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Chemical Stabilization of Coal Fly Ash for Simultaneous Suppressing of As, B, and Se Leaching

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Additional information is available at the end of the chapter

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Abstract

The discard of coal fly ash produced from the combustion of pulverized coal in a coal-fired boiler of thermal power plants has led to environmental concerns. Due to the interaction of fly ash particles with weathering and hydrological processes, the rainfall leaches out toxic elements in coal fly ash from the ash heaps. This situation has been pointed out as a potential contamination of soil, surface, and groundwater. In this chapter, the available fly ash treatment techniques to minimize future release of toxic trace elements (arsenic, boron, and selenium) have been documented, and the recent investigations dealing with leaching suppression effect of arsenic, boron, and selenium from coal fly ash have been reviewed. The leaching characteristics of arsenic, boron, and selenium are discussed, and a simple and low-cost leaching control method is presented in the context of treating the fly ash through chemical stabilization technique using additives containing high levels of calcium. Experimental results described in this chapter show the chemical stabilization technique using additives technique for simultaneous suppressing of As, B, and Se leaching from coal fly ash.

Keywords: chemical stabilization technique, coal fly ash, leaching, calcium, arsenic, boron, selenium

1. Introduction

Coal fly ash from coal burning power generation is one of the major sources of environmental pollution due to the discharge of large amounts of fly ash into the environment. Coal fly ash has been utilized in different ways such as a substitute material for Portland cement, structural fills (usually for road construction), soil stabilization, and mineral filler in asphaltic concrete because of its physical (selfhardening) properties [1, 2], and in recent years, coal fly ash has



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been utilized as a potential material to treat acid mine drainage (AMD) because of its chemical (high degree of alkalinity) properties to neutralize AMD [3–8]. However, most of the fly ash is disposed in landfills [1], this disposal involves the interaction of fly ash particles with weathering and hydrological processes where rainfall leaches out toxic elements, anions, and cations from the ash heaps, which pose an environmental hazard through contamination of soil, surface, and groundwater [9-11]. During combustion, the organic matter in coal is destroyed, and as a result, the concentrations of trace elements are increased relative to the source coal. Among the elements that can be leached from fly ash, Ag, As, B, Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb, Se, Sb, Sn, and Zn are of the greatest concern [12, 13] as environmental hazard. The leaching of trace elements such as As, B, and Se from coal fly ash (CFA) is likely to occur as these elements tend to form hydrophilic oxides that are dissolved as oxyanion forms [10]. The beneficial reuse of fly ash as a potential material to treat acid mine drainage (AMD) has great potential in minimizing the amount of disposed fly ash [3-8]; however, since the coal fly ash itself contain leachable trace elements and the usage of fly ash in treating AMD could lead to trace element accumulation with negative consequences to the environment [14], it is particularly important to be able to assess the leachability of coal fly ash (since the results can determine not only whether the ash is environmentally acceptable for use as the soil supplements, construction material, or neutralization material to treat AMD but to extend of isolation that might be required for disposal in landfill) and to treat the coal fly ash before the utilization to avoid the trace elements leaching into the environment.

To predict the possible effect of coal fly ash on the environment, it is particularly important to understand the factors that control the leaching behavior of trace elements in coal fly ash. Research studies on the leaching behavior of As, B, and Se in coal fly ash have been carried out with the promising results. The results demonstrated that the leaching behavior of arsenic, boron, and selenium from fly ash was affected by pH, solid-to-liquid ratio, leaching time, and ash type [15–19]. The leaching of As increased with increasing pH values in acidic fly ashes [19] and increased with decreasing pH values in alkaline fly ashes [20], while the leaching of B decreased with increasing pH values [18, 21] and the leaching of Se tends to decrease as pH was raised for an alkaline ash with high Ca composition [18]. The leaching of As, B, and Se from CFA generally increased with increases in the S/L ratio and leaching time, and adsorption/desorption played a major role in As and Se leaching from the CFA [22]. The leaching of As and Se from acidic ashes could be described by sorption of iron oxide, while the leaching from the alkaline ashes appeared to be controlled by sorption in the alkaline calcium phase [20, 23]. The presence of Ca in fly ash plays an important role in the leaching behavior of As, B, and Se, in which the leaching of As, B, and Se may involve the trapping of As, B, and Se species by the ettringite phase (3CaO·Al₂O₃·3CaSO₄·32H₂O), leading to a decrease in leaching under alkaline conditions [18, 19, 24-28]. Therefore, Ca content and the sorption process are known to play important roles in the release of As, B, and Se from CFA.

Different treatments and stabilization processes of fly ash have been proposed by the scientific community. The most common used techniques for removing toxic elements from fly ash and APC (air pollution control) residue are (1) extraction and separation, (2) chemical stabilization, (3) solidification, and (4) thermal treatment [29]. Several studies have chemically treated fly ash produced in power plants to immobilize the toxic trace elements before disposal. These studies used chemicals such as calcium aluminates [30], phosphoric acid [31], NaOH [32], and chelating surfactants such as ED3A [33]. Arsenic trioxide contaminated soil was successfully treated with a ferrous sulfate solution to promote the formation of insoluble metal-bearing phases [34] and the coal fly ash treatment with ferrous sulfate shown to be an effective method for the sequestration of As, B, Cr, Mo, Se, and V associated with coal fly ash, where the mobility of As, B, Cr, Mo, Se, and V were substantially reduced [35]. Recently, the coal fly ash chemical treatment using other waste sources containing high level of calcium has been applied [27]. The advantage of this technique is that it can be used for reducing As, B, and Se leaching at low cost with the abundant chemical available, since it utilizes wastes from other industry. The aims of this chapter are to review what is known about the factors which control the leaching of As, B, and Se in fly ashes and the method to reduce As, B, and Se leaching from fly ash. Experimental results of simultaneously leaching suppression of As, B, and Se were described in this chapter.

2. Coal fly ash and overview of leaching characteristics of arsenic, boron, and selenium from coal fly ash

2.1. Coal fly ash

Coal fly ash, a by-product of coal-fired power plants, produced from the combustion of pulverized coal in a coal-fired boiler of thermal power plants. The fly ash particles are removed from the flue gases using electrostatic precipitators, FGD systems, or bag houses and are collected and stored dry for recycling. Fly ash consists of fine particles, predominantly spherical in shape, either solid or hollow, ranging in diameter from <1 µm up to 150 µm formed from the mineral matter in coal, consisting of the noncombustible matter in coal plus a small amount of carbon that remains from incomplete combustion. Properties of fly ash vary significantly with coal composition and plant-operating conditions. Fly ash contains the primary inorganic components of SiO₂, Al₂O₃, Fe₂O₃, and CaO, less amount of MgO, Na₂O, K₂O, SO₂, MnO, TiO₂, and C and varying levels of trace elements [36–38]. Based on its chemical composition (ASTM C618), fly ash can be classified into two classes, C and F. Class C ash (high-calcium, ≥10% CaO) is normally produced from lignite or subbituminous coals and contains less SiO₂ + Al₂O₃ + Fe₂O₃ (>50%) but more calcium hydroxide or lime and higher amount of alkalis (combined sodium and potassium). Class F ash (low-calcium, <10% CaO) is generally produced from burning anthracite or bituminous coal and contains at least 70% of SiO₂ + Al₂O₃ + Fe₂O₃. [38–43]. The mineralogy of fly ash is greatly influenced by the parent coal from which it was derived. Owing to the rapid cooling of burned coal in the power plant, fly ashes consist of amorphous glass ($\leq 90\%$) and a small amount of crystalline material [44–49]. This predominant portion of the glass gives fly ash its pozzolanic properties (harden with water after activation with an alkaline substance such as lime) [50]. The major crystalline phases in fly ashes are quartz (SiO₂), mullite (3Al₂O₃·2SiO₂), magnetic spinel includes; magnetite (Fe₂O₄), and hematite (Fe₂O₂). Although the total percentage of magnetic matrix of the ash is small, particular attention should be given because of its reactivity and potential for carrying and releasing toxic elements. [47].

Fly ash particle surfaces are often enriched in highly environmentally reactive trace elements (such as As, Se, Cd, Cr, Ni, Sb, Pb, Sn, Zn, and Mo [10, 51]) due to the largely emission of various trace elements in coal during coal combustion [52–55]. It has been reported that trace element concentrations in fly ash are sometimes 4–10 times higher than their original concentrations in coal samples due to the condensation of elements, which are volatilized during combustion, onto solid particles at different rates and in varying amounts as the combustion gases cool down [56–60]. As a result, these elements readily react when the fly ash particle is exposed to water and release into the environment [35, 59]. However, the release of the elements from fly ashes is controlled by precipitation or dissolution mainly and possibly by desorption. Understanding the factors that control the leaching behavior of trace elements is critical in predicting the potential impacts of fly ash on the environment. Since As, B, and Se have recently become a major problem in soil contamination in Japan, the leaching behavior of As, B, and Se has been growing in the recent investigations and described in the following sections.

2.2. Overview of leaching characteristic of arsenic, selenium, and boron from coal fly ash

Several mechanisms have been observed to elucidate arsenic, boron, and selenium leaching behavior from fly ash. Generally, the leaching behavior of As, B, and Se was affected by pH, solid-to-liquid ratio, leaching time, and ash properties, in which these ash properties including chemical composition, chemical/mineralogical speciation, the particle morphology, and the fraction of a species are available for leaching [16–19, 26, 28, 61].

Arsenic and Selenium releases from acidic fly ash increase with pH, whereas in alkaline fly ash, this trend is reversed and the leaching of As and Se from acidic fly ash could be described by sorption on iron oxide, while leaching from alkaline fly ash seems to be controlled by sorption on an alkaline Ca phase [20]. This finding is relevant with that from Zielinski et al., where in a highly acidic fly ash, the mode of occurrence of arsenic is associated with iron oxide, oxyhydroxide, or sulfate, while in a highly alkaline ash, arsenic is associated with a phase similar to calcium arsenate (detected using XAFS (X-ray absorption fine structure) spectroscopy) [62]. It is well known that Ca-rich ash tends to make the formation of insoluble Ca-arsenate [63], whereas low-lime fly ash provides less chance for this phase to precipitate. At pH > 11.5, the precipitation of ettringite $(3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O)$ contributes to the dramatic reduction of As in leaching solution, along with other oxyanionic species [10, 64]. It is also reported that the formation of ettringite $(3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O)$ contributes to the stabilization of selenium in subbituminous coal ash [65, 66]. The adsorption of selenite in fly ash was also likely controlled by aluminum oxide [23, 51, 67].

Boron is the most mobile trace element in coal ash [21], since it is associated frequently with the smallest particles in the ash, where it can accumulate on the surfaces of particles and in water-soluble fraction which promote high leachability rates [51]. Although the leachability of B does not depend significantly upon pH at nearly neutral values (pH 6–8), the initial rate of leaching is increased by an increase in acidity and it decreases with further increase in pH, and the trend shows no substantial difference between acidic and alkaline ash [21]. On the

contrary, the boron leachability depends on its element concentration in coal fly ash [18], and the ligand exchange mechanisms are considered as a reason for the lower concentrations of B under mildly acidic conditions [68, 69], although much greater leaching rates are achieved when under strongly acidic conditions [69, 70]. Previous studies indicate the tendency for ettringite to incorporate B within its mineral lattice and lead to the decreasing of solubility/ dissolved concentrations of B at pH \approx 11.5 [18, 71]. It has been also indicated that under alkaline conditions, the co-precipitation of B with CaCO₃ may significantly captured B in alkaline fly ash [18], to some extent, in acidic-natured fly ash, this process is unlikely to take place [19].

3. Arsenic, boron, and selenium: properties, contamination pathways, and their harmful effects

3.1. Arsenic

Arsenic is a semi metallic element with atomic number 33, atomic mass 74.92 g mol⁻¹ and density 5.72 g cm⁻³ at 14°C [72]. It is an odorless, tasteless, and notoriously poisonous metalloid with various allotropic forms: black, yellow, and gray, in which the gray form is the most common, and it is used for industrial purposes. It is distributed throughout our environment, mainly in earth crust, air, water, soil, sediments, etc. Arsenic is emitted into the atmosphere by high-temperature processes such as coal-fired power generation plants, burning vegetation, and volcanism [73]. Some forms of arsenic are inorganic which do not contain carbon, and others are organic, which always contain carbon. The examples for organic arsenic compounds are arsanilic acid (4-aminophenylarsonic acid, C₆H₈AsNO₃), arsenobetaine (2-trimethylarsoniumylacetate, C₅H₁₁AsO₂), methylarsonic acid (monomethylarsonate, CH₅AsO₂), etc. [74]. Inorganic arsenic compound exists in four oxidation states: -3 (arsenide), 0 (metallic arsenic), +3 (arsenite) and +5 (arsenate). The examples for arsenide compounds are alkali and alkaline earth metal arsenides (e.g., sodium arsenide Na₃As), arsenides of group III elements (e.g., gallium arsenide GaAs) [75], etc. The most common forms of arsenite compounds are arsenic sulfide (As₂S₂), arsenic trichloride (AsCl₂), potassium arsenite (AsO₂·K), sodium arsenite (AsO₂·Na), etc. [76]. The general form of arsenate is AsO₄³⁻ and exists in different forms such as arsenic acid (H₃AsO₄) at strong acidic condition, dihydrogen arsenate (H₂AsO4⁻) at weak acidic condition, hydrogen arsenate (HAsO₄²⁻) at weak basic condition, and arsenate ion (AsO4³⁻) at strong basic condition. Examples of arsenate compounds are arsenic pentoxide (As₂O₅), calcium arsenate ((AsO₄)₂·3Ca), lead arsenate (HAsO₄·Pb), potassium arsenate $(H_2AsO_4\cdot K)$, sodium arsenate $(H_2AsO_4\cdot Na)$, etc. [76]. Arsenate is thermodynamically stable at aerobic condition, while arsenite is stable at anaerobic conditions [77]. Generally, inorganic forms of arsenic are more toxic to the environment than organic forms, and among inorganic forms, arsenite is more toxic than arsenate due to higher cytotoxic, genotoxic, mobile, and soluble nature of arsenite [78].

Humans may be exposed to arsenic through the usage of arsenic containing water for drinking purposes, food, cosmetics, cigarettes, etc. [79]. The sources of arsenic contamination in water medium can be classified as natural and anthropogenic sources. The natural sources of arsenic contamination in water medium are due to the mobilization of arsenic in natural condition which depends on its oxidation states, mobilization mechanism, and the parent mineral form [80]. The anthropogenic sources of arsenic contamination in water medium include the wastes generated from industries manufacturing wool and cotton, glass, ceramics, semiconductor, pesticide, etc. and from industries like rare earth industry, chemical industries, petroleum refining, etc. [81, 82].

The health effects on arsenic may come both from different forms of arsenic (inorganic and organic forms) and categorized based on the level of contamination. Among the effect of inorganic arsenic exposure, disturbance of the stomach and digestive organs, diminished generation of red and white blood cells, skin changes, and lung irritation have been reported in many health cases. The take-up of significant amounts of inorganic arsenic has been proposed to increase the possibility of cancer development, particularly the possibility of skin cancer development, lung, liver, and lymphatic cancer. Barrenness and miscarriages with women, skin irritation, declined protection from diseases, heart disruptions, brain damage with both men and women, and DNA damage have been reported as the effects of a very high exposure to inorganic arsenic. The effects of organic arsenic are almost the same with inorganic arsenic, which can cause neither cancer nor DNA damage, but high doses exposure may cause nerve injury.

3.2. Boron

Boron is a nonmetallic element with atomic number 5, atomic mass 10.81 g mol⁻¹, density 2.3 g cm⁻³ at 20°C, and a poor electrical conductor at room temperature. It has several allotropes in the form of amorphous boron, a dark powder, unreactive to oxygen, water, acids, and alkalis; crystalline boron, silvery to black, and extremely hard. It is found in nature in a low concentration in oceans, earth crust, rock, soil, and water [83] and mostly in the form of over 200 minerals with different amounts of calcium, sodium, or magnesium and available as calcium, sodium, and magnesium borates. Among them, the most popular are borax, tincal, colemanite, ulexite, and kernite [84]. Boron has various oxidation states in compounds, but the most significant and common is +3. It appears in lower oxidation states +1, 0, or less than 0, but these states are found in compounds such as higher borates only [85, 86]. Boron enters the environment mainly through the weathering of rocks, boric acid volatilization from seawater, and volcanic and geothermal activity. Boron is released to the environment from anthropogenic sources e.g., via industrial air emissions, fertilizer and herbicide applications, and municipal and industrial wastes from industries manufacturing borosilicate glass, detergents, semiconductor, cosmetics, flame retardants, fertilizers, and dyestuff production [87]. Two anthropogenic boron compounds, boron trichloride and boron trifluoride, are listed as toxics release inventory (TRI) chemicals.

Human causes of boron contamination include releases to air from power plants, chemical plants, and manufacturing facilities. Contamination of water can come directly from industrial wastewater and municipal sewage, as well as indirectly from air deposition and soil runoff. Borates in detergents, soaps, and personal care products can also contribute to the presence of boron in water. Boron can be found in surface water in the form of undissociated

orthoboric acid, partially dissociated borate anions in the form of polyborates, complexes of transition metals, and fluoroborate complexes, and it is also found in ground water, brackish water, or hot springs, especially at geothermal or tectonic areas [88].

Among the effect of long-term consuming of food and water with increased boron content, cardiovascular, coronary, nervous, reproductive systems, changes in blood composition, neurological effects, physical disorders, and intellectual development of children have been reported in many health problems. For pregnant women, abundance of boron can be notably harmful as it raises the risk of birth pathology. Testicular decay and degeneration have been detected as the effects of high daily doses of boron. Queasiness, retching, diarrhea, and lack of appropriate weight gain or weigh loss have been detected as the effects of consuming of food and water with doses greater than 500 mg/day [89].

3.3. Selenium

Selenium is a nonmetallic element with atomic number 34, atomic mass 78.96 g mol⁻¹, and density 4.79 g cm⁻³ at 20°C. Selenium has a number of allotropes including a gray crystalline hexagonal selenium, a red crystalline form, an amorphous (which has a disordered atomic structure) red powder, and a black vitreous (glass-like) form. Amorphous selenium is a photoconductor (a light-dependent semiconductor), and it has had a long history of use in light-based applications—it was used to make the first solar cell in 1883. Selenium is a rare component of the Earth's crust that is mostly found as selenide associated with heavy metal sulfide ores, such as copper and lead sulfides [90]. Selenium species can be grouped into the four major categories: (1) inorganic selenium, (2) volatile and methylated selenium, (3) protein and amino acid selenium, and (4) nonprotein amino acids and biochemical intermediates. Selenium compounds commonly exist in the oxidation states -2, +2, +4, and +6. It is usually found as the oxyanions selenate (SO₄²⁻) and selenite (SO₃²⁻) in oxidized systems and as elemental selenium (Se[0]) and selenides (HSe-) in aerobic zones and unweathered mineral formations [91]. Though complexed selenium is of low toxicity, selenate (SeVI) and selenites (SeIV) are very toxic. These two forms of selenium are generally found in water and display bioaccumulation and bioavailability. Under acidic conditions, the extremely toxic and corrosive hydrogen selenide gas can be generated from selenium containing species.

Selenium contamination typically occurs in the aqueous stream and bioaccumulation of selenates and selenites in waste water can threat all aquatic life downstream. Natural processes that redistribute selenium include volcanic activity, terrestrial weathering of rocks and soils, wildfires, and volatilization from plants and water bodies. The anthropogenic sources of selenium to aquatic systems are including mining, fossil fuel combustion, oil refining, and discharge of seleniferous drainage water from irrigated agriculture [92]; these sources will end up in groundwater or surface water through irrigation.

Humans may be exposed to selenium through food or water or contact with soil or air that contains high concentrations of selenium. The health effects of various forms of selenium can vary from brittle hair and deformed nails, to rashes, heat, swelling of the skin, and severe

pains. Exposure to selenium through air can cause dizziness, fatigue, and irritations of the mucous membranes. Among the effect of selenium overexposure, red staining of the nails, teeth, and hair have been reported in many health cases. Due to the fact that selenium is an eye and upper respiratory irritant and a sensitizer, selenious acid produced from the reaction of selenium dioxide with moisture may cause corrosive to the skin and eyes. Accumulation of fluid in the lungs, pneumonitis, bronchitis, bronchial asthma, shortness of breath, sore throat, chills, fever, headache, conjunctivitis, queasiness, retching, abdominal pain, diarrhea, and enlarged liver has been reported as the effects of overexposure of selenium fumes.

4. Fly ash treatment techniques

Treatment of fly ash before utilization is important to minimize leaching of contaminants and/or utilize in the best possible manner in which methodologies for detoxifying fly ash including reducing the concentrations of the contaminants (e.g., through washing), astriction the leaching of the contaminants by forming steady blocks or inertial compounds with additives or binders (e.g., by stabilization methods), or reducing the mobility of the contaminants (e.g., through S/S methods) [93]. Several researchers have produced numerous treatments and disposal solutions for fly ash over the recent decades, some of these are only tested in the laboratory, while others are available commercially. Based on the main principle of operation, the treatment techniques may be classified in four categories [29, 94]:

- 1. extraction and separation,
- 2. chemical stabilization,
- 3. solidification, and
- 4. thermal treatment.

4.1. Extraction and separation

Extraction and separation techniques have the main purpose to remove or recover specific components or fractions from fly ash which focus on removing heavy metals and to some extent salts from fly ash, mainly using water or acidic solutions. The processes of this treatment technique are typically relatively simple, but the main disadvantage is the generation of process water with high content of metals and salts.

The main extracting agent used in this technique including water [95], acid [96], and microorganisms [97]. The electrodialysis process which involve ion exchange technique [98] and particle size fractionation process based on the settling velocities of fly ash particles in a water filled reactor [99] are also including in this extraction and separation techniques. For the comprehensive overview of the principles of these techniques, see Refs. [94, 100].

4.2. Chemical stabilization

Chemical stabilization technique has the main purpose to bind and immobilize pollutants in the fly ash matrix which focus on binding heavy metals by alterations to the fly ashes geochemical properties [101, 102]. Generally, the processes of the chemical stabilization technique are simple and low cost, which significantly improve the leaching properties of the fly ash, such as water extraction, chemical reactions, and then, de-watering. The main disadvantage is the generation of metal and salt containing process water.

Various chemical stabilization processes have been developed, and most of them involve the use of $FeSO_4$ [35, 95, 103], $FeSO_4 + CaCO_3$ [35], CO_2 [104, 105] CO_2 , and H_3PO_4 [106] Phosphate (PO₄³⁻) [107], Sulfide (S²⁻) [108], Ca(OH)₂, and paper sludge ashes [27], Ca(OH)₂ and cement [109, 110], colloidal silica [111], and silica fume [112].

4.3. Solidification

Solidification technique is often discussed as stabilization processes (S/S: solidification and stabilization) in which solidification involves the transformation of a liquid or sludge into solids and may not lead to a chemical interaction of the constituent of concern with the solidifying agent. This technique has the main purpose to physically and hydraulically encapsulate the fly ashes and reduces the mobility of the contaminants in fly ashes because of the reduced surface area and low permeability. On the other hand, the main goal of stabilization is to convert the contaminants into less soluble or less toxic forms, with or without solidification [113]. The main advantages of this technique come from the fact that this technology is simple, well established, and low cost, which significantly decrease the leaching of contaminants and improve the mechanical properties. The main disadvantages of this technique are related to significant increase in the mass disposed of, and the physical integrity of the product may deteriorate over time resulting in increased metals leaching.

The main solidifying agent used in this technique including water [114], cement [93], and cement [115]. For the comprehensive overview of the principles of these techniques, see Refs. [94, 100, 116].

4.4. Thermal treatment

Thermal treatment technique involves a heating of fly ashes and thereby changing the physical and chemical properties of fly ashes in which the stable and very dense product can be produced with sufficient leaching properties [117]. This method very efficient at destroying dioxins, furans, and other toxic organic compounds due to the high temperatures used [118]. In some cases, encapsulation of fly ash is also occurred [101]. The main disadvantages are the high cost due to the high-energy demands for the process and generation of flue gas containing volatile metals.

Three major types of thermal treatment technique are sintering, vitrification, and melting.

- **1.** Sintering processes involves heating to a level at which individual particles are bound together and the chemical species of interest can achieve a reconfiguration [119]. Temperatures are around 900–1300°C, and a denser and less porous material is produced.
- 2. Vitrification processes involves melting of a mixture of fly ash and additives (glass precursors (i.e., Si)) to fix the contaminants in the final matrix (alumina silicates). This mixture is typically heated to around 1300–2000°C and then cooled to form a single solid phase (an amorphous and homogenous glassy material). In this process, fly ash components are bound in the glassy materials thereby also encapsulating the fly ash.
- **3.** Melting (or fusion) processes are very similar to vitrification processes; however, in this case, no additives (glass forming materials) are added. The final product consists of multiple metal phases [118] which can possibly be separated utilizing different melting temperature of individual metal phases. Therefore, the product obtained can be used as a construction material, for example, as a sub-base in road construction or for pavements [120]. The temperatures involve in this melting processes are like vitrification processes.

5. Experimental results of simultaneous leaching suppression of As, B and Se from coal fly ash

Considering the leaching of arsenic, boron, and selenium from fly ash has recently become a major problem in soil contamination in Japan [27, 121], the current research focuses on the development of effective technologies for the improving leaching properties of fly ash. As described in section 4, several pre-treatment options have been proposed for minimizing the leaching of toxic trace elements, including addition of Ca(OH)₂ to fly ash [109, 110]. Based on this method, the Laboratory of Environmental Engineering Systems of Gifu University-Japan, one of the founding members of the Next Generation Energy Research Center, developed its scientific research on "Experimental study on simultaneous leaching suppression of trace elements including As, B, and Se from coal fly ash" which analyzes the leaching properties and promotes the methods for control of the trace elements leachates from coal fly ash, utilizing the chemical stabilization technique by using Ca(OH)₂, paper sludge ash, and filter cake, which are waste generated in the papermaking and lime industry processes [27].

In this study, a low calcium content fly ash sample named fly ash H (FAH) (2.05% of CaO, detected using X-ray fluorescence) with a high concentration of trace elements leaching (As 48.66 μ g/L, B 5.39 mg/L, Se 86.9 μ g/L, detected using ICP-AES) that was collected from coal-fired power plant in Japan was treated through chemical stabilization technique with the addition of additives (Ca(OH)₂, three kinds of paper sludge ashes (PS Ash 3, 4, 5) and one kind of filter cake (FC)) under 5 and 10% Ca content in additives and subjected in a detailed characterization and leaching test regarding its chemical properties and its leaching behavior. **Table 1** lists the composition of inorganic elements in FAH and additives. **Figure 1** depicts experimental process of chemical stabilization in this study. Fly ash sample and additives characterization

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Sample			FAH (1s) ¹	PS Ash 3	PS Ash 4	PS Ash 5	FC
Ash composition	SiO ₂	(%)	59.25	31.47	44.21	42.36	23.31
	Al_2O_3		25.63	12.40	22.23	19.80	13.87
	TiO ₂		1.99	0.38	2.56	2.11	0.06
	Fe ₂ O ₃		7.49	5.13	2.63	5.56	2.33
	CaO		2.05	46.31	18.77	19.51	59.18
	MgO		0.79	3.28	3.42	3.30	0.96
	Na ₂ O		0.60	0.24	0.95	0.41	0.03
	K ₂ O		1.56	0.20	2.09	1.99	0.25
	P_2O_5		0.18	0.18	1.75	1.54	0.00
	MnO		_	0.03	0.05	0.06	0.04
	V_2O_5		0.03	0.01	0.02	0.02	0.02
	SO ₃		0.42	0.36	1.31	3.33	0.00
pH of the leachate			10.38	13.72	12.71	12.26	7.28
Leached Ca ion		(mg/L)	121	1405	246.5	597	15.45
Leaching concentration	As	(µg/L)	48.66				
	В	(mg/L)	5.39				
	Se	(µg/L)	86.9				

¹Sample fly ash H, from the chamber 1 of electrostatic precipitator.

Table 1. Composition of inorganic elements in fly ash and additives.

include the following measurements: pH, elemental composition, trace elements (As, B and Se) leaching and Ca ion concentrations (**Table 1**), thermogravimetric (TG) analysis, X-ray diffraction (XRD) analysis, and leachate analysis (pH, trace elements (As, B and Se) leaching and ions concentrations). This treatment technique, using additives addition, was examined in order to evaluate their effectiveness in the improvement of fly ash leaching properties. Additives may reduce the leachability of As, B and Se contained in ash by promoting the formation of ettringite or precipitation with calcium in ash, which are resistant to leaching. For the classification of untreated and treated ash samples, the procedure of standard leaching tests for fly ash (Notification No. 13 by the Environmental Agency of Japan) was employed as the protocol for leaching tests in this study.

Figure 2 depicts the leaching concentration of As, B, and Se for fly ash H alone and fly ash H under five kinds of additives addition for 5% and 10% Ca content samples, and pH values of leachate. As indicated in **Figure 2**, the results showed that the leaching concentrations of As, B, and Se in FAH tremendously decreased below the soil environmental standard in Japan for both 5% and 10% Ca content in additives and further decreased with the increase of Ca content. Especially, the leaching concentration of As, B, and Se reduced to 91–100% with Ca(OH)₂ addition. Among three kinds of paper sludge ashes (PS Ash



Figure 1. The experimental scheme of chemical stabilization process.

3, 4, 5) addition, As and B leaching concentrations reduced to 89–96% and 83–92%, respectively, with PS Ash 3 addition; and Se leaching concentration reduced to 87-96% with PS Ash 5 addition. While As and B leaching concentration did not influenced by filter cake (FC) addition (owing to the composition of FC is calcium carbonate based, which is not a water-soluble calcium compound (Figure 3)), but Se leaching concentration reduced to 58–78% (owing to the presence of Al₂O₃ and Fe₂O₃ in FC contributing for selenium to being hard to leach). Figure 3 depicts XRD patterns of several calcium compounds and additives. According to the leaching mechanism of selenium, Al₂O₃ and Fe₂O₃ may provide additional surface area for positively charged ions to be attached through the sorption reaction process, which made contributions to lower concentration of Se in aqueous solutions (FAH-FC mixture leachates) [122–124]. It is also indicated in Figure 2 that pH values of chemical treated products range from 9.23 to 12.98. It could be seen that the pH of mixture leachates increased with the addition of all additives excepting FC. Especially, pH values of FAH-Ca(OH), and FAH-Ps Ash 3 mixture leachates increased to approximately 12.98 and 11.94, respectively. This exhibited that relatively high CaO content included in PS Ash 3 and Ca(OH), itself being a water-soluble calcium compound could promote the pH values of leachates. However, FC which contained the highest CaO content did not have any influence on the pH values of mixture leachates, this was likely to be caused as calcium compound included in FC is composed of CaCO₃ being an insoluble substance in water (Figure 3). Figure 2 demonstrated that the minimum solubility of As, B, and Se was obtained when the pH of mixture leachates became 11.5 or higher. Obviously, higher pH

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Figure 2. Trace element leaching concentration for fly ash H alone, and fly ash H under five kinds of additives addition for 5% and 10% Ca content samples: (a) arsenic; (b) boron; and (c) selenium.



Figure 3. XRD Patterns of several calcium compounds and additives.

of mixture leachates in this study was favorable to lowering leaching concentrations of As, B, and Se and the mobility of As, B, and Se indeed decreased in **Figure 2**, implying that the efficiency of method in this study was susceptible to pH value of leachate. The results revealed that all additives (other than filter cake) showed a simultaneous leaching suppression effect of As, B, and Se from coal fly ash.

6. Conclusion

Treatment of trace elements (arsenic, boron, and selenium) contained in coal fly ash is a necessity to minimize leaching of trace elements and utilized in the best possible manner. Chemical stabilization of trace elements (arsenic, boron, and selenium) contained in coal fly ash offers a simple and low-cost environmentally friendly technique that if properly and thoroughly carried can bring our environment into a better place for both human and animal well-being due to its enormous advantages over other treatment methods. According to fly ash treatment through the addition of Ca-containing-additives experimental results, the leaching concentration of As, B, and Se can greatly be reduced simultaneously until 89–96%, 83–92%, and 87–96%, respectively. Paper sludge ash 3 as a waste generated in the papermaking process has been found as an effective and best additive (suppressing material) to reduce the leaching concentration of As, B, and Se from coal fly ash. Therefore, the chemical stabilization technique utilizing Ca-containing-additives is an effective technique for simultaneous suppressing As, B, and Se leaching from coal fly ash.

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References

- [1] World-Wide Coal Combustion Products Network (WWCCPN). 2017). [Accessed on March, 2017]. Available from: http://www.wwccpn.net/
- [2] American Coal Ash Association (ACAA). An American Recycling Success Story: Beneficial Use of Coal Combustion Products; 2015
- [3] Jia Y, Maurice C, Öhlander B. Effect of the alkaline industrial residues fly ash, green liquor dregs, and lime mud on mine tailings oxidation when used as covering material. Environmental Earth Sciences. 2014;**72**:319-334
- [4] Prasad B, Mortimer RJG. Treatment of acid mine drainage using fly ash zeolite. Water, Air, and Soil Pollution. 2011;**218**:667-679
- [5] Backstrom M, Sartz L. Mixing of acid rock drainage with alkaline ash leachates-fate and immobilisation of trace elements. Water, Air, and Soil Pollution. 2011;**222**:377-389
- [6] Pérez-López R, Cama J, Miguel Nieto J, Ayora C, Saaltink MW. Attenuation of pyrite oxidation with a fly ash pre-barrier: Reactive transport modelling of column experiments. Applied Geochemistry. 2009;24:1712-1723
- [7] Pérez-López R, Nieto JM, de Almodóvar GR. Utilization of fly ash to improve the quality of the acid mine drainage generated by oxidation of a sulphide-rich mining waste: Column experiments. Chemosphere. 2007;67:1637-1646
- [8] Gitari MW, Petrik LF, Etchebers O, Key DL, Iwuoha E, Okujeni C. Treatment of acid mine drainage with fly ash: Removal of major contaminants and trace elements. Journal of Environmental Science and Health, Part A. 2006:1729-1747
- [9] Carlson CL, Adriano DC. Environmental impacts of coal combustion residues. Journal of Environmental Quality. 1993;**22**:227-247
- [10] Jones DR. (1995). The leaching of major and trace elements from coal ash, In: Swaine, DJ, Goodarzi, F. eds. Environmental Aspects of Trace Elements in Coal, Dordrecht, the Netherlands: Kluwer Academic Publisher, Vol. 228, pp. 221-262

- [11] Kim AG, Kazonich G. Mass release of trace elements from coal combustion byproducts. In: International Ash Utilization Symposium. Lexington, KY: Center for Applied Energy Research, University of Kentucky; 1999
- [12] Mehnert E, Hensel BR. Coal combustion by-products and contaminant transport in groundwater. In: Coal Combustion By-Products Associated with Coal Mining Interactive Forum. Carbondale: Southern Illinois University at Carbondale, IL; 1996
- [13] U.S. Environmental Protection Agency (USEPA). 2014. Coal Combustion Residuals (CCR)—Surface Impoundments with High Hazard Potential Ratings. [Accessed March 1, 2015]. http://www.epa.gov/wastes/nonhaz/industrial/special/fossil/ccrs-fs/index.htm
- [14] Karapanagioti HK, Atalay AS. Laboratory evaluation of ash materials as acid disturbed land amendments. Global NEST Journal: The International Journal. 2001;**3**:11-21
- [15] Brunori C, Balzamo S, Morabito R. Comparison between different leaching/extraction tests for the evaluation of metal release from fly ASH. International Journal of Environmental Analytical Chemistry. 1999;75:19-31
- [16] Baba A, Kaya A. Leaching characteristics of fly ash from thermal power plants of Soma and Tunçbilek, Turkey. Environmental Monitoring and Assessment. 2004;91:171-181
- [17] Otero-Rey JR, Mato-Fernandez MJ, Moreda-Pineiro J, Alonso-Rodriguez E, Muniategui-Lorenzo S, Lopez-Mahia P, Prada-Rodriguez D. Influence of several experimental parameters on arsenic and selenium leaching from coal fly ash samples. Analytica Chimica Acta. 2005;531:299-305
- [18] Iwashita A, Sakaguchi Y, Nakajima T, Takanashi H, Ohki A, Kambara S. Leaching characteristics of boron and selenium for various coal fly ashes. Fuel. 2005;84:479-485
- [19] Jankowski J, Colin RW, French D, Groves S. Mobility of trace elements from selected Australian fly ashes and its potential impact on aquatic ecosystems. Fuel. 2006;85:243-256
- [20] Van der Hoek EE, Bonouvrie PA, Comans RNJ. Sorption of As and Se on mineral components of fly ash: Relevance for leaching processes. Applied Geochemistry. 1994;9:403-412
- [21] Cox JA, Lundquist GL, Przyjazny A, Schmulbach CD. Leaching of boron from coal ash. Environmental Science & Technology. 1978;12:722-723
- [22] Wang T, Wang J, Tang Y, Shi H, Ladwig K. Leaching characteristics of arsenic and selenium from coal fly ash: Role of Calcium. Energy & Fuels. 2009;23:2959-2966
- [23] Van der Hoek EE, Commans RNJ. Modelling As and Se leaching from acidic fly ash by sorption on iron (hydr) oxide in the fly ash matrix. Environmental Science & Technology. 1996;30:517-523
- [24] Jiao F, Ninomiya Y, Zhang L, Yamada N, Sato A, Dong Z. Effect of coal blending on the leaching characteristics of arsenic in fly ash from fluidized bed coal combustion. Fuel Processing Technology. 2012;106:769-775

- [25] Myneni SCB, Traina SJ, Waychunas GA, Logan TJ. Vibrational spectroscopy of functional group chemistry and arsenate coordination in ettringite. Geochimica et Cosmochimica Acta. 1998;62:3499-3514
- [26] Hartuti S, Kambara S, Takeyama A, Hanum FF. Leaching characteristic of arsenic in coal fly ash. Journal of Materials Science and Engineering B. 2017a;7:19-26
- [27] Hartuti S, Hanum FF, Takeyama A, Kambara S. Effect of additives on arsenic, boron and selenium leaching from coal fly ash. Minerals. 2017b;7:99
- [28] Hartuti S, Takeyama A, Kambara S. Arsenic leachability of coal fly ashes from different types of coal fired power plants. Journal of Materials Science and Engineering A. 2017c;7: 169-177
- [29] Astrup T. Management of APC Residues from W-t-E Plants An Overview of Management Options and Treatment Methods. 2nd ed; Produced by members of ISWA-WG (International Solid Waste Association-Working Group Thermal Treatment of Waste, Subgroup on APC Residues from W-t-E plants). ISWA, Copenhagen, 2008
- [30] Auer S, Kuzel HJ, Pollmann H, Sorrentino F. Investigation on MSW fly ash treatment by reactive calcium aluminates and phase formed. Cement and Concrete Research. 1995;25:1347-1359
- [31] Bournonville B, Nzihou A, Sharrock P, Depelsenaire G. Stabilization of heavy metal containing dusts by reaction with phosphoric acid: Study of the reactivity of fly ash. Journal of Hazardous Materials. 2004;**116**:65-74
- [32] Phair JW, Van Deventer JSJ, Smith JD. Effect of Al source and alkali activation on Pb and Cu immobilization in fly ash based geopolymers. Applied Geochemistry. 2004;**19**:423-434
- [33] Qian G, Zhang H, Zhang X, Chui P. Modification of MSW fly ash by anionic chelating surfactant. Journal of Hazardous Materials. 2005;121:251-258
- [34] Yang L. Evaluation of in situ chemical fixation for remediation of arsenic contaminated soil. PhD Dissertation. University of Alabama; 2005
- [35] Bhattacharyya S, Donahoe RJ, Patel D. Experimental study of chemical treatment of coal fly ash to reduce the mobility of priority trace elements. Fuel. 2009;88:1173-1184
- [36] Kim AG, Cardone C. Preliminary Statistical Analysis of Fly Ash Disposal in Mined Areas. Proc: 12th International Symposium on Coal Combustion By-Product Management and Use. American Coal Ash Association; 1997. Vol. 1. pp. 11-1 to 11-13
- [37] Kim AG, Kazonich G. Release of Trace Elements from CCB: Maximum Extractable Fraction. Proceedings 14th International Symposium on Management and Use of Coal Combustion Products (CCPs); 2001. Vol. 1. pp. 20-1 to 20-15
- [38] Ramezanianpour AA. Fly Ash. Cement Replacement Materials: Properties, Durability, Sustainability. Berlin, Heidelberg: Springer Berlin Heidelberg; 2014. pp. 47-156

- [39] American Society for Testing and Materials. Specification for Fly Ash and Raw of Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete. Philadelphia, PA, ASTM C618-78: ASTM; 1978
- [40] Mehta PK. Testing and correlation of fly ash properties with respect to pozzolanic behavior. Palo Alto, CA: Electric Power Research Institute; 1994, Report CS3314
- [41] Mehta PK. Pozzolanic and cementitious by-products as mineral admixtures for concrete—A critical review. In: Malhotra VM, editor. Proceedings of 1st International Conference on the Use of Fly Ash, Silica Fume, Slag, and Other Mineral By-products in Concrete, Montebello, PQ, July 31–Aug 5, 1983. Detroit, MI: American Concrete Institute; 1983, Special Publication SP-79
- [42] ACI Committee 226. Fly ash in concrete. ACI Materials Journal. 1987;84:381-409
- [43] Diamond S, Symposium N. Annual Meeting of the Materials Research Society, Boston, MA; 1981. pp. 12-23
- [44] Watt JD, Thorne DJ. Composition and pozzolanic properties of pulverized fuel ashes: Composition of fly ashes from some British power stations and properties of their component particles. Journal of Applied Chemistry. 1965;15:585-594
- [45] Liem H, Sandstrom M, Wallin T, Carne A, Rydevik U, Thurenius B, Moberg P. Studies on the leachate and weathering processes of coal ashes. Water Science and Technology. 1983;15:163
- [46] Hartlen J, Lundgren T. Disposal of waste material Evaluation in the KHM project of short and long-term effects. Water Science and Technology. 1983;15:49
- [47] E1-Mogazi E, Lisk D, Weinstein L. A review of physical, chemical, and biological properties of fly ash and effects on agricultural ecosystems. The Science of the Total Environment. 1988;74:1
- [48] Cheremisinoff P. Coal flyash: Power plant waste or by-product? Power Engineering. 1988;**92**(7):40
- [49] Tazaki K, Fyfe W, Sahu K, Powell M. Observation on the nature of fly ash particles. Fuel. 1989;68:727
- [50] Electric Power Research Institute (EPRI). Fly Ash Design Manual for Road and Site Applications, Vols. 1 and 2, EPRI TR-100472; 1992, Project 2422-2
- [51] Hansen LD, Fisher GL. Elemental distribution in coal fly ash particles. Environmental Science & Technology. 1980;14:1111-1117
- [52] Jegadeesan G, Al-Abed SR, Pinto P. Influence of trace metal distribution on its leachability from coal fly ash. Fuel. 2008;87:1887-1893
- [53] Choi SK, Lee S, Song YK, Moon HS. Leaching characteristics of selected Korean fly ashes and its implications for the groundwater composition near the ash mound. Fuel. 2002;81:1080-1090

- [54] Galbreath KC, Zygarlicke CJ. Formation and chemical speciation of arsenic-, chromium-, and nickel-bearing coal combustion PM 2.5. Fuel Processing Technology. 2004;85:701-726
- [55] Świetlik R, Trojanowska M, Jóźwiak MA. Evaluation of the distribution of heavy metals and their chemical forms in ESP-fractions of fly ash. Fuel Processing Technology. 2012;95:109-118
- [56] Eary LE, Rai D, Mattigod SV, Ainsworth CC. Geochemical factors controlling the mobilization of inorganic constituents from fossil fuel combustion residues: II. Review of the minor elements. Journal of Environmental Quality. 1990;19:202-214
- [57] Vorres KS. Chemistry of mineral matter and ash in coal: An overview. In: Mineral Matter and Ash in Coal, ACS Symposium Series. Washington, DC: American Chemical Society; 1986. pp. 1-8
- [58] Ugurlu A. Leaching characteristics of fly ash. Environmental Geology. 2004;46:890-895
- [59] Fernandez-Turiel JL, de Carvalho W, Cabanas M, Querol X, Lopez-Soler A. Mobility of heavy metals from coal fly ash. Environmental Geology. 1994;**23**:264-270
- [60] Merrick D. Trace Elements from Coal Combustion: Emission. London, UK: IEA Coal Research; 1987
- [61] Kalogirou E, Themelis N, Samaras P, Karagiannidis A, Kontogianni S. Fly Ash Characteristics From Waste-to-Energy Facilities and Processes For Ash Stabilization. In: Proceedings of ISWA World Congress 2010, Hamburg, Germany, 15-18 November; 2010
- [62] Zielinski RA, Foster AL, Meeker GP, Brownfield IK. Mode of occurrence of arsenic in feed coal and its derivative fly ash, Black Warrior Basin, Alabama. Fuel. 2007;86:560-572
- [63] Yudovich YE, Ketris MP. Arsenic in coal: A review. International Journal of Coal Geology. 2005;61:141-196
- [64] Cornelis G, Johnson CA, Gerven TV, Vandecasteele C. Leaching mechanisms of oxyanionic metalloid and metal species in alkaline solid wastes: A review. Applied Geochemistry. 2008;23:955-976
- [65] Hassett DJ, Pflughoeft-Hassett DF, McCarthy GJ. Ettringite formation in coal ash as a mechanism for stabilization of hazardous trace elements. Proc: 9th Int. Ash Use Symp. 2, 31-1 to 31-17; 1991
- [66] Lecuyer I, Bicocchi S, Ausset P, Lefevre R. Physico-chemical characterization and leaching of desulfurization coal fly ash. Waste Management and Research. 1996;14:15-28
- [67] Rajan SSS. Adsorption and desorption of sulfate and charge relationships in allophonic clays. Soil Science Society of America Journal. 1979;43:65-69
- [68] Jankowski J, Ward CR, French D. Preliminary Assessment of Trace Element Mobilization from Australian Fly Ashes. Co-operative Research Centre for Coal in Sustainable Development, Research Report 45; 2004. 44 pp. http://pandora.nla.gov.au/pan/64389/20 080828-1328/www.ccsd.biz/publications/425.html

- [69] Izquierdo M, Querol X. Leaching behaviour of elements from coal combustion fly ash: An overview. International Journal of Coal Geology. 2012;94:54-66
- [70] Dreesen DR, Gladney ES, Owens JW. Comparison of levels of trace elements extracted from fly ash and levels found in effluent waters from a coal-fired power plant. Environmental Science and Technology. 1977;11:1017-1019
- [71] Hassett DJ, Pflughoeft-Hassett DF, Heebink LV. Leaching of CCBs: Observations from over 25 years of research. Fuel. 2005;84:1378-1383
- [72] Nidheesh PV, Singh TSA. Arsenic removal by electrocoagulation process: Recent trends and removal mechanism. Chemosphere. 2017;**181**:418-432
- [73] IPCS (International Program on Chemical Safety) and WHO (World Health Organization). Environmental Health Criteria for Arsenic and Arsenic Compounds. Geneva: GreenFacts; 2001
- [74] Henke KR, Hutchison A. Arsenic chemistry. In: Arsenic: Environmental Chemistry, Health Threats and Waste Treatment. Hoboken, New Jersey: John Wiley & Sons, Ltd; 2009. pp. 9-68
- [75] Henke KR. Arsenic in natural environments. In: Arsenic: Environmental Chemistry, Health Threats and Waste Treatment. Hoboken, New Jersey: John Wiley & Sons, Ltd; 2009. pp. 69-235
- [76] IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Arsenic, metals, fibres, and dusts. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. 2012;100:11-465
- [77] Jiang JQ. Removing arsenic from groundwater for the developing world-a review. Water Science and Technology. 2001;44:89-98
- Singh R, Singh S, Parihar P, Singh VP, Prasad SM. Arsenic contamination, consequences and remediation techniques: A review. Ecotoxicology and Environmental Safety.
 2015;112:247-270
- [79] Chung JY, Yu S, Do Hong YS. Environmental source of arsenic exposure. Journal of Preventive Medicine and Public Health. 2014;47:253-257
- [80] Al-Abed SR, Jegadeesan G, Purandare J, Allen D. Arsenic release from iron rich mineral processing waste: Influence of pH and redox potential. Chemosphere. 2007;**66**:775-782
- [81] Duarte AALS, Cardoso SJA, Alçada AJ. Emerging and innovative techniques for arsenic removal applied to a small water supply system. Sustainability. 2009;1:1288-1304
- [82] Song S, Gallegos-Garcia M. Arsenic removal from water by the coagulation process. In: Fanun M, editor. The Role of Colloidal Systems in Environmental Protection. Elsevier; 2014. pp. 261-277
- [83] Jay Murray F. A human health risk assessment of boron (boric acid and borax) in drinking water. Regulatory Toxicology and Pharmacology. 1995;22:221-230

- [84] Sahin S. A mathematical relationship for the explanation of ion exchange for boron removal. Desalination. 2002;**143**:35-43
- [85] Tu KL, Ngheim LD, Chivas AR. Boron removal by reverse osmosis membranes in seawater desalination. Separation and Purification Technology. 2010;75:87-101
- [86] Power PP, Woods WG. The chemistry of boron and its speciation in plants. Plant and Soil. 1997;**193**:1-13
- [87] Isa MH, Ezechi EH, Ahmed Z, Magram SF, Kutty SRM. Boron removal by electrocoagulation and recovery. Water Research. 2014;51:113-123
- [88] Wyness AJ, Parkaman RH, Neal C. A summary of boron surface water quality data throughout the European Union. Science of the Total Environment. 2003;314-316:255-269
- [89] Wolska J, Bryjak M. Methods for boron removal from aqueous solutions A review. Desalination. 2013;310:18-24
- [90] RACI (Royal Australian Chemical Institute). 2011. Selenium. Available at: www.raci. org.au
- [91] Sandy T, DiSante C. Review of Available Technologies for the Removal of Selenium from Water. Englewood, Colorado: CH2M HILL Inc; 2010. pp. 2-223
- [92] Moore L, Mahmoudkhani A. Methods for removing selenium from aqueous systems. In: Proceedings Tailings and Mine Waste 2011, Vancouver, BC, November 6 to 9; 2011
- [93] Sabbas T, Polettini A, Pomi R, Astrup T, Hjelmar O, Mostbauer P, Cappai G, Magel G, Salhofer S, Speiser C. Management of municipal solid waste incineration residues. Waste Management. 2003;23:61-88
- [94] Fruergaard T, Astrup T. Life cycle assessment of management of APC residues from waste incineration. In: Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium, Sardinia, Italy, 1-5 October; 2007
- [95] Lundtorp K. The Ferrox-process in an industrial scale Developing a stabilization process for air pollution control residues from municipal solid waste incineration. PhD Thesis. Technical University of Denmark, Environment & Resources DTU; 2001
- [96] Hong KJ, Tokunaga S, Ishigami Y, Kajiuchi T. Extraction of heavy metals from MSW incinerator y ash using saponins. Chemosphere. 2000;**41**:345-352
- [97] Bosshard PP, Bachofen R, Brandl H. Metal leaching of y ash from municipal waste incineration by *Aspergillus niger*. Environmental Science and Technology. 1996;**30**:3066-3070
- [98] Pedersen AJ, Ottosen LM, Villumsen A. Electrodialytic removal of heavy metals from different fly ashes - Influence of heavy metal speciation in the ashes. Journal of Hazardous Materials. 2003;100:65-78
- [99] Crillesen K. Information about the "Askepot" Project, Personal Communication. Denmark: I/S Vestforbraending; 2005

- [100] Quina MJ, Bordado JC, Quinta-Ferreira RM. Treatment and use of air pollution control residues from MSW incineration: An overview. Waste Management. 2008;**28**:2097-2121
- [101] Gong B, Deng Y, Yang Y, He Y, Sun X, Ge L-Y, et al. Stabilization of lead in incineration fly ash by moderate thermal treatment with sodium hydroxide addition. PLoS One. 2017;12(6):e0178816
- [102] Chi M. Effects of modulus ratio and dosage of alkali-activated solution on the properties and microstructural characteristics of alkali-activated fly ash mortars. Construction and Building Materials. 2015;99:128-136
- [103] Lundtorp K, Jensen DL, Christensen TH. Stabilization of APC residues from waste incineration with ferrous sulfate on a semi-industrial scale. Journal of the Air & Waste Management Association. 2002;52:722-731
- [104] Ecke H, Menad N, Lagerkvist A. Carbonation of municipal solid waste incineration fly ash and the impact on metal mobility. Journal of Environmental Engineering. 2003:435-440
- [105] Jiang J, Chen M, Zhang Y, Xu X. Pb stabilization in fresh fly ash from municipal solid waste incinerator using accelerated carbonation technology. Journal of Hazardous Materials. 2009;161(2-3):1046-1051
- [106] Hjelmar O, Birch H, Hansen JB. Development of a process for treatment of air pollution control residues from MSW incinerators prior to landfilling. In: Christensen TH, Cossu R, Stegmann R, editors. Seventh International Waste Management and Landfill Symposium, 543-548. Sardinia, CISA, Italy. 1999
- [107] Kim S, Matsuto T, Tanaka N. Evaluation of pre-treatment methods for landfill disposal of residues from municipal solid waste incineration. Waste Management & Research. 2003;21:416-423
- [108] Youcai Z, Lijie S, Guojian L. Chemical stabilization of MSW incinerator fly ashes. Journal of Hazardous Materials. 2002;**B95**:47-63
- [109] Vandecasteele C, Dutr'e V, Geysen D, Wauters G. Solidification/stabilisation of arsenic bearing fly ash from the metallurgical industry. Immobilisation Mechanism of Arsenic, Waste Management. 2002;22:143-146
- [110] Dutre V, Vandecasteele C. Immobilization of arsenic in waste solidified using cement and lime. Environmental Science & Technology. 1998;32:2782-2787
- [111] Zacco A, Gianoncelli R, Ardesi S, Sacrato LG, Bontempi E. Use of colloidal silica to obtain a new inert from municipal solid waste incinerator (MSWI) fly ash: First results about reuse. Clean Technologies and Environmental Policy. 2012;14(2):291-297
- [112] Rodella N, Bosio A, Zacco A, Borgese L, Pasquali M, Dalipi R, Depero LE, Patel V, Bingham PA, Bontempi E. Arsenic stabilization in coal fly ash through the employment of waste materials. Journal of Environmental Chemical Engineering. 2014;2:1352-1357

- [113] Conner JR, Hoeffner SL. A critical review of stabilization/solidification technology. Critical Reviews in Environmental Science and Technology. 1998;**28**:397-462
- [114] Todorovic J, Ecke H, Lagerkvist A. Solidification with water as a treatment method for air pollution control residues. Waste Management. 2003;23:621-629
- [115] IAWG (International Ash Working Group), Chandler AJ, Eighmy TT, Hartlen J, Hjelmar O, Kosson DS, Sawell SE, van der Sloot HA, Vehlow J. Municipal Solid Waste Incinerator Residues. Studies in Environmental Science. Amsterdam: Elsevier Science; 1997. p. 67
- [116] Margallo M, Taddei MBM, HernaÂndez-PelloÂn A, Aldaco R, Irabien AÂ. Environmental sustainability assessment of the management of municipal solid waste incineration residues: A review of the current situation. Clean Technologies and Environmental Policy. 2015;17(5):1333-1353
- [117] Lindberg D, Molin C, Hupa M. Thermal treatment of solid residues from WtE units: A review. Waste Management. 2015;37:82-94
- [118] Sakai S, Hiraoka M. Municipal solid waste incinerator residue recycling by thermal processes. Waste Management. 2000;20:249-258
- [119] Wey MY, Liu KY, Tsai TH, Chou JT. Thermal treatment of the fly ash from municipal solid waste incinerator with rotary kiln. Journal of Hazardous Materials. 2006;137(2):981-989
- [120] Ecke H, Sakanakura H, Matsuto T, Tanaka N, Lagerkvist A. State-of-the-art treatment processes for municipal solid waste incineration residues in Japan. Waste Management and Research. 2000;18:41-51
- [121] Hartuti S, Kambara S, Takeyama A, Kumabe K, Moritomi H. Direct quantitative analysis of arsenic in coal fly ash. Journal of Analytical Methods in Chemistry. 2012;2012:438,701
- [122] Cervera ML, Arnal MC, de la Guardia M. Removal of heavy metals by using adsorption on alumina or chitosan. Analytical and Bioanalytical Chemistry. 2003;375:820-825
- [123] Su T, Guan XH, Gu GW, Wang JM. Adsorption characteristics of As(V), Se(IV) and V(V) onto activated alumina: Effects of pH, surface loading, and ionic strength. Journal of Colloid and Interface Science. 2008;**326**:347-353
- [124] Cornell RM, Schwertmann U. The Iron Oxides: Structure, Properties, Reactions, Occurrences and Uses. 2nd ed. Weinheim, Germany: Wiley-VCH; 2003



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