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Review

The application of coal combustion by-products in mine site rehabilitation

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A B S T R A C T

Coal combustion by-products (CCBs) generated from coal-fired power plants have been considered in some circumstances and in some applications as alternatives for natural materials. This review focused on the beneficial use of CCBs for mine sites. The alkaline pH of CCBs has been shown to play a neutralising role for acid mine drainage and the consequent precipitation of metals from solution, mainly as metal hydroxides. Coal combustion by-products have also been used for soil restoration, having been shown to improve one or more of the physical, chemical and biological properties of degraded soils which in turn has led to improvements in revegetation outcomes. In addition, fly ash has been used as a one of the materials in engineered covers that are constructed to encapsulate and isolate potentially hazardous mine wastes. The use of CCBs for mine void backfilling has been considered an opportunity for the bulk utilization of CCBs. Backfilling of underground mine voids with these materials presents the potential to reduce acid mine drainage, limit the risk of land subsidence and minimise and control the likelihood of mine fires. Even though the proactive use of CCBs may eliminate or reduce an environmental burden that remains if separate storage or disposal of these otherwise 'waste' materials is required, there may be adverse side effects that could occur through such uses of CCBs, such as the leaching of deleterious elements. Therefore, in the case of their use in mine backfilling, for example, possible environmental impacts need to be assessed and monitored during a testing phase in the context of other variables, and before backfilling with such materials is used on a large-scale. There is still a lack of well-researched information on the practical use of CCBs, and their potential environmental and health effects, and in their use for mine site rehabilitation purposes, effective guidelines and regulations are also limiting factors. In most countries, government regulations regard CCBs as a waste but not a hazardous waste. However, given the high potential CCBs have in a number of roles and functions relating to mine rehabilitation and mine closure, more research at the practical level, and more engagement at a government level, is required.

1. Introduction

Coal combustion by-products (CCBs), including boiler slag, bottom ash, fly ash and flue gas desulphurisation (FGD) material, are solid residues that remain after the burning of coal (Kalyoncu and Olson, 2001; Scheetz and Earle, 1998). The global production of CCBs in 1992 was 459 million tonnes with China as the largest producer followed by Russia and the USA (Manz, 1997). Among the produced CCBs, 33% was used for cement, grout, blocks, lightweight aggregate, bricks or ceramics, asphalt filler, landfill, and as filler for mine pits. In 2010, the annual production of CCBs worldwide was estimated to be around 600 million tonnes (Ahmaruzzaman, 2010). The American Coal Ash Association (ACAA) reported that 110 million tonnes of CCBs was generated in the USA in 2012, of which 52 million tonnes (47%) was utilised (ACAA, 2012). In Australia, the annual production of CCBs in 2012 was 13 million tonnes and 42% was utilized (ADAA, 2012). Figures on production and utilisation of CCBs in Australia, Canada, European union (EU), Japan and USA are presented in Table 1.

The non-utilisation approach means that disposal of CCBs requires a substantial area of land in the form of purpose-built ash ponds, which can pose a risk to the local environment due to the potential mobilisation of material through erosion and leaching of contaminants (Ahmaruzzaman, 2010). CCBs can be used as a replacement for natural materials, including Portland cement and structural fills (Jala and Goyal, 2006), and numerous studies have

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Abbreviations

CCBs	Coal combustion by-products
FGD	Flue gas desulphurisation
ACAA	American Coal Ash Association
EU	European Union
KOSPO	Korea Southern Power Co. Limited
MIRECO	Mine Reclamation Corporation
ASTM	American Society for Testing and Materials
AMD	Acid mine drainage
EC	Electrical conductivity
NAS	National Academies of Science
TCLP	Toxicity Characteristic Leaching Procedure
USEPA	USA Environmental Protection Agency
SPLP	Synthetic Precipitation Leaching Procedure
MWLP	Mine Water Leaching Procedure
CRC	Cooperative Research Centre
ANZECC	Australian and New Zealand Environment Conservation Council
RCRA	Resource Conservation and Recovery Act
OSM	Office of Surface Mining
SMCRA	Surface Mining Control and Reclamation Act
NSW EPA	New South Wales Environmental Protection Authority

reported their use in agriculture and for the remediation of contaminants. Fly ash in particular has been used to promote plant growth and agricultural yield (Khan and Khan, 1996; Mishra and Shukla, 1986; Singh and Siddiqui, 2003).

Mine surface rehabilitation and underground mine backfilling (Fig. 1) are two important end uses of CCBs that can have favourable environmental outcomes (Ram and Masto, 2010). Vories (2005) reported that approximately 2% of the CCBs produced in the USA were used at about 2% of the mines sites where they originated. It has been shown that the use of CCBs at mine sites has beneficial impacts on human health and the environment, including prevention of acid mine drainage (Rios et al., 2008; Porter and Nairn, 2010), acting as an agricultural supplement, providing a flowable fill that seals and stabilises abandoned underground mines to prevent subsidence, a construction material, and an earthlike fill material for final pit voids (Vories, 2005; Sivakugan et al., 2006; Wang et al., 2009; Mishra and Das, 2010). The backfilling of underground voids has been shown to enhance land stability and ensure that mining of the surrounding areas is safer and more effective (Sivakugan et al., 2006).

This review outlines properties of CCBs, their applications at mine sites, including the limitations, and the regulations in place relating to the use of CCBs for the environmental management of mines. It focuses on the application of fly ash for mine void backfilling, and discusses the chemical and physical properties that must be taken into account before and after backfilling to ensure the benefits are maximised and the risks are minimal.

2. Methods

This research was initiated by the request of Korea Southern Power Co. Limited (KOSPO) and the Mine Reclamation Corporation (MIRECO) to review the potential uses of power station CCBs for mine reclamation purposes, and to further provide guidance on the regulatory principles for the recycling of CCBs. The chemical and physical properties of a particular coal ash are dependent on the composition of the parent coal, conditions during coal combustion, efficiency of emission control devices, and practices used during storage. Therefore, the types and properties of CCBs were firstly described and we reviewed current international literature relating to the use of CCBs for mine reclamation and mine fill purposes. We also reviewed chemical and physical properties that are required to be measured and monitored if CCBs are to be used for structural or land application purposes in order to ensure safety and environmental values are appropriately maintained. An assessment of policies, guidelines and legislation relating to CCBs was undertaken for some developed countries where potential alternate and/or beneficial uses have been identified. To cover these aspects we collected data and information from personnel communication (3.8%), books (5.3%), government websites (9.1%) especially for regulations, reports (7.6%), conference proceedings (4.5%) and journal papers (69.7%). Journal papers were classified based on research topic and showed that major researches using CCBs on mine reclamation (35%) were conducted on soil restoration and revegetation (Fig. 2).

3. Types and properties of coal combustion by-products

When CCBs are produced, coarse particles (bottom ash and boiler slag) accumulate at the bottom of the combustion chamber while fine fractions (fly ash) are removed from the flue gas by electrostatic precipitators or other gas-scrubbing systems (Kalyoncu and Olson, 2001). Boiler slag, comprising 3% of CCBs, is a glass-like molten coal residual material that is collected at the bottom of the boilers and released into a water-filled pit (Kalyoncu and Olson, 2001; Scheetz and Earle, 1998). Bottom ash is defined as the coarser coal residue that accumulates at the bottom of the boiler and accounts for 16% of total CCBs (Scheetz and Earle, 1998). Fly ash is the fine fraction of the CCBs which comprises 57% of CCBs and generally ranges in size from 0.5 to 200 μm (Scheetz and Earle, 1998). Since fly ash forms a major part of CCBs, many research studies exploring the

Table 1
Production and utilisation of coal combustion by-products (unit: kilo tonnes).

Country	Australia	Canada	EU	Japan	USA
Year	2012	Averaged over 2009–2011	2009	2003	2012
Production	12 797	7042	51 806	9870	109 750
Utilisation	5385 (42.1%)	1724 (24.5%)	47 755 (92.2%)	8380 (84.9%)	51 887 (47.3%)
Utilisation in detail					
Cement	1904	581	5958	6327	5324
Construction work	361	1010	20 417	1014	27 901
Mining application	81	97	Included in construction work	204	12 812
Soil modification	41	Included in other	20 633	93	510
Agriculture	0.6	Included in other	59	79	683
Waste stabilisation	34.5	Included in other	206	5	3053
Others	2963	36	482	658	1604
References	(ADAA, 2012)	(CIRCA, 2013)	(ECOBA, 2009)	(JCOAL, 2003)	(ACAA, 2012)