Applied Geochemistry 81 (2017) 155–165

Contents lists available at ScienceDirect

Applied Geochemistry

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

Stabilization/solidification of zinc-contaminated kaolin clay using ground granulated blast-furnace slag and different types of activators

Amir Reza Goodarzi [a, *], Mehran Movahedrad [b]

[a] Faculty of Engineering, Hamedan Branch, Islamic Azad University, Hamedan, Iran
[b] Faculty of Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

Article history:
Received 7 December 2016
Received in revised form
18 April 2017
Accepted 28 April 2017
Available online 29 April 2017

Editorial Handling by Prof. M. Kersten

Keywords:
Zn-contaminated soil
Activated slag
Cementing phases
Buffering capacity
Stabilization/solidification

ABSTRACT

This paper presents a multiscale investigation on the viability of employing ground granulated blast-furnace slag (GGBS) alone and the slag activated with cement (C-GGBS) and MgO (M-GGBS) in stabilization/solidification (S/S) of zinc (Zn) contaminated clayey soil that may offer a range of environmental and economic benefits. The macro and micro level test results showed that the addition of GGBS up to 30 wt% will not successfully stabilize the kaolin sample even with low contents of Zn. The cement-slag treatment exhibits a higher sorption capability as compared to the GGBS application, but in this case, the acidic attack dramatically decreases the potential of Zn retention, leading to a marked increase in the needed amount of agent (by nearly 60%) to gain the acceptable leaching characteristics. Moreover, the physicochemical reactions of Zn with C-GGBS have negative impacts on the microstructure, and thus, the engineering properties of the treated material. MgO gives a better cementation structure-bonding and a more pH-buffering capacity to the slag-amended soil, two features which are found to alleviate the restructuring of S/S product upon contact with the metal ions or the aggressive environments. This can play a vital role in enhancing the geo-mechanical performance and Zn immobilization of M-GGBS system with a lower quantity of the agent (to about 50%) and shorter curing ages (21 days) than the C-GGBS blend. Overall, it seems that the activated slag can be used as an effective S/S binder. However, the optimum dosage of binder will be strongly influenced by the activator composition.

1. Introduction

Heavy metals (HMs) can significantly affect the human health, and therefore, soil contamination by HMs has received increased attention of environmentalists over the years (Çoruh et al., 2013; Tiberg et al., 2016). Although several techniques can be implemented for the remediation of such soils, stabilization/solidification (S/S) appears an appropriate way to treat contaminated soils (El-Eswed et al., 2015; Jin et al., 2016). During the S/S process, with the introduction of a binding agent into the contaminated media, HMs get much less mobile (or toxic) and are physically encapsulated into a monolithic solid with a reduced surface area (Yoon et al., 2010; Zhang et al., 2015; Su et al., 2016). Whilst various binders and their combinations have been utilized for the S/S treatment, cement is considered the most adaptable agent currently available for the remediation of contaminated lands. However, it may show limited efficiency in some cases such as when it is used in the presence of organic materials or high amounts of soluble sulfates (Özbay et al., 2013; Deng et al., 2015). Additionally, due to the calcination of limestone and the consumption of fossil fuels, the cement production emits a large content of greenhouse gas into the atmosphere (Jin and Al-Tabbaa, 2014; Gu et al., 2015).

The mentioned disadvantages and the increased cost associated with the use of cement have given the researchers the impetus to replace it with more sustainable and more effective stabilizers like industrial wastes, either for economic considerations, resource and environment conservations or enhancement of the engineering characteristics of S/S products. Among those alternative binders, ground granulated blast-furnace slag (GGBS), an industrial by-product of the steel production, has been shown to be a promising option to partially replace cement (or lime) in the treatment of problematic soils (Oti et al., 2009; Keramatikerman et al., 2016), since it can aid the densification of the soil matrix. This occurs by transforming the free $Ca(OH)_2$ in the system to form more calcium silicate hydrate (CSH) gel, which can lead to higher strength, lower

* Corresponding author.
E-mail address: amir_r_goodarzi@yahoo.co.uk (A.R. Goodarzi).

http://dx.doi.org/10.1016/j.apgeochem.2017.04.014

permeability, higher resistance to chemical attack, superior durability, and lower heat of hydration in comparison to the sole cement (Thomas et al., 2012; Aydın and Baradan, 2014). Besides the above technical advantages, GGBS has extremely low energy consumption and CO_2 emission compared with cement or lime.

The use of activated GGBS by reactive magnesia (MgO) is also a recent development offering a range of geo-mechanical and durable advantages over the utilization of the traditional agents (Jin et al., 2015). Yi et al. (2013) and Du et al. (2016) report that the stabilized soil with MgO-GGBS blend may achieve a greater strength (about 4 times as much) relative to the soil treated by sole cement. Other studies confirm the positive effects of GGBS with alkali additives on the decrease of soils volumetric instability and leachability of contaminants from hazardous wastes (Liu et al., 2008; Celik and Nalbantoglu, 2013; Falciglia et al., 2014; Wang et al., 2015). However, the application of GGBS alone and with different types of activators for the S/S treatment of HM contaminated clayey soils has not been fully considered in the published literature. Besides, there is a lack of detailed studies to determining the required dosage of such binders for the successful modification of contaminated soil with various levels of HM. Thus, the current study is conducted to address the potential use and effectiveness of GGBS alone and the slag activated with cement (C-GGBS) and MgO (M-GGBS) in the S/S process of the contaminated soil samples containing several concentrations of Zn ions.

2. Materials and methods

2.1. Materials

In line with Ouhadi et al. (2010), John et al. (2011) and Suzuki et al. (2013), kaolin clay was used to prepare the contaminated soil samples. As summarized in Table 1, the engineering properties and geo-environmental characteristics of the used kaolinite were determined in accordance with ASTM methods (ASTM, 2006) and the Environmental Protection Agency (EPA) manual (EPA, 1983). Zn was selected as the target HM, since it not only is one of the most soluble and mobile of the divalent trace metal ions but also has greater concentrations in natural soil than other HMs do (Qian et al., 2003; Stephan et al., 2008; Coz et al., 2009; Erdem and Özverdi, 2011). In addition, Zn is listed as a priority pollutant by the EPA and represents one of the most common HMs encountered in contaminated lands (Moon et al., 2010; Li et al., 2014; Chiang et al., 2016). Of course, it should be noted that as a nutrient, Zn is an essential element for plants and humans but it can be toxic once the concentration is high (Zhou et al., 2009). The GGBS was obtained from Esfahan Steel Co., Esfahan, Iran, and two types of additives including cement and medium reactive magnesia (MgO) were used as its activators. The reasons for selecting medium type of MgO were its reasonable cost and its good potential in activating GGBS as shown in other studies (Jin et al., 2014, 2015; Du et al., 2016). The main chemical compositions of the used kaolinite and the binders are listed in Table 2.

2.2. Preparation of specimens

The soil was contaminated by adding 5, 10, 15, 20 and 30 cmol kg-soil^{-1} of Zn. Such Zn levels are sometimes encountered at landfill sites and contaminated soils of urban areas as reported by Du et al. (2013) and Goodarzi and Zandi (2016). To get the desired concentration, the needed Zn (in the form of zinc nitrate) was first dissolved in the required amount of distilled water for each test and was then added to the soil samples until they were visually homogeneous. Afterwards, the Zn-spiked clays were blended with GGBS alone, C-GGBS and M-GGBS at doses between 5 and 30 wt%. Following Li and Pang (2014), Gu et al. (2015) and Yi et al. (2016), the activator to GGBS ratio was set as 1:3. The mixtures were homogenized and placed in air-tight plastic bags and were cured in a warm humid chamber at temperatures 22 ± 1 °C and a relative humidity of 85%. At the end of each curing period (i.e. 1–28 days), the mechanical and micro-structural characteristics of the S/S products were evaluated.

2.3. Macro and micro level experiments

To determine the Zn adsorption capability of the soil samples, a series of batch equilibrium experiments were performed based on EPA (1983). Following preparation and equilibration of the soil-electrolyte suspensions at a 1:20 solid-solution ratio, they were

Table 2
Main chemical compositions of used kaolin clay sample, ground granulated blast-furnace slag (GGBS), cement and reactive magnesia (MgO).

Chemical composition	Percentage in weight (%)			
	Kaolin clay	GGBS	Cement	MgO
SiO_2	58.26	34.14	21.52	1.1
Al_2O_3	29.43	16.51	4.95	0.12
Fe_2O_3	1.14	1.27	3.82	0.45
CaO	0.89	31.49	63.49	1.39
MgO	0.16	9.21	1.55	94.1
Na_2O	<0.1	0.36	0.48	–
K_2O	0.51	0.69	0.75	–
P_2O_5	–	–	–	–
SO_3	–	2.28	2.07	–
TiO_2	<0.1	1.63	–	–
Loss of ignition	9.23	1.76	1.01	2.76

Table 1
Engineering and geo-environmental properties of kaolin clay sample.

Characteristics	Quantity measured	Reference for measurement method
Mineral composition in decreasing amount	kaolinite (≈70%), Quartz	Goodarzi et al., 2016b
pH	8.82	Ouhadi et al., 2006
Electrical conductivity (EC), mS/cm	0.15	EPA manual, 1983
Specific surface area (SSA), m^2/g	25	Eltantawy and Arnold, 1973
Cation exchange capacity (CEC), cmol/kg	11.2	Hendershot and Duquette, 1986
Clay fraction, %	68	ASTM D422
Specific gravity, G_S	2.69	ASTM D854
Liquid limit (LL), %	38.2	ASTM D4318
Plasticity index (PI), %	19	ASTM D4318
Soil classification	CL	ASTM D2487
Maximum dry density, gr/cm^3	1.56	ASTM D698
Optimum moisture content, %	28.5	ASTM D698
Unconfined compression strength, MPa	0.18	ASTM D2166