO_2 capture and wastewater treatment (Zheng et al., 2012; Wee, 2013), etc. However, some important and fundamental aspects, such as the generation of fly ash worldwide, and the modes of utilization are not considered. Thus, this review first attempts to investigate the fly ash generation in major countries (China, India and US), its physicochemical properties and hazards, and then focuses on its current and potential applications, including use in the soil amelioration, construction industry, ceramic industry, zeolite synthesis, catalysis, depth separation, etc. Finally, the advantages and disadvantages of these applications, the mode of ash utilization and directions for future research are considered. This paper will add to the further understanding of current utilizations of coal fly ash and identifying the promising applications.

2. Generation, characterizations and hazards

2.1. Global generation

Coal fly ash accounts for 5–20 wt.% of feed coal and is typically found in the form of coarse bottom ash and fine fly ash, which represent 5–15 and 85–95 wt.% of the total ash generated, respectively. Coal ash is discharged by both wet and dry methods of coal combustion. Bottom ash refers to the ash that falls down through the airflow to the bottom of the boiler and is mechanically removed (Jala and Goyal, 2006; Yao, 2013). The term fly ash, by contrast, is most often used to refer to fine fly ash, particles of which are captured from flue gas and collected by electrostatic or mechanical precipitation.

From the beginning of widespread electricity use, coal has fueled, and continues to fuel, the largest share of worldwide electric power production, and coal consumption has increased significantly over this period and is expected to continue increasing. In 2011, coal-fired generation accounted for 29.9% of the world electricity supply, and its share is anticipated to be 46% by 2030. Sustained high prices for oil and natural gas make coal-fired generation more attractive economically, particularly in nations that are rich in coal resources, such as China, the US and India (Lior, 2010). China is the largest coal consumer in the world and accounts for 50.2% of the world coal consumption in 2012. Rounding out the top 10 behind China, the US (11.7%) and India (8%), the followers were Japan (3.3%), Russian Federation (2.5%), South Africa (2.4%), South Korea (2.2%), Germany (2.1%), Poland and Indonesia (1.4%) (see Fig. 1). China's industrial growth depends on coal, which contributed to 68.49% of the total primary energy consumption in 2012 (see Fig. 2). The proportions were 20, 53, and 21.78% for the US, India and Japan. Taking these data into account, a more up-to-date estimate of annual worldwide generation of fly ash is approximately 750 million tonnes (Blissett and Rowson, 2012; Izquierdo and Querol, 2012). Fig. 3 shows the generation and utilization of coal fly ash in China, the US and India. For China, the annual fly ash generation is still increasing and is anticipated to reach 580 million tonnes by 2015. According to the Central Electricity Authority (CEA) annual report on fly-ash generation–utilization, the fly ash generation and utilization in India were calculated and displayed in Fig. 3. It can be seen that approximately 160 million tonnes of fly ash is presently generated annually with a utilization rate of approximately 60%. The American Coal Ash Association (ACAA) surveys and published data on the generation and utilization of coal combustion products (CCPs) including fly ash, bottom ash, boiler slag, flue gas desulfurization (FGD) gypsum, FGD material wet/dry scrubbers, FGD other and fluidized bed combustion (FBC) ash. According to the annual CCPs' Production and Use Survey Report released by the ACAA, the generation and utilization of fly ash, bottom ash, boiler slag and FBC ash were calculated. The present ash utilization in the US is approximately 50% and total generation is estimated to be around 130 million tonnes by 2015.

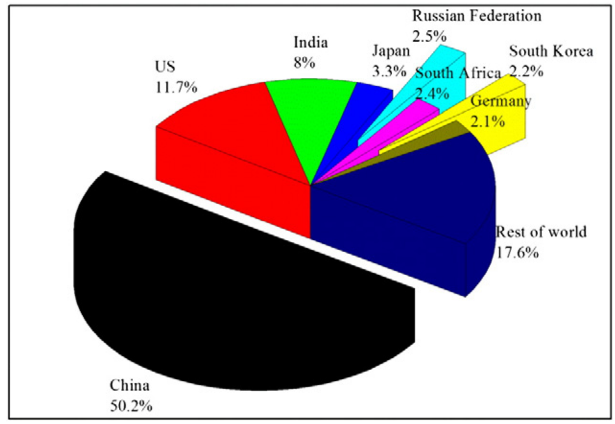

Fig. 1. Distribution of coal consumption worldwide in 2012.

2.2. Characterizations

Understanding the physical, chemical and mineralogical properties of coal fly ash is important, as these properties influence its subsequent use and disposal. The specific properties depend on the type of coal used, the combustion conditions, and the collector setup, among other factors. Physically, fly ash occurs as fine particles with an average size of <20 μm and has low to medium bulk density (0.54–0.86 g/cm^3), high surface area (300–500 m^2/kg) and light texture. The iron and unburnt carbon contents present influence the apparent color, which ranges from water-white to yellow, orange to deep red, or brown to opaque (Fisher et al., 1978). The pH values vary from 1.2 to 12.5, with most ashes tending toward alkalinity (Kolbe et al., 2011). The pH value of the ash–water system depends mainly on the Ca/S molar ratio in ash, although other minor alkalis or alkaline earth cations may also contribute to the balance (Ward et al., 2009; Izquierdoa and Querol, 2012). Based on the Ca/S ratio and pH value, fly ash can be classified into three main groups: strongly alkaline ash (pH 11–13), mildly alkaline ash (pH 8–9) and acidic ash.

Micromorphology observation reveals that the fly ash particles are predominantly spherical in shape and consist of solid spheres, cenospheres, irregular-shaped debris and porous unburnt carbon (see Fig. 4). In FBC ash, spherical particles are rarely observed and most of the particles exhibit irregular shapes, primarily because most minerals in the coal do not undergo melting but soften only, under the relatively