

## Review Article

# Review on Cement Stabilization/Solidification of Municipal Solid Waste Incineration Fly Ash

Chengcheng Fan, Baomin Wang, and Tingting Zhang 

*Institute of Building Materials, School of Civil Engineering, Dalian University of Technology, Dalian 116024, China*

Correspondence should be addressed to Tingting Zhang; [tingtingzhang@dlut.edu.cn](mailto:tingtingzhang@dlut.edu.cn)

Received 8 August 2018; Accepted 27 September 2018; Published 29 October 2018

Academic Editor: Ling B. Kong

Copyright © 2018 Chengcheng Fan et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Municipal solid waste incineration (MSWI) fly ash must be treated properly prior to being disposed in the security landfill due to its serious pollution toxicity. Nowadays, lots of studies have demonstrated that cement-based stabilization/solidification could reduce the toxicity pollution effectively by encapsulating the heavy metals into cement matrix, which leads to greater capacity and weight. This paper compares and discusses the MSWI fly ash treatment with the mostly used matrix materials such as Portland cement, phosphate cement, aluminate cement, and alkaline activated cement. Moreover, immobilization mechanism introduced by the interaction between the MSWI fly ash and hydrated cement matrix materials, such as the physical cementing effect, adsorption, isomorphous replacement, and complex precipitation, was explored in depth. The paper also pointed out some reasonable development directions for cement-based stabilization/solidification technology to improve the effectiveness and application of cement-based stabilization/solidification technology.

## 1. Introduction

Waste incineration technology has been widely used globally because it can achieve the goal of harmlessness, waste minimization, and resource utilization of municipal solid waste incineration. Nonetheless, there will be a large amount of MSWI fly ash coupled with various types of toxic heavy metal materials with high concentration after the incineration, accounting about 3 to 5 percent of the total waste, which not only has severely restricted the enterprise's survival and development, but also causes a great threat to the human survival environment and health. Therefore, disposing MSWI fly ash and solving the problem of heavy metal pollution properly is a task which brooks no delay.

Nowadays, cement-based stabilization/solidification technology has been widely used all over the world for 60 years, it and has become an economic efficiency approach to immobilize toxic and harmful heavy metal in the MSWI fly ash by being fixed in the hydration products, such as calcium silicate hydrate gel (C-S-H) and ettringite (AFt) which were formed by chemical reaction between cement and water [1–4]. Besides, the advantages of cement-based stabilization/solidification not only have simple operation and low processing cost, but also

significant reduction of percolation of heavy metal ions in the hazardous waste landfill, which could meet the Standard for Pollution Control on the Security Landfill. Thus, the United States Environmental Protection Agency (EPA) has considered the method as the best way to deal with poisonous and harmful waste in the world so far [5].

On the basis of existing research, this paper made a comparative analysis on the effect of MSWI fly ash immobilized with different types of cementitious materials, such as Portland cement, phosphate cement, aluminate cement, and alkaline activated cement, and then further explored the influence factors and immobilization mechanism through the interactions between cement hydration products and heavy metals. Moreover, some suggestions were also put forward on the application and development of cement-based stabilization/solidification technology in the next studies.

## 2. Characteristics of MSWI Fly Ash

Comparative analysis of MSWI fly ash around the world showed that the composition of MSWI fly ash was relatively complicated. It not only consisted of silicate, chlorine salt, calcium hydroxide, and sulfate, but also absorbed a lot of the

poisonous and harmful substances in the flue gas, including dioxins, furans, mercury (Hg), copper (Cu), lead (Pb), manganese (Mn), cadmium (Cd), chromium (Cr), nickel (Ni), and so on [6, 7], which had already become a serious threat to the ecological environment, food safety, and human health. However, the organic matters would decompose and evaporate during the incineration process, and its content in the MSWI fly ash was generally below 2%, thus it meant that the treatment and remediation of heavy metals had become the main target in the stabilization/solidification process of MSWI fly ash. Moreover, once heavy metals caused harm to human health and natural environment, it would be serious, long-term, latent, cumulated, and irreversible [8–10]. Therefore, finding the solutions to solve the heavy metal pollution of MSWI fly ash has become a top priority. Tables 1 and 2 summarize the sources and chemical speciation of heavy metals in the MSWI fly ash, which could provide some theory guidance for the MSWI fly ash immobilization study in the following.

### 3. Effect of Different Cementitious Matrix Materials on MSWI Fly Ash Immobilization

**3.1. Portland Cement.** Lombardi et al. and Poletini et al. [11, 12] reported that cement could effectively immobilize contaminants, but the compressive strength will be reduced and leaching concentration will be increased when the MSWI fly ash addition is increased. Also, Dermatas and Meng [13] pointed out that the most obvious shortcoming of cement stabilization/solidification was high capacity, weight increased rate, and poor long-term stability. The capacity and weight increased rate was up to 2.0. However, when the MSWI fly ash was prewashed with water, phosphoric acid, or other solutions before cement-based stabilization/solidification, it would drastically reduce the toxicity of heavy metals and reduce the consumption of cement. However, there was still tricalcium aluminate ( $C_3A$ ) in the cement solidified body after the 28-day curing period, but  $C_3A$  would greatly reduce its compressive strength [14], and it was difficult for Portland cement solidified body to achieve high mechanical strength whether the MSWI fly ash was pretreated or not [15].

What is more, some literature studies proposed that some heavy metals in the MSWI fly ash such as  $Cr^{6+}$ ,  $Cd^{2+}$ ,  $Pb^{2+}$ , and  $Cu^{2+}$  could dramatically accelerate  $C_3S$  hydration whether it was in the late or initial stage of hydration reaction, but the  $Zn^{2+}$  only promoted the  $C_3S$  hydration during the later period of hydration [16, 17]. But some studies reported that heavy metals would delay the cement hydration to some extent. In detail,  $Cu^{2+}$  and  $Pb^{2+}$  usually bound on the surface of cement clinker particles in the form of insoluble salt, such as carbonates and sulfates, which inhibited the cement hydration. Ma et al. [18] proposed that Cu, Zn, and Pb could not obviously change the cement hydration process according to the analysis of XRD spectrum, and Cu, Zn, and Pb were immobilized within cement hydration products through a series of effect mechanism, such as physical fixation and adsorption mechanisms. Vogg et al. [19] pointed out that heavy metals would leak out little by little in an acidic environment, but there would be no

detection of Cd, Cu, Pb, and Zn under the condition at pH value of 10.0.

**3.2. Phosphate Cement.** Magnesium phosphate cement was also used to immobilize MSWI fly ash, the reason of which was not only the alkalescence of potassium phosphate cement with the characteristic of dense structure and high strength, but also the widespread use of phosphate as curing agents. It was found that the compressive strength and leaching toxicity for magnesium phosphate cement on  $Cr^{3+}$ ,  $Pb^{2+}$ ,  $Ni^{2+}$ ,  $Cd^{2+}$ , and  $Zn^{2+}$  could meet the national corresponding standards [20–22]. On the one hand, there were some macropores and gassy surface in the light burned magnesia powder crystal with a high activity, which brought the strong adsorption for heavy metals. On the other hand, magnesia powder with higher activity could give impetus to the violent reaction with magnesium salt solution and chemical precipitation of heavy metals [23]. Therefore, it was easy for magnesium hydroxide to absorb and remove heavy metals from industrial waste water under the help of its high specific surface area and adsorption capacity.

Besides, the solidification effect on  $Pb^{2+}$  of magnesium phosphate cement would be more prominent in contrast with other heavy metals. It was the results from both chemical reaction and physical encapsulation. On the one hand,  $Pb^{2+}$  was more likely to react with  $PO_4^{3-}$  and  $HPO_4^{2-}$ , and then generate insoluble phosphate precipitation containing Pb. Moreover, the heavy metals could be encapsulated securely because of compact reticular structure of magnesium phosphate cement, in which the radioactive elements can be solidified effectively as well [24–26]. And the heavy metals such as Pb, Cd, and Cr almost could not be detected when the addition of magnesium potassium phosphate cement was up to 40%. Besides, it was noted that the leaching concentration of heavy metals always followed a descending order of  $Cu > Zn > Ni > Pb > Cd > Cr$  when eluviated in different leaching environments.

**3.3. Aluminate Cement.** There were very few studies on the heavy metals immobilization in aluminate cement and sulphoaluminate cement. But Sahu et al. and Luo et al. [27–29] found that sulphoaluminate cement could also reduce the leaching toxicity of heavy metals, and it might be prone to fix  $Pb^{2+}$  than  $Zn^{2+}$ ,  $Cd^{2+}$ , and  $Cu^{2+}$  due to the selectivity of its hydration products. Besides, the heavy metals mainly deposited in the complex chemical speciation. For example,  $Pb^{2+}$  is mainly in the form of  $2PbCO_3 \cdot Pb(OH)_2$ ;  $Cd^{2+}$  mainly exists in the form of  $CdPbO_3$ . Overall, the adsorption stability of  $Pb^{2+}$ ,  $Cu^{2+}$ ,  $Cd^{2+}$ , and  $Zn^{2+}$  immobilized by sulphoaluminate cement is good, especially for  $Pb^{2+}$ .

**3.4. Alkaline Activated Cement.** Alkaline activated cement is a kind of cementitious material formed by reaction of the alkaline activator and materials with volcanic activity or latent hydraulicity. The chemical reactions including the precipitation of calcium silicoaluminate gel (CASH) and sodium

TABLE 1: Source of heavy metals in MSWI fly ash.

Heavy metal	Source
Pb	Gasoline additives, ammunition, solder, paint, pesticide
Hg	Electrical manufacturing, pharmaceuticals, paints, plastics, paper, batteries, coal, mercury smelters, and mercury preparation plants
Cd	Plastic, enamels with pigment, electroplating, metal covering
Cr	Mine, smelting plant, electroplating factory, chrome tanning system
As	Atmospheric dust, tailings and pesticide, leather, chemical pharmaceutical, metallurgy, decolorant
Cu	Mine, metal processing, machinery manufacturing, steel production
Zn	Galvanizing, smelting, machinery manufacturing, organic synthesis, mine

TABLE 2: Chemical speciation of heavy metals in MSWI fly ash.

Heavy metal	Speciation
Pb	PbCl <sub>2</sub> , PbCO <sub>3</sub> , PbO, Pb <sub>3</sub> SiO <sub>3</sub> , Pb <sub>3</sub> SiO <sub>4</sub> , Pb <sub>3</sub> O <sub>2</sub> SO <sub>4</sub> , Pb <sub>3</sub> Sb <sub>2</sub> O <sub>7</sub>
Cd	Cd(OH) <sub>2</sub> , CdO, CdSO <sub>4</sub> , CdCl <sub>2</sub> , CdSiO <sub>4</sub>
Zn	ZnCl <sub>2</sub> , ZnO, Zn(OH) <sub>2</sub> , ZnCO <sub>3</sub> , ZnSO <sub>4</sub> , K <sub>2</sub> ZnCl <sub>4</sub>
Fe	Fe <sub>2</sub> O <sub>3</sub> , Fe <sub>3</sub> O <sub>4</sub>
Cu	Cu(OH) <sub>2</sub> , CuO, CuCO <sub>3</sub>

TABLE 3: MSWI fly ash immobilized with different cementitious matrix materials.

Cement	Advantages	Disadvantages
	(1) Simple operation	(1) High capacity and weight increased rates
Portland cement	(2) Low cost (3) Moderate compressive strength	(2) Poor long-term security and stability
Phosphate cement	(1) High compressive strength (2) Good dry shrinkage (3) Low cost	(1) High capacity and weight increased rates (2) Poor long-term security and stability
Aluminate cement	(1) Simple operation (2) Low cost	(1) High capacity and weight increased rates (2) Poor stability (3) Poor dry shrinkage
Alkali activated cement	(1) High compressive strength (2) Low cost (3) Good long-term security and stability	(1) High capacity and weight increased rates (3) Poor dry shrinkage

silicoaluminate gel (NASH) may occur during the process of setting and hardening, then forming a three-dimensional aluminum silicate network structure which consists of AlO<sub>4</sub> and SiO<sub>4</sub> tetrahedral structure units, which could be used to seal the contaminants tightly in the cavity [30, 31].

Zak and Deja [32] used chemical reagents to synthesize C-S-H, CASH, and NASH, and then found that Zn<sup>2+</sup>, Cd<sup>2+</sup>, Pb<sup>2+</sup>, Cr<sup>3+</sup>, and Cr<sup>6+</sup> inhibited the synthesis of C-S-H, CASH, and NASH structures, and C-S-H and NASH could immobilize heavy metal at the degree of 99.9% and 93.1%, respectively. It could be deduced that the alkaline activated cement could be used to seal heavy metals, which was in line with the conclusion from Davidovits [33]; meanwhile, he also stated that the network skeleton of alkaline activated cement was of perfect stability even though under nuclear radiation.

From the above, cement-based stabilization/solidification could effectively fix the heavy metal in the cement with the advantages of simple operation, low cost, and high strength of cement solidified body, but it also gave rise to poor stability, high capacity, and weight increased rate. Furthermore, it should be noted that the cement-based stabilization/solidification of MSWI fly ash just belonged to temporary concentration control, which could not guarantee its long-term security and stability, especially under the acid environment. Moreover, it was indeed feasible to fix the MSWI fly ash with cement when mixed with little MSWI fly ash, but it was hard to ensure that the performances of cement solidified body meet the national landfill standards with increased MSWI fly ash. If there were special salts in the MSWI fly ash, the salts would hinder the cement-hardening process and weaken its mechanical strength, leading to high leaching rates of heavy metals.

Comparative analysis of the effect of different cementitious matrix materials on MSWI fly ash immobilization was summarized in Table 3. There are lots of smaller capillary pores in the magnesium phosphate cement,

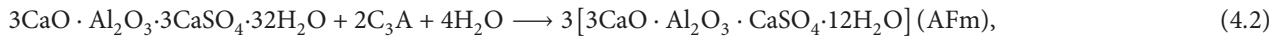
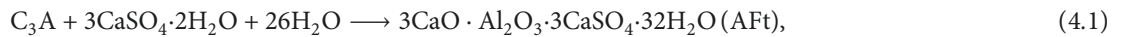
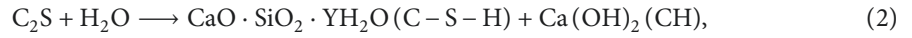
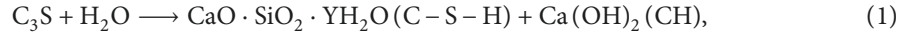
resulting in a more compact microstructure, thus it could immobilize the heavy metals more effectively in theory. However, what calls for special attention is that magnesium phosphate cement would lose the strength and burst into fragments when exposed to the humid environment for a long time due to the poor water resistance, which would put the disposal of MSWI fly ash at risk. Alkaline activated cement was of the ideal performances, including excellent mechanical properties and durability, whereas shrinkage cracking and weak anticarbonization were the two fatal flaws of this material, which would result in secondary pollution to the environment, ultimately affecting the health of human beings. It can be concluded from these literature studies that the solidification effect of these cementitious materials on MSWI fly ash is alkali activated cement > magnesium phosphate cement > Portland cement > aluminate cement.

#### 4. Immobilization Mechanisms

During the process of cement hydration, heavy metals eventually settled in the cement hydration products in the form of hydroxide or complex by reacting with cement by means of the physical cementing effect, chemical absorption,

isomorphous replacement, and complex precipitation. Meanwhile, cement also provides the alkaline environment for solidified body so as to effectively inhibit the infiltration of heavy metals. Besides, these hydration products including C-S-H, AFt, single sulfur hydrated calcium thioaluminate (AFm), and CASH, rather than calcium hydroxide, were

difficult to dissolve, and these insoluble hydrated products would play important roles during heavy metal immobilization. Thus, the immobilization of MSWI fly ash in cement-based stabilization/solidification was investigated in depth mainly from these aspects such as hydration products and immobilization effect.



**4.1. C-S-H.** C-S-H is a type of amorphous microporous phase with high specific surface area and high-density hydrogen bonding, which could tightly bind heavy metals with strong chemical adsorption. In general, the C-S-H colloid of rich calcium with positive charges on the surface has preferential adsorption of anions including  $OH^-$ ,  $Cl^-$ ,  $SO_4^{2-}$ , and so on, but the C-S-H colloids of rich silicon are preferentially adsorbed cations [34]. Furthermore, it was confirmed that the adsorption of heavy metals is always significantly influenced by pH value, and it would decrease obviously when the pH value surpasses 9.0 [35].

In addition to this, C-S-H had significant cation exchange capacity, and some heavy metals such as  $Cr^{6+}$ ,  $Cd^{2+}$ ,  $Zn^{2+}$ , and  $Pb^{2+}$  often had stronger adsorption affinity in contrast with alkali metal ions. The heavy metals were thus prone to ions exchange, and they would then stabilize in the lattice.  $Ca^{2+}$ ,  $Al^{3+}$ , and  $Si^{4+}$  in the cement solidified body are easily replaced by heavy metal cation, and  $SO_4^{2-}$  and  $OH^-$  can be easily replaced by heavy metal anions [36]. Similarly,  $Zn^{2+}$  could replace the  $Ca^{2+}$  in C-S-H or react with Ca to produce the oxides or hydroxides containing Ca and Zn [37]. Moreover,  $Cr^{3+}$  could be combined into C-S-H by replacing  $Si^{2+}$  in C-S-H [38], and  $CrO_4^{2-}$  could be fixed in the cement solidified body by replacing  $SO_4^{2-}$ .

However,  $Pb^{2+}$  in C-S-H cannot replace  $Ca^{2+}$ , but it can be fixed in C-S-H in the form of hydroxide precipitation and carbonate precipitation, while Pb-C-S-H was observed by means of X-ray photoelectron spectroscopy (XPS) and SEM/EDS in the research of Cocke [39]. It should be noted that weak alkaline environment could further retard leaching toxicity of heavy metals in cement solidified body in most cases. It should be noted that hydroxide precipitation occurs when the pH value of leaching solution dissolved heavy metals is raised to some optimum level for a specific metal. Table 4 exhibits that the optimum pH value is always different for each metal and for different valence states of

a single metal. For example, the leaching rates for  $Cd^{2+}$  decreased when the pH value is more than 8.0, and  $Pb^{2+}$  leached to the least when the pH value is 10.3 [40, 41].

**4.2. AFt and AFm.** AFt phase,  $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ , is one of the main hydration products of cement, but it can be easily changed into AFm ( $Ca_2Al(OH)_6 \cdot 0.5X \cdot H_2O$ ) when chloride or sulfate is insufficient. As shown in Figure 1, AFt phases are chemically and mineralogically complex, in which columns of  $Ca_6Al(OH)_6 \cdot 24H_2O$  are lines of  $Al(OH)_6^{3-}$  octahedrally bonded with three calcium polyhedrons, and each calcium polyhedron is with  $OH^-$  and four water molecules, which presents an orientational column structure on the whole.

In most cases, AFt can absorb and immobilize the heavy metals through the isomorphous replacement and chemical adsorption; a plenty of studies demonstrated that AFt have a very strong lattice binding effect on heavy metal ions. For example, Cs, Sn, and other metal ions could also be adsorbed on the cylinder surface of AFt [42, 43]. On the one hand,  $Cd^{2+}$ ,  $Ni^{2+}$ ,  $Zn^{2+}$ ,  $Pb^{2+}$ , and  $Co^{2+}$  could replace  $Ca^{2+}$ , and  $Cr^{3+}$ ,  $Ti^{3+}$ ,  $Mn^{3+}$ ,  $Si^{4+}$ , and  $Fe^{3+}$  can replace  $Al^{3+}$  in AFt; on the other hand,  $Cl^-$ ,  $CO_3^{2-}$ ,  $SeO_4^{2-}$ ,  $BrO_3^-$ ,  $AsO_4^{2-}$ , and  $ClO_3^-$  can replace  $SO_4^{2-}$  [44–47]. Besides, Sabine and Lan et al. found that  $Cr^{3+}$ ,  $CrO_4^{2-}$ , and  $Cr_2O_7^{2-}$  can get inside the AFt lattice and then stabilize in the AFt phases. Tashiro et al. [48–50] found that heavy metal oxides and hydroxides could promote the formation and crystal growth of ettringite and produce some changes in microstructure and  $Cr_2O_3$  and  $Cu(OH)_2$  exert a considerable influence. Similar to AFt,  $Ca^{2+}$ ,  $Al^{3+}$ ,  $CO_3^{2-}$ , and  $SO_4^{3-}$  in AFm phases are easy to be replaced by other ions, and AFm have a more stable structure than AFt. Several studies have been put forward to explain that AFm could effectively reduce the content of heavy metal ions in the water, such as  $Cr^{3+}$ ,  $CrO_4^{2-}$ ,  $Cd^{2+}$ ,  $B^{3+}$ ,  $Se^{6+}$ , and so on [44, 51, 52].

TABLE 4: Optimum pH value of heavy metal precipitates.

Heavy metals	$\text{Cd}(\text{OH})_2$	$\text{Pb}(\text{OH})_2$	$\text{Fe}(\text{OH})_2$	$\text{Zn}(\text{OH})_2$	$\text{Cu}(\text{OH})_2$
pH value	11.0	9.7	7.2	6.7	5.5

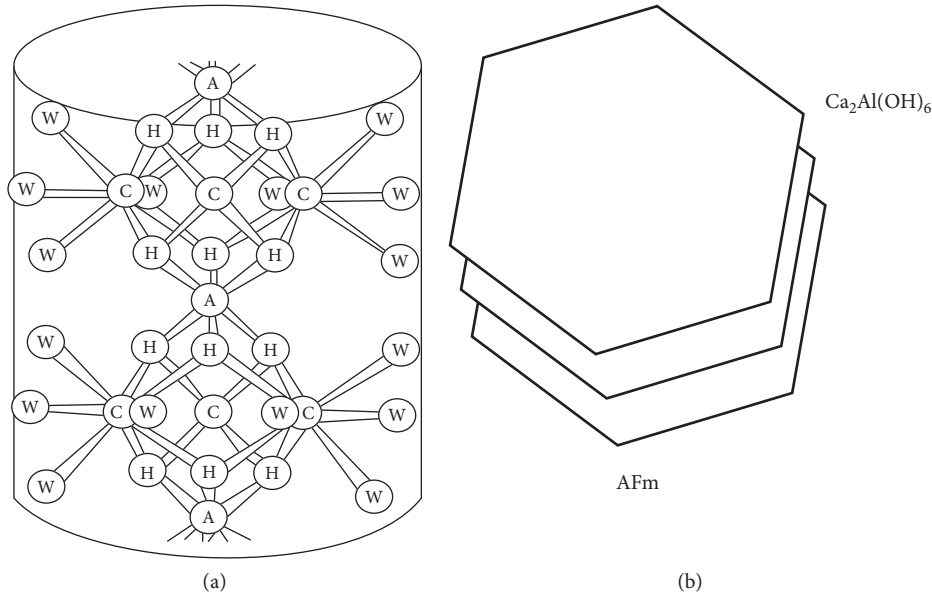


FIGURE 1: Cellular structure of AFt and AFm.

Isomorphous replacement is also known as isomorphous substitution. In mineral crystallization, the position occupied by some ions or atoms in the crystal structure is partly occupied by other ions or atoms of similar nature and size, but the crystal structure is basically unchanged. The electronegativity of  $\text{Cr}^{3+}$  and  $\text{Al}^{3+}$  is close, and both ions' electricity price is the same, so it can replace the calcium alum stone  $\text{Al}^{3+}$  form relatively stable substitutional solid solution. On the contrary,  $\text{Cr}^{6+}$  would change the molecular symmetry and cause a great influence on the lattice structure of AFt when entered into the lattice structure. Therefore, AFt is prone to solidly immobilizing  $\text{Cr}^{3+}$  than  $\text{Cr}^{6+}$ .

**4.3. CASH.** CASH is a kind of zeolite minerals composed of oxygen-silicon tetrahedron, which has strong ability of adsorption and ion exchange capacity due to its higher specific surface area with 500~1000  $\text{m}^2/\text{g}$ . However,  $\text{Si}^{4+}$  in the oxygen-silicon tetrahedron always be substituted by  $\text{Al}^{3+}$  and form a alumina tetrahedron with some extra negative charge, which needs alkali metal cations to achieve the charge balance. There is poor binding force between alkali metal cations and the CASH crystal, because most of the alkali metal cations are located in a cavity or pore structures. Besides, these heavy metal ions including  $\text{Cr}^{3+}$ ,  $\text{Cd}^{2+}$ , and  $\text{Pb}^{2+}$  have stronger adsorption ability than alkali metal cations in CASH, so the heavy metal ions are more likely to be effectively immobilized in CASH.

## 5. Summary and Prospect

The comparative analysis of the solidification effect and leaching toxicity of MSWI fly ash treated by various types of cement has been investigated and discussed in depth in this paper and found that it was more effective to use the phosphate cement and alkali activated cement to immobilize the heavy metals. And this paper also looks at the interaction of cement hydration products and heavy metals in particular. However, there are also lots of controversies about immobilization mechanism of heavy metals with cement-based stabilization/solidification technology. For example, these immobilization mechanisms always change with external environment and matrix materials structure, and meanwhile, the heavy metal hydrolyses always give rise to variation of pH values and cement hydration process, which would make the study on immobilization mechanisms and hydration products fixing effects of heavy metal more complex. But beyond all that, there are few in-depth studies on the long-term safety and stability after the landfill of MSWI fly ash solidification and no universal practical method to realize the reutilization of MSWI fly ash. Therefore, it is to be hoped that the proper treatment and disposal of MSWI fly ash would be realized with the efforts in the next few years.

## Conflicts of Interest

The authors declare no conflicts of interest.

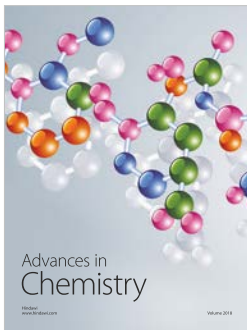
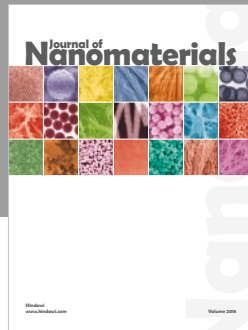
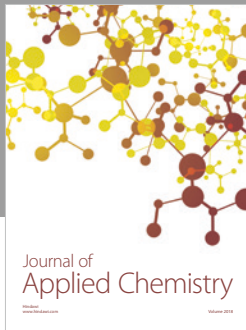
## Acknowledgments

The financial support of this work was supported by the National Science Foundation of China (51578108 and 51778101), the Fundamental Research Funds for the Central Universities DUT18ZD211, National Key R&D Program of China (2017YFE0107000), and Dalian High-level Talent Innovation Program (2017RQ051). Thanks are due to all authors of those cited references for the data and achievements. They make it well-founded for this study.

## References

- [1] U. Richers and L. Birnbaum, "Detailed investigations of filter ashes from municipal solid waste incineration," *Waste Management and Research*, vol. 16, no. 2, pp. 190–194, 1998.
- [2] A. Poletti, R. Pomi, L. Trinci, A. Muntoni, and S. L. Mastro, "Engineering and environmental properties of thermally treated mixtures containing MSWI fly ash and low-cost additives," *Chemosphere*, vol. 56, no. 10, pp. 901–910, 2004.
- [3] J. Tang, R. Ylmén, M. Petranikova, C. Ekberg, and B. M. Steenari, "Comparative study of the application of traditional and novel extractants for the separation of metals from MSWI fly ash leachates," *Journal of Cleaner Production*, vol. 172, pp. 143–154, 2018.
- [4] G. Weibel, U. Eggenberger, D. A. Kulik et al., "Extraction of heavy metals from MSWI fly ash using hydrochloric acid and sodium chloride solution," *Waste Management*, vol. 76, pp. 457–471, 2018.
- [5] C. H. K. Lam, J. P. Barford, and G. McKay, "Utilization of municipal solid waste incineration ash in portland cement clinker," *Clean Technologies and Environmental Policy*, vol. 13, no. 4, pp. 607–615, 2011.
- [6] L. L. Forestier and G. Libourel, "Characterization of flue gas residues from municipal solid waste combustors," *Environmental Science and Technology*, vol. 32, no. 15, pp. 2250–2256, 1998.
- [7] F. Lombardi, T. Mangialardi, and L. Piga, "Mechanical and leaching properties of cement solidified hospital solid waste incinerator fly ash," *Waste Management*, vol. 18, no. 2, pp. 99–106, 1998.
- [8] Z. Yang, S. Tian, L. Liu, X. Wang, and Z. Zhang, "Application of washed MSWI fly ash in cement composites: long-term environmental impacts," *Environmental Science and Pollution Research*, vol. 25, no. 12, pp. 12127–12138, 2018.
- [9] J. Seniunaitė and S. Vasarevičius, "Heavy metals leaching of MSWI bottom ash: effect of short-term natural weathering," in *Proceedings of 10th International Conference "Environmental Engineering"*, Vilnius, Lithuania, August 2017.
- [10] M. D. Dimitrijević, M. M. Nujkić, S. Č. Alagić, S. M. Milić, and S. B. Tošić, "Heavy metal contamination of topsoil and parts of peach-tree growing at different distances from a smelting complex," *International Journal of Environmental Science and Technology*, vol. 13, no. 2, pp. 615–630, 2016.
- [11] F. Lombardi, T. Mangialardi, L. Piga, and P. Sirini, "Mechanical and leaching properties of cement solidified hospital solid waste incinerator fly ash," *Waste Management*, vol. 18, no. 2, pp. 99–106, 1998.
- [12] A. Poletti, R. Pomi, P. Sirini, and F. Testa, "Properties of Portland cement-stabilized MSWI fly ashes," *Journal of Hazardous Materials*, vol. 88, no. 1, pp. 123–138, 2001.
- [13] D. Dermatas and X. Meng, "Utilization of fly ash for stabilization/solidification of heavy metal contaminated soils," *Engineering Geology*, vol. 70, no. 3–4, pp. 377–394, 2003.
- [14] N. Alba, E. Vázquez, S. Gassó, and J. M. Baldasano, "Stabilization/solidification of MSW incineration residues from facilities with different air pollution control systems. Durability of matrices versus carbonation," *Waste Management*, vol. 21, no. 4, pp. 313–323, 2001.
- [15] X. Gao, W. Wang, T. Ye, F. Wang, and Y. Lan, "Utilization of washed mswi fly ash as partial cement substitute with the addition of dithiocarbamic chelate," *Journal of Environmental Management*, vol. 88, no. 2, pp. 293–299, 2008.
- [16] Y. Yao, X. Wang, B. L. Yan, L. Wang, and C. Liu, "The research on heavy metal ions curing and its influence on the cement hydration process," *Bulletin of the Chinese Ceramic Society*, vol. 7, no. 2, p. e31494, 2012.
- [17] M. A. Trezza, "Hydration study of ordinary portland cement in the presence of zinc ions," *Materials Research*, vol. 10, no. 4, pp. 331–334, 2007.
- [18] B. G. Ma, J. R. Wang, and X. G. Li, "Effect of heavy metals and leaching toxicity of magnesium potassium phosphate cement," *Applied Mechanics and Materials*, vol. 117–119, pp. 1080–1083, 2012.
- [19] H. Vogg, H. Braun, M. Metzger, and J. Schneider, "The specific role of cadmium and mercury in municipal solid waste incineration," *Waste Management Research*, vol. 4, no. 1, pp. 65–73, 1986.
- [20] Y. Su, J. Yang, D. Liu, S. Zhen, N. Lin, and Y. Zhou, "Effects of municipal solid waste incineration fly ash on solidification/stabilization of cd and pb by magnesium potassium phosphate cement," *Journal of Environmental Chemical Engineering*, vol. 4, no. 1, pp. 259–265, 2016.
- [21] I. Buj, J. Torras, M. Rovira, and J. d. Pablo, "Leaching behaviour of magnesium phosphate cements containing high quantities of heavy metals," *Journal of Hazardous Materials*, vol. 175, no. 1–3, pp. 789–794, 2010.
- [22] S. C. Zhen, Y. Xun, and B. Q. Miao, "Solidification/stabilization of heavy metals by magnesium potassium phosphate cement," *Advanced Materials Research*, vol. 664, pp. 683–689, 2013.
- [23] Y. Li and B. Chen, "Factors that affect the properties of magnesium phosphate cement," *Construction and Building Materials*, vol. 47, pp. 977–983, 2013.
- [24] J. H. Yang, M. S. Jin, H. L. Chang, C. M. Heo, M. K. Jeon, and K. H. Kang, "Stabilization of Cs/Re trapping filters using magnesium phosphate ceramics," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 295, no. 1, pp. 211–219, 2013.
- [25] A. Covill, N. C. Hyatt, J. Hill, and N. C. Collier, "Development of magnesium phosphate cements for encapsulation of radioactive waste," *Advances in Applied Ceramics*, vol. 110, no. 3, pp. 151–156, 2011.
- [26] X. Xu, J. Yang, and Y. Gu, "Properties of magnesium potassium phosphate cement containing heavy metal Pb," *Journal of Building Materials*, vol. 19, no. 1, pp. 29–34, 2016.
- [27] S. Sahu, J. Havlica, V. Tomková, and J. Majling, "Hydration behaviour of sulphoaluminate belite cement in the presence of various calcium sulphates," *Thermochimica Acta*, vol. 175, no. 1, pp. 45–52, 1991.
- [28] Z. T. Luo, B. G. Ma, Z. Q. Yu et al., "Influence of heavy metal Pb on hydration and leaching toxicity of sulphoaluminate cement," *Journal of Qingdao Technological University*, vol. 30, no. 4, pp. 130–133, 2009.
- [29] A. Gabrisová, J. Havlica, and S. Sahu, "Stability of calcium sulphoaluminate hydrates in water solutions with various pH

- values,” *Cement and Concrete Research*, vol. 21, no. 6, pp. 1023–1027, 1991.
- [30] G. Huang, Y. Ji, J. Li, Z. Hou, and C. Jin, “Use of slaked lime and portland cement to improve the resistance of MSWI bottom ash-gbfs geopolymer concrete against carbonation,” *Construction and Building Materials*, vol. 166, pp. 290–300, 2018.
- [31] A. Wongsas, K. Boonserm, C. Waisurasingha, V. Sata, and P. Chindaprasirt, “Use of municipal solid waste incinerator (MSWI) bottom ash in high calcium fly ash geopolymer matrix,” *Journal of Cleaner Production*, vol. 148, pp. 49–59, 2017.
- [32] R. Zak and J. Deja, “C-S-H, C-A-S-H and N-A-S-H phases as a matrices for the immobilization of heavy metals,” in *Proceedings of 14th International Congress on the Chemistry of Cement*, Beijing, China, October 2015.
- [33] J. Davidovits, “Properties of geopolymer cements alkaline cements,” in *Proceedings of the First International Conference on Alkali Cements and Concretes*, pp. 131–149, Ukraine, October 1994.
- [34] D. L. Cocke, M. Y. A. Mollah, T. R. Hess, and R. K. Vempati, “Advanced concepts in cement solidification and stabilization technology,” *International Organization*, vol. 18, no. 1, pp. 207–209, 2010.
- [35] E. Fourest and J. C. Roux, “Heavy metal biosorption by fungal mycelial by-products: mechanisms and influence of pH,” *Applied Microbiology and Biotechnology*, vol. 37, no. 3, pp. 399–403, 1992.
- [36] N. J. Coleman, Q. Li, and A. Raza, “Synthesis, structure and performance of calcium silicate ion exchangers from recycled container glass,” *Physicochemical Problems of Mineral Processing*, vol. 50, no. 1, pp. 5–16, 2014.
- [37] A. Mollha, M. Yousuf, J. R. Pargat, and D. L. Cocke, “An infrared spectroscopic examination of cement-based solidification/stabilization systems-Portland types V and IP with zinc,” *Environmental Letters*, vol. 27, no. 6, pp. 1503–1519, 1992.
- [38] L. Rozumová, O. Motyka, K. Čabanová, and J. Seidlerová, “Stabilization of waste bottom ash generated from hazardous waste incinerators,” *Journal of Environmental Chemical Engineering*, vol. 3, no. 1, pp. 1–9, 2015.
- [39] D. L. Coeke, “The binding chemistry and leaching mechanisms of hazardous substances in cementitious solidification/stabilization systems,” *Journal of Hazardous Materials*, vol. 24, no. 2-3, pp. 231–253, 1990.
- [40] X. D. Li, C. S. Poon, H. Sun, I. M. C. Lob, and D. W. Kirkc, “Heavy metal speciation and leaching behaviors in cement based solidified/stabilized waste materials,” *Journal of Hazardous Materials*, vol. 82, no. 3, pp. 215–230, 2001.
- [41] P. Billen, B. Verbinnen, M. D. Smet et al., “Comparison of solidification/stabilization of fly ash and air pollution control residues from municipal solid waste incinerators with and without cement addition,” *Journal of Material Cycles and Waste Management*, vol. 17, no. 2, pp. 229–236, 2015.
- [42] J. W. Ahn, K. S. You, G. C. Han, and K. H. Cho, “Stabilization behavior of heavy metals derived from wastes on cementitious minerals and hydrates,” *Materials Science Forum*, vol. 510–511, pp. 630–633, 2006.
- [43] K. S. You, J. W. Ahn, H. C. Cho, G. C. Han, D. Y. Han, and K. H. Cho, “Competing ion effect of stabilization by Cr (III) and Cr(VI) in ettringite crystal structure,” *Solid State Phenomena*, vol. 124–126, no. 2, pp. 1629–1632, 2007.
- [44] M. L. D. Gougar, B. E. Scheetz, and D. M. Roy, “Ettringite and C-S-H Portland cement phases for waste ion immobilization: a review,” *Waste Management*, vol. 16, no. 4, pp. 295–303, 1996.
- [45] H. Y. Na and T. W. Song, “Heavy metal ion immobilization properties of microporous ettringite body,” *Journal of the Korean Ceramic Society*, vol. 46, no. 6, 2009.
- [46] M. Chrysochoou and D. Dermatas, “Evaluation of ettringite and hydrocalumite formation for heavy metal immobilization: literature review and experimental study,” *Journal of Hazardous Materials*, vol. 136, no. 1, pp. 20–33, 2006.
- [47] M. Chrysochoou and D. Dermatas, “Application of ettringite on heavy-metal immobilization: a literature review and experimental study,” *Journal of Hazardous Materials*, vol. 136, no. 3, pp. 20–33, 2004.
- [48] K. A. Saeed, K. A. Kassim, H. Nur, and N. Z. M. Yunus, “Strength of lime-cement stabilized tropical lateritic clay contaminated by heavy metals,” *KSCE Journal of Civil Engineering*, vol. 19, no. 4, pp. 887–892, 2014.
- [49] C. Tashiro and J. Oba, “The effects of Cr<sub>2</sub>O<sub>3</sub>, Cu(OH)<sub>2</sub>, ZnO and PbO on the compressive strength and the hydrates of the hardened C3A paste,” *Cement and Concrete Research*, vol. 9, no. 2, pp. 253–258, 1979.
- [50] J. N. Diet, P. Moszkowicz, and D. Sorrentino, “Behaviour of ordinary portland cement during the stabilization/solidification of synthetic heavy metal sludge: macroscopic and microscopic aspects,” *Waste Management*, vol. 18, no. 1, pp. 17–24, 1998.
- [51] M. A. Trezza and M. F. Ferraiuelo, “Hydration study of limestone blended cement in the presence of hazardous wastes containing Cr(VI),” *Cement and Concrete Research*, vol. 33, no. 7, pp. 1039–1045, 2003.
- [52] I. Baur, P. Keller, D. Mavrocordatos, B. Wehrli, and C. A. Johnson, “Dissolution-precipitation behaviour of ettringite, monosulfate, and calcium silicate hydrate,” *Cement and Concrete Research*, vol. 34, no. 2, pp. 341–348, 2004.



**Hindawi**  
Submit your manuscripts at  
[www.hindawi.com](http://www.hindawi.com)

