Journal of Environmental Management 91 (2010) 603–617

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

An appraisal of the potential use of fly ash for reclaiming coal mine spoil

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ARTICLE INFO

Article history:
Received 8 May 2008
Received in revised form
26 September 2009
Accepted 8 October 2009
Available online 14 November 2009

Keywords:
Coal mining
Land degradation
Reclamation
Mine spoil
Fly ash
Amendments

ABSTRACT

Growing dependence on coal-fired power plants for electrical generation in many countries presents ongoing environmental challenges. Burning pulverized coal in thermal power plants (TPPs) generates large amounts of fly ash (FA) that must be disposed of or otherwise handled, in an environmentally-sound manner. A possible option for dealing with fly ash is to use it as an amendment for mine spoil or other damaged soil. It has been demonstrated through studies in India and other countries that FA alone or in combination with organic or inorganic materials can be used in a productive manner for reclamation of mine spoil. The characteristics of FA, including silt-sized particles, lighter materials with low bulk density (BD), higher water holding capacity, favorable pH and significant concentrations of many essential plant nutrients, make it a potentially favorable amendment for mine spoil reclamation. Studies have indicated that the application of FA has improved the physical, chemical and biological qualities of soil to which it is applied. The release of trace metals and soluble salts from FA could be a major limitation to its application. This is particularly true of fresh, un-weathered FA or acidic FA, although perhaps not a concern for weathered/pond ash or alkaline FA. Some potential contaminants, especially metals and other salt ions, could be immobilized and rendered biologically inert by the addition of certain inorganic and organic amendments. However, in view of the variability in the characteristics of FAs that are associated with location, feed coal, combustion conditions and other factors, the suitability of a particular FA for a specific soil/mine spoil needs to be critically evaluated before it is applied in order to maximize favorable results and eliminate unexpected consequences. FA generated in India tends to be mostly alkaline, with lower levels of trace elements than are often found in FAs from other countries. The concentrations of potential chemical stressors, predominantly metals, in Indian FAs are often less than established or proposed permissible limits and are thus better suited for soil application. A major logistic limitation to the use of FA could be the cost involved in transport of ash from production to utilization sites.

1. Introduction

Although renewable energy sources are gaining increasing attention, coal will continue to play a major role in meeting the global demand for energy. World production of coal is about 3.5×10^9 t a^{-1}, most of which is used for generating 38% of the world's electricity (AUA, 2007). In India about 70% of the total energy requirement is met through coal, and this contribution is likely to continue long into the future in view of the enormous coal reserves in India (287.0×10^9 t, Coal India, 2007) and the country's steadily growing economy. Unfortunately, coal mining can have substantial negative environmental effects. In India, for every million tons of coal extracted by surface mining, 4 ha of land are damaged (Ghose, 1990). Coal mining, especially opencast (open pit) mining, produces undesirable dumps and tailing dams which, along with other associated mining activities, damage microbial communities and alter the nutritional status of the soil in the mined area through excessive leaching and stockpiling (Piha et al., 1995; Corbett et al., 1996). While 99.9 % of the human food supply (measured by calories) comes from the land, the per capita availability of cropland throughout the world has declined by 20% over the past decade (FAO, 2002). In response to this loss of arable land, the reclamation of abandoned mines for forestry and agricultural use is an important and relevant topic.

An estimated 550 Mt a^{-1} of fly ash (FA) is produced through coal combustion in thermal power plants (TPPs) around the world (Querol et al., 2001). China, the United States, India, Europe, South Africa, Australia, Greece, Japan and Italy have the highest rates of FA production (i.e., 160, 120, 118, 40, 24, 13, 10, 9 and 1 Mt a^{-1}, respectively) (ACAA, 1998; Truter, 2002; Koukouzas et al., 2005; Yoshiaki et al., 2005; Yunusa et al., 2006; NCMFA, 2007; Skodras et al., 2007). The amount of FA (currently ~118 Mt a^{-1}) generated

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0301-4797/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2009.10.004

by India's 85 TPPs is likely to increase significantly in future in view of the ever-increasing demand for electricity (OECD/IEA, 2002; NCMFA, 2007). The amount of FA generated is related to the quality of the coal burned, and represents an additional environmental concern, as the use of high-ash coal with a low calorific value increases in response to depletion of better-quality coal supplies. High-ash coal can generate 4–10 times more ash (mineral matter) during combustion (Fernandez-Turiel et al., 1994). In India over the last 20 years there has been considerable research into improving the beneficial utilization of FA. As a result, utilization increased from 1 Mt a^{-1} in 1994 (3% of annual production (40 Mt)) to about 48 Mt a^{-1} in 2005–2006 (41% of annual production (118 Mt)), which is still far below the utilization already achieved by some other countries (NCMFA, 2007). The policy guidelines in India restrict the use of topsoil for building materials and encourage the use of at least 25% ash (FA, bottom ash (BA) or pond ash (PA)) in clay bricks manufactured within a radius of 100 km from coal- and lignite-based TPPs (NCMFA, 2007). There is also a directive to increase FA use to 100% in the near future.

Numerous studies suggest a significant potential for using coal combustion residues to increase productivity and amend problematic soils (wastelands, low-lying areas, dumping sites, surface-mine soils) (Saxena et al., 1997; Ram et al., 2006a). Although management of FA or PA through phytoremediation is one of the best alternatives for bulk use and reclamation of problematic soils and mine spoils, there are limitations to plant growth imposed by the physicochemical properties of the medium. Many coal FAs are rich in soluble salts, trace metals and radionuclides. Yunusa et al. (2006) evaluated the potential of FA for crop or plant growth in Australia and recommended a careful assessment of (i) FA disposal and utilization, (ii) its bulk use in agriculture and forestry and (iii) its use as an ameliorant to convert problematic soils into soils suitable for agriculture and afforestration. The objective of this review was to identify and discuss (i) the characteristics of FA in relation to soil application, (ii) how FA application alters the quality of the soil/spoils to which it is applied, (iii) the response of plants grown on media treated with ash, (iv) potential uses of FA in mine spoil reclamation, (v) probable environmental constraints for sustained use of FA and (vi) limitations for the bulk use of FA in mining situations.

2. Fly ash generation, classification and characteristics

Ash, the inorganic residue derived from the burning of coal, represents the noncombustible impurities originally present in the coal. The ash generated in TPPs is either FA or BA. FA (80% of total ash), being the lighter fraction, is carried by flue gases into the chimney and collected by electrostatic precipitators. The FA fraction is chemically reactive and finer in texture (0.01–100 μm) than the BA fraction. BA (20% of total ash) is the heavy, coarse fraction (>100 μm) that accumulates at the bottom of the furnace. It consists of coarse-grained, spherical and cenospherical clinkers. A mixture of both FA and BA, commonly referred to as pond ash (PA), is disposed of as a slurry through pipelines to ash ponds. Ash is also collected dry. In India many of the TPPs do not have automated dry ash collection systems.

FAs are categorized as class C (high CaO content) or class F (low CaO content) (Manz, 1999). According to ASTM standards (ASTM C618), bituminous and sub-bituminous coal in India produces class F ash, while lignite produces class C ash that possesses a higher self-hardening capacity (www.flyashindia.com, assessed on 23 May 2009). Ash classifications have also been based on the amount of Si, Fe, Ca and Mg oxides, as well as the reactive water-soluble and amorphous phases in FA, as a means of determining beneficial uses for FA (Dewey et al., 1996). Recently, Vassilev and Vassileva (2006) presented a new ash classification approach based on the origin, phase-mineral and chemical composition, properties and behavior of FA.

The physicochemical and mineralogical characteristics of FA have been comprehensively reviewed and, in general, vary with coal source and quality, combustion process, extent of weathering, particle size and age of the ash (Page et al., 1979; Adriano et al., 1980; Carlson and Adriano, 1993; McCarthy and Dhar, 1999; Mohapatra and Rao, 2001; Bhattacharjee and Kandpal, 2002). Coal FA is a heterogeneous material, both among and within the particles themselves. It consists of very fine to fine particles (Natusch and Wallace, 1974; Khandkar et al., 1993; Baba, 2002). Recently, Sarkar et al. (2005) investigated the distribution profile of coal ash in terms of particle size and magnetic and nonmagnetic components. FA is composed of many minute glass-like particles having a specific density of 2.1–2.6 Mg m^{-3} (Davison et al., 1974); the mean particle density for nonmagnetic and magnetic particles is 2.7 and 3.4 Mg m^{-3}, respectively (Natusch and Wallace, 1974). Bulk density (BD) of FA varies from 0.81 to 1.16 Mg m^{-3}; moisture retention from 6.1 to 13.4%; electrical conductivity (EC) at saturation from 0.63 to 55.00 dS m^{-1}; water-holding capacity (WHC) from 45 to 60% (Aitken et al., 1984; Chatterjee et al., 1988; Kene et al., 1991; Sarkar et al., 2005; Jala and Goyal, 2006; Sarkar and Rano, 2007). The pH of FA varies from 4.5 to 12.0, but the majority of the FAs produced worldwide, including in India, are alkaline (Plank and Martens, 1974; Page et al., 1979; Mishra and Shukla, 1986a, b; Tripathi et al., 2004; Ram et al., 2006b).

The phase and mineral composition of FA includes inorganic, organic and fluid constituents with non-crystalline, crystalline, liquid, gas, and gas–liquid inclusions (Vassilev and Vassileva, 2006). The ferro-aluminosilicate glassy materials consist of variable amounts of unburned C with quartz, mullite, hematite and magnetite as the major mineral phases (Hodgson and Holliday, 1996; Tripathy and Sahu, 1997). Chemically, 90–99% of the FAs consist of Si, Al, Fe, Ca, Mg, Na, and K. Si, Al, Fe and Ca are the major elements present in most compounds, with minor amounts of Mg, Ti and K, and traces of silicates, oxides, sulphates and borates, along with lesser amounts of phosphates and carbonates (Elseewi et al., 1980; Carlson and Adriano, 1993; Jackson et al., 1999; Schumann and Sumner, 2000). FA also contains major- and micronutrients, such as P, B, Cu, Zn and Mn, apart from some trace elements and radioisotopes (Furr et al., 1978a, b; Aitken and Bell, 1985; Jankowski et al., 2006). FAs contain naturally occurring radionuclides from the U and Th series, as well as ^{40}K.

FA contains most of the essential plant nutrients (Khandkar et al., 1996; Ramesh and Chhonkar, 2001; Gupta et al., 2002), except N, which is attributable to the oxidation of C and N during coal combustion (Hodgson and Holliday, 1996). The application of FA in agriculture and forestry, because of its favorable physicochemical properties including appreciable amounts of K, Ca, Mg, S and P, has been advocated for three decades (Page et al., 1979; El-Mogazi et al., 1988; Iyer and Scott, 2001; Yunusa et al., 2006). FA with predominantly amorphous aluminosilicate glassy spheres is comparable to soil particles (El-Mogazi et al., 1988) and, being a non-expanding material, works well as an amendment for clay soil (Adriano et al., 1980). The Ca-rich, alkaline type of FA has proven to be useful for neutralizing acidic soils (Mishra and Shukla, 1986a, b; Taylor and Schuman, 1988). Many physical and chemical characteristics of FA may benefit plant growth and ameliorate unfavorable agronomic properties of the soil to which it is added (Truter, 2002). Indian FAs are mostly rich in available major and secondary nutrients (Table 1). Weathered FA has more organic carbon (Khandkar et al., 1993) than fresh FA, and concentrations of some trace metals, such as Zn, Cu, Ni, Cr and V, are higher in FA derived from lignite than they are in bituminous and sub-bituminous FA (Sadasivan and Negi, 1991). SiO_2 is the major constituent in Indian ashes, which also have