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Laboratory-scale model of carbon dioxide deposition for soil stabilisation

Mohammad Hamed Fasihnikoutalab [a,*], Afshin Asadi [b], Bujang Kim Huat [a], Paul Westgate [c], Richard J. Ball [c], Shahram Pourakbar [a]

[a] *Department of Civil Engineering, University Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[b] *Housing Research Centre, Department of Civil Engineering, University Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[c] *BRE Centre for Innovative Construction Materials, Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, UK*

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ABSTRACT

Olivine sand is a natural mineral, which, when added to soil, can improve the soil's mechanical properties while also sequester carbon dioxide (CO_2) from the surrounding environment. The originality of this paper stems from the novel two-stage approach. In the first stage, natural carbonation of olivine and carbonation of olivine treated soil under different CO_2 pressures and times were investigated. In this stage, the unconfined compression test was used as a tool to evaluate the strength performance. In the second stage, details of the installation and performance of carbonated olivine columns using a laboratory-scale model were investigated. In this respect, olivine was mixed with the natural soil using the auger and the columns were then carbonated with gaseous CO_2. The unconfined compressive strengths of soil in the first stage increased by up to 120% compared to those of the natural untreated soil. The strength development was found to be proportional to the CO_2 pressure and carbonation period. Microstructural analyses indicated the presence of magnesite on the surface of carbonated olivine-treated soil, demonstrating that modified physical properties provided a stronger and stiffer matrix. The performance of the carbonated olivine-soil columns, in terms of ultimate bearing capacity, showed that the carbonation procedure occurred rapidly and yielded a bearing capacity value of 120 kPa. Results of this study are of significance to the construction industry as the feasibility of carbonated olivine for strengthening and stabilizing soil is validated. Its applicability lies in a range of different geotechnical applications whilst also mitigates the global warming through the sequestration of CO_2.

1. Introduction

Traditional calcium-based binders (i.e. lime and cement) are frequently used as additives for ground improvement (Sariosseiri and Muhunthan, 2009; Celaya et al., 2011; Horpibulsuk et al., 2011; Dash and Hussain, 2012). However, their production involves the emission of carbon dioxide (CO_2). This is a contributing factor to the significant global warming expected in future decades. The production of these traditional binders, i.e. lime and cement, typically produces 600–700 kg and 800–900 kg of CO_2 per tonne, respectively. This is because they require energy (both fuel and electricity) and the production process releases CO_2. For instance, the cement industry alone accounts for around 5% of global CO_2 emissions (Feely et al., 2004; Sabine et al., 2004).

Recent soil stabilisation methods have highlighted the need for full or partial replacement of the traditional binders with cleaner and more sustainable materials (e.g. reactive magnesia, zeolite, fly ash, rice husk ash, cement kiln dust, calcium carbide residue, palm oil fuel ash, ground granulated blast furnace slag) (Rahman, 1987; Yin et al., 2008; Horpibulsuk et al., 2009; Jegandan et al., 2010; Kroehong et al., 2011; Kampala and Horpibulsuk, 2013; Yi et al., 2014; Pourakbar et al., 2015a, b). Most of these methods have focused on using alternative materials to replace traditional cementitious binders and reduce greenhouse gas emissions.

Another promising technique to reduce the industry's greenhouse gas emissions involves capturing the CO_2 to make other products such as carbonates or bicarbonates. It is an attractive sequestration method for the permanent and safe storage of CO_2. Mineral carbonation is a process whereby CO_2 reacts chemically with calcium- and/or magnesium-containing minerals to form stable carbonate phases (Oelkers et al., 2008).

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* Corresponding author. Tel.: +60 173372970.
E-mail address: hfasih@gmail.com (M.H. Fasihnikoutalab).

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Serpentine, olivine, wollastonite, steel slag, Estonian oil shale ash, and Mg-oxides have been widely proposed for direct carbonation by several researchers (Maroto-Valer et al., 2004; Hänchen et al., 2006; Liu, 2006; Hangx and Spiers, 2009; Velbel, 2009; Bernal et al., 2010; Rudge et al., 2010; Sissmann et al., 2013; Yi et al., 2013a–c; Song et al., 2014). Accordingly, the recent studies demonstrated that the in situ carbonation can be achieved by injection of CO_2 through a perforated pipe installed in the ground (Andreani et al., 2009; Yi et al., 2013a–c; Cai et al., 2015).

Amongst a wide variety of natural materials for the mineral carbonation process, olivine Mg_2SiO_4 is one of the most promising candidates (Kelemen and Hirth, 2012; Olsson et al., 2012; Saldi et al., 2013). Olivine is widely distributed around the world: Egypt, Myanmar, South Africa, Russia, Pakistan, Norway, Sweden, France, Brazil, Germany, Mexico, Australia, China and also the USA. Geological survey of Malaysia shows that there is a large number of volcanic rocks of the andesite-dacite-basalt in Tawau Mountains in Sabah which is the main source of olivine (Tahir et al., 2010).

The CO_2 from the atmosphere dissolves in available water forming carbonic acid with a pH value around 5.6. Then, the dissolution of olivine in the carbonated water occurs, and finally a stable magnesium carbonate ($MgCO_3$) and silica are precipitated. The carbonated products may have potential to bond soil particles together (Fasihnikoutalab et al., 2015). The carbonation reaction of Mg-rich olivine can be described by

$$\begin{aligned} &Mg_2SiO_4 + 4CO_2 + 2H_2O \rightarrow 2Mg^{2+} + SiO_2 \\ &\quad + 4HCO_3^- \leftrightarrow 2MgCO_3 + SiO_2 + 2CO_2 + 2H_2O \qquad (1) \end{aligned}$$

The aim of this study is to investigate the strength performance of carbonated olivine treated soil at different carbonation pressures and times. In this stage, unconfined compression test was used as a tool to evaluate the performance. Moreover, the bearing capacity of treated soil using carbonated olivine columns was determined by a laboratory-scale set of experiments using specific pressure and time. Microstructural analysis of olivine under the natural condition and carbonated olivine treated soil was also traced.

2. Materials and method

2.1. Properties of materials used

2.1.1. Soil properties

A clayey soil composed of 10% sand, 60% silt and 30% clay was used. The optimum water content and maximum dry density of natural soil were 23.3% and 1.58 g/cm^3, respectively. Liquid and plastic limits were determined to be 54% and 30%, respectively. Based on the unified soil classification system (USCS), the soil was classified as highly plastic (CH). Table 1 shows the engineering properties of soil and 15% olivine sand treated soil. Fig. 1 clarifies the particle size distribution of soil.

2.1.2. Olivine properties

The olivine in this investigation was supplied by the Maha Chemicals Company of Malaysia. Fig. 2 shows the particle size distribution obtained from a sample of the olivine supplied by the supplier. A laser diffraction particle size analyser (Mastersizer 2000E, ver. 5.52) was used to determine the specific surface area of olivine. The specific surface area and D_{50} (mean particle size) of the olivine sand were 6.07 m^2/g and 2.24 μm, respectively. Table 2 shows the chemical composition of olivine sand according to the supplier in this study.

Analysis using a Jeol 6480 LV scanning electron microscope (SEM) revealed particles with sizes ranging from approximately 500 μm down to sub-micrometre sized particles (see Fig. 3). Moreover, the crystalline phase composition of the olivine was determined by X-ray diffraction (XRD). Data were collected over the 2θ range from 3° to 50°. The relative intensities of the peaks at the critical 2θ angles can be seen in Fig. 4. Analysis of the XRD data confirmed the presence of peaks at 2θ values of 16.55°, 24.8°, 25.52°, 32°, 36.5°, 39.36°, and 44.58° which are in agreement with those reported by Swanson and Tatge (1951) for forsterite, the Mg-rich form of olivine.

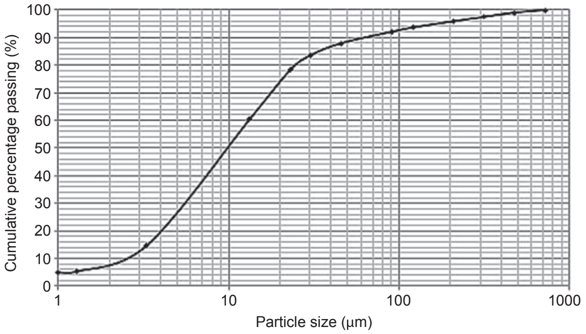

Fig. 1. The particle size distribution curve of soil.

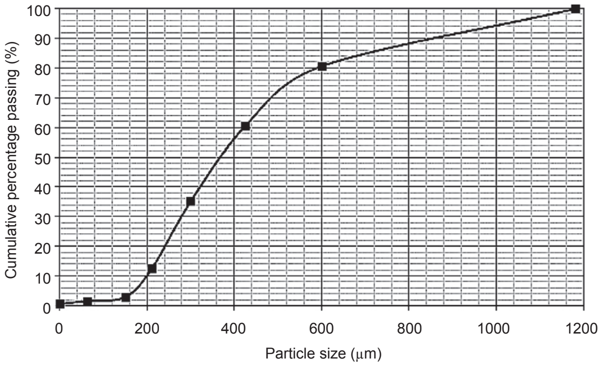

Fig. 2. The particle size distribution curve of olivine.

Table 2
Chemical composition of olivine sand (%).

MgO	SiO_2	Al_2O_3	Fe_2O_3	CaO	Loss on ignition
48.28	40.32	1.37	8.9	–	1.13

Table 1
Engineering properties of soil and 15% olivine sand treated soil.

Optimum water content (%)	Optimum water content of soil + 15% olivine sand (%)	Plastic limit (%)	Liquid limit (%)	Plasticity index (%)	Specific gravity	Maximum dry density (g/cm^3)	Maximum dry density of soil + 15% olivine sand (g/cm^3)	Particle content (%)		
								Sand	Silt	Clay
23.3	17.4	30	54	24	2.65	1.58	1.719	10	60	30