

## Soil stabilization by ground bottom ash and red mud

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(Received April 5, 2017, Revised July 4, 2018, Accepted July 9, 2018)

**Abstract.** This paper presents results of a compressive investigation conducted on weathered soil stabilized with ground bottom ash (GBA) and red mud (RM). The effects of water/binder ratio, RM/GBA ratio, chemical activator (NaOH and Na<sub>2</sub>SiO<sub>3</sub>) and curing time on unconfined compressive strength of stabilized soils were examined. The results show that the water/binder ratio of 1.2 is optimum ratio at which the stabilized soils have the maximum compressive strength. For 28 days of curing, the compressive strength of soils stabilized with alkali-activated GBA and RM varies between 1.5 MPa and 4.1 MPa. The addition of GBA, RM and chemical activators enhanced strength development and the rate of strength improvement was more significant at the later age than at the early age. The potential environmental impacts of stabilized soils were also assessed. The chemical property changes of leachate from stabilized soils were analyzed in terms of pH and concentrations of hazardous elements. The observation revealed that the soil mixture with ground bottom ash and red mud proved environmentally safe.

**Keywords:** soil stabilization; ground bottom ash; red mud; weathered soil; compressive strength; leaching

### 1. Introduction

Soil stabilization can improve soil characteristics to satisfy engineering requirement. Chemical stabilization is one of the techniques to enhance strength and durability of problematic soils by mixing the soil with stabilizing additives such as cement, lime, fly ash, and other organic and inorganic cementing agents (Gupta and Kumar 2017). Today, the chemical stabilization is widely used in various geoengineering applications, e.g., highways, railways, embankment, foundation base and slope protection. Using industrial solid waste in such constructions is eco-friendly because of reduced landfilling and energy consumption for virgin geomaterial production (Mohanty *et al.* 2017).

Bottom ash is a cementitious byproduct of the combustion of pulverized coal in power generating plants, which can be a cost-effective alternative binder. Bottom ash is a coarse granular material in contrast to the fine spherical particles of fly ash. Several studies highlighted the beneficial use of bottom ash in improving soil performance. For example, Consoli *et al.* (2007) investigated the small to large strain behaviors of bottom ash and noted that the mechanical behavior of bottom ash compares favorably

with conventional granular materials. Yoon *et al.* (2009) evaluated the suitability of bottom and fly ash mixtures by monitoring data obtained from instrumented demonstration embankment. Kim and Do (2012) reported the increase of strength and stiffness of bottom ash-based dredged soil by the fabric change and particle bonding effect. Gullu (2014) examined the effective dosage rate of bottom ash to improve the strength properties of fine-grained soil and suggested that the bottom ash addition of 30% is adequate for the improvement of the low-plastic clay. Lopez *et al.* (2015) evaluated the potential of bottom ash to stabilize roadway subgrade soils and revealed that the addition of bottom ash leads to decreasing plasticity and increasing load-bearing capacity of the soils.

Red mud is a complex residue resulting from Bayer process used in the production of alumina from bauxite. Red mud contains high levels of alkalinity and typically consists of large amounts of iron, aluminum, calcium and sodium (Senff *et al.* 2014). Newson *et al.* (2006) studied the mechanical properties of red mud and stated that the material has compression behavior similar to clayey soils but frictional response closer to sandy soils. Some attempts have been made for the potential use of red mud as landfill cover (Kalkan 2006), tailings dam (Rout *et al.* 2013), and structural fill (Panda *et al.* 2017). Alam *et al.* (2017) characterized the coarse fraction of red mud and analyzed their physical, chemical and morphological properties.

This paper presents the effectiveness of using solid waste materials (bottom ash and red mud) as additives to weathered soil in the presence of water and chemical (NaOH and Na<sub>2</sub>SiO<sub>3</sub>) solutions. Unconfined compressive strength tests were performed after aging soil samples with different amounts of bottom ash and red mud. The pH and

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Table 1 Index properties of materials

Material	G <sub>s</sub>	% passing No.200	D <sub>10</sub> (mm)	D <sub>30</sub> (mm)	D <sub>60</sub> (mm)	C <sub>u</sub>	C <sub>c</sub>	LL	PL	PI	USCS
Weathered soil	2.62	15.05	0.06	0.11	0.21	3.22	0.86	27.8	N.P	-	SM
Bottom ash	2.07	5.38	0.13	0.74	2.02	15.82	2.13	-	-	-	-
Ground bottom ash	2.05	19.77	0.07	0.09	0.12	1.81	0.92	-	-	-	-
Red mud	3.15	100	0.0011	0.0017	0.0032	2.98	0.89	-	-	-	-

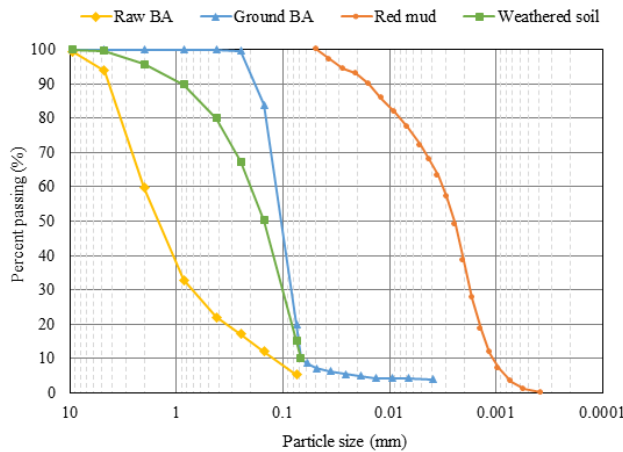


Fig. 1 Particle size distributions of materials

leaching assessments of toxic elements were also conducted for environment consideration.

## 2. Experimental program

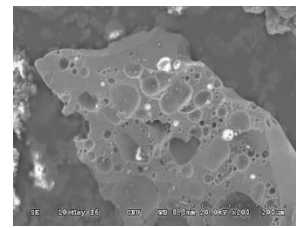
### 2.1 Materials

Weathered soil (WS) was used and its index properties are summarized in Table 1. It is noted that all properties of the soil were determined following the recommended procedures by American Society of Testing and Materials (ASTM). The weathered soil was sieved to a particle size ranging between 0.075 mm and 10 mm and its particle size distribution is shown in Fig. 1. The weathered soil is classified as SM according to the Unified Soil Classification System (USCS).

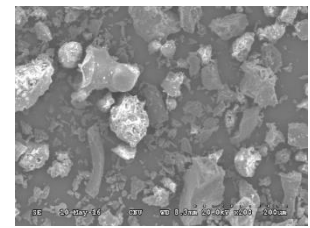
Bottom ash (BA) was taken in a wet state from the Honam power plant located in Yeosu, South Korea. The bottom ash was primarily comprised of sand-sized particles with some gravel-sized particles. In order to improve the hydraulic reactivity of bottom ash, the following procedures were used: first, the bottom ash was dried at a temperature of 105°C for 2 days to ensure that water was removed. Subsequently, the grinding of bottom ash was done to reduce the particle size and modify the shape and surface roughness of particles. A laboratory ball mill machine (UBM-100L, RAMT) was utilized with 40 balls of 40 mm diameter. Batches of bottom ash 500 g were processed for 3 hours, keeping the mill rotation of 120 rpm. After grinding, the fineness of bottom ash particles was determined complying with ASTM C204-16 where the Blaine air-permeability apparatus is used. The obtained value of specific surface area per unit weight of bottom ash was above 2,000 cm<sup>2</sup>/g, the bottom ash of which is referred to as

Table 2 Chemical composition of bottom ash and red mud (% by weight)

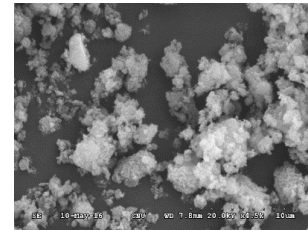
Component	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	MgO	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	LOI
Bottom ash	62.53	20.91	1.80	0.69	8.70	1.28	1.44	0.39	1.85
Red mud	15.12	19.87	7.10	0.37	22.21	5.24	0.11	14.92	13.68



(a) Raw bottom ash



(b) Ground bottom ash



(c) Red mud

Fig. 2 Scanning electron microscope (SEM) images of materials

the ground bottom ash (GBA) in this study. Fig. 1 shows the particle size distributions of bottom ash before and after grinding. It can be observed that the particle size of raw bottom ash ranges between 0.075 mm and 10 mm whereas that of ground bottom ash varies from 0.004 mm to 0.25 mm. In order to determine the chemical compositions of bottom ash, the X-ray fluorescence test was performed and the result is given in Table 2. The major compositions identified include SiO<sub>2</sub> (62.53%) Al<sub>2</sub>O<sub>3</sub> (20.91%) and Fe<sub>2</sub>O<sub>3</sub> (8.70%), with a total of 92.14% by weight. The scanning electron microscopy (SEM) test was conducted on raw and ground bottom ash to investigate the microfabrics of particles. For the raw bottom ash (Fig. 2(a)), particles are subangular and irregular in shape and had smooth surface texture. Some large particles are externally and internally porous, making the particles easily crushable. As shown in Fig. 2(b), the particles of ground bottom ash are angular and roughened as they are produced through the mill process. Meanwhile, shown in Fig. 3 is the pattern of bottom ash obtained from X-ray diffraction test (XRD), indicating that the bottom ash predominantly consists of quartz and mullite which represent silica and alumina, respectively. Hence, the ground bottom ash may be used as a pozzolanic source for soil stabilization (Jaturapitakkul and Cheerarat 2003). As pointed out by Kim *et al.* (2016), the

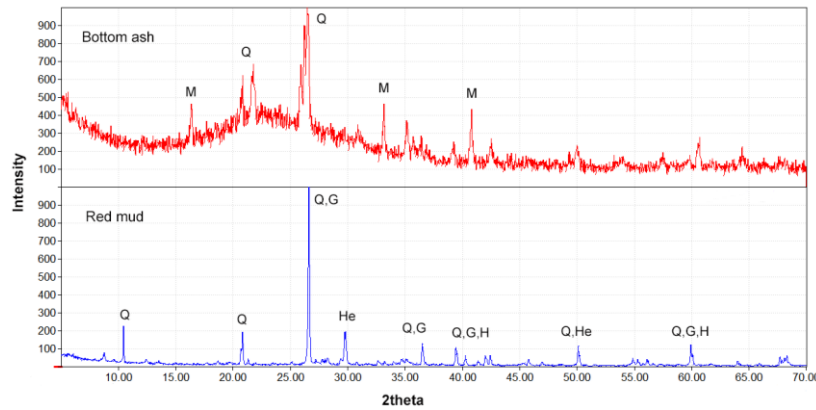


Fig. 3 XRD powder pattern of bottom ash and red mud

grinding can change the microfabrics of the binder, resulting in making it more reactive with aluminosilicate ingredients.

To activate the ground bottom ash, sodium hydroxide (NaOH) and sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) solutions were used. NaOH solution was concocted by dissolving the pellets, having 98% purity, in a distilled water. The molarities of NaOH solutions were varied from 2M to 8M with an increment of 2M. In order to obtain 1 liter of sodium hydroxide solution with a concentration of 2M, the amounts of water and sodium hydroxide pellets were 1 liter and 81.6 g (by reflecting the purity of NaOH), respectively. In the same manner, the amounts of NaOH pellets per 1 liter solution for 4M, 6M and 8M concentrations were 163.2 g, 244.8 g and 326.4 g, respectively. The pH of NaOH solutions ranges between 12.54 and 12.66.  $\text{Na}_2\text{SiO}_3$  solution (known as water glass) with a  $\text{SiO}_2\text{:Na}_2\text{O}$  molar ratio of 3:1 was used, which consists of  $\text{Na}_2\text{O}$  (10%),  $\text{SiO}_2$  (30%) and water (60%) by weight. The specific gravity and pH of  $\text{Na}_2\text{SiO}_3$  solution were 1.41 and 11.2, respectively. The viscosity of  $\text{Na}_2\text{SiO}_3$  solution was estimated to be 400 mPa·s at 20°C.

Red mud (RM) was collected from an alumina plant, Naju, South Korea, which was dried and pulverized to obtain fine powders. A series of experiments were performed, including the particle size analysis, SEM, XRD and XRF. The test results of red mud are shown in Figs. 1-3 and Tables 1-2, along with those of ground bottom ash for comparison. In this study, the red mud was utilized as a partial replacement of ground bottom ash to improve engineering properties of soil mixtures with chemical solutions. It is noteworthy that only the  $\text{Na}_2\text{SiO}_3$  solution was used for mixtures containing red mud because the red mud had a high level of residual alkalinity (pH=11.6).

## 2.2 Specimen preparation

Test specimens were made by applying distinctive two binder groups, i.e., *GB binder* and *GBR binder*, depending on the solid waste and solution: the former is the combination of the ground bottom ash, NaOH and  $\text{Na}_2\text{SiO}_3$  solutions; the latter is the combination of the ground bottom ash, red mud and  $\text{Na}_2\text{SiO}_3$  solution.

For GB binder group, the effects of water/GBA ratio,

Table 3 Mixture proportions for soil mixtures with GB binder

Notation	GBA/ soil	Water/ GBA	NaOH conc.	$\text{Na}_2\text{SiO}_3$ / NaOH	(NaOH+ $\text{Na}_2\text{SiO}_3$ )/GBA
W1.0-4M-Si1.5	0.33	1	4 M	1.5	0.5
W1.2-4M-Si1.5	0.33	1.2	4 M	1.5	0.5
W1.4-4M-Si1.5	0.33	1.4	4 M	1.5	0.5
W1.6-4M-Si1.5	0.33	1.6	4 M	1.5	0.5
W1.2-2M-Si1.5	0.33	1.2	2 M	1.5	0.5
W1.2-4M-Si1.5	0.33	1.2	4 M	1.5	0.5
W1.2-6M-Si1.5	0.33	1.2	6 M	1.5	0.5
W1.2-8M-Si1.5	0.33	1.2	8 M	1.5	0.5
W1.2-4M-Si0.5	0.33	1.2	4 M	0.5	0.5
W1.2-4M-Si1.0	0.33	1.2	4 M	1	0.5
W1.2-4M-Si1.5	0.33	1.2	4 M	1.5	0.5
W1.2-4M-Si2.0	0.33	1.2	4 M	2	0.5
W1.2-4M-Si2.5	0.33	1.2	4 M	2.5	0.5

NaOH concentration and  $\text{Na}_2\text{SiO}_3$ /NaOH ratio on the mechanical and geochemical properties of chemically stabilized soils. For this, the ratio of water and GBA was controlled by varying from 1 to 1.6. The molarity of NaOH solution and the ratio of  $\text{Na}_2\text{SiO}_3$  solution to NaOH solution were varied from 2M to 8M and 0.5 to 2.5, respectively. The activator/GBA ratio, i.e., the ratio of NaOH- $\text{Na}_2\text{SiO}_3$  solution to GBA, of 0.5 was used for all GB binder specimens. The details of mixing proportions for GB binder group is presented in Table 3.

For GBR binder group, the ratios of RM/GBA, water/(GBA+RM), and  $\text{Na}_2\text{SiO}_3$ /(GBA+RM) were considered. Each ratio was controlled by varying from 1 to 1.6, from 0 to 0.5 and from 0.3 to 0.6, respectively. The detailed proportions of mixtures for GBR binder group are given in Table 4.

Paste mixtures were prepared using a high-shear blender-type mixer based on following procedure. First, the required amounts of raw materials (i.e., soil, ground bottom ash, red mud and water) and activator solutions were calculated and weighed. The dry solid materials were initially mixed for 3 min. The water and solution were subsequently added to the dry mixture and mixed for 10 min. The paste mixtures were then cast into the plastic cylindrical molds (50 mm in diameter and 100 mm in

Table 4 Mixture proportions for soil mixtures with GBR binder

Notation	RM/ GBA	(GBA+RM)/ soil	Water/ (GBA+RM)	Na <sub>2</sub> SiO <sub>3</sub> / (GBA+RM)
W1.0-R0.2-Si0.5	0.2	0.33	1	0.5
W1.2-R0.2-Si0.5	0.2	0.33	1.2	0.5
W1.4-R0.2-Si0.5	0.2	0.33	1.4	0.5
W1.6-R0.2-Si0.5	0.2	0.33	1.6	0.5
W1.2-R0.0-Si0.5	0	0.33	1.2	0.5
W1.2-R0.1-Si0.5	0.1	0.33	1.2	0.5
W1.2-R0.2-Si0.5	0.2	0.33	1.2	0.5
W1.2-R0.3-Si0.5	0.3	0.33	1.2	0.5
W1.2-R0.4-Si0.5	0.4	0.33	1.2	0.5
W1.2-R0.5-Si0.5	0.5	0.33	1.2	0.5
W1.2-R0.2-Si0.3	0.2	0.33	1.2	0.3
W1.2-R0.2-Si0.4	0.2	0.33	1.2	0.4
W1.2-R0.2-Si0.5	0.2	0.33	1.2	0.5
W1.2-R0.2-Si0.6	0.2	0.33	1.2	0.6

height) by dividing into three layers and tamping 25 times for each layer. The tamping was carried out manually by using a 5 mm diameter steel rod to eliminate the entrapped air in paste mixture as well as to improve the homogeneity of the specimens. Ten identical specimens were made under each paste. Nine were used to measure the unconfined compressive strength, whereas the other one was used to determine the element concentrations and pH of leachate from the specimen. The prepared specimens were cured at the ambient condition with the temperature of 25°C and the humidity of 50%.

### 2.3 Test procedures

The unconfined compressive strength of the specimens was determined after 7, 14 and 28 days of curing. Triplicate specimens for each curing were tested as per the procedures described in ASTM D2166 (ASTM 2016). The displacement rate adopted was 1 mm/min.

For measurement of elements concentrations and pH of the stabilized soil, the leachate samples were obtained following the procedures presented in Razak *et al.* (2009) for bottom ash-based mortars: at the 7 days of curing, one specimen was demolded and immersed in a tank filled with distilled water. The amount water filled in the tank was eight times the specimen volume. The tank was kept closed at room temperature. The leachate samples were collected from the tank, 1h after immersion and then 7, 14, 21 days after immersion. The trace element concentrations of the leachates after 21 days of immersion were measured by using inductively coupled plasma mass spectrometer (ICP-MS) in conformity with ASTM D5673 (ASTM 2016). The resulting leachates were filtered and acidified to pH<2 for the elemental analysis. Six hazardous elements [cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn)] were selected for qualitative analysis. The pH of leachates was also measured according to ASTM D1293 (ASTM 2012). To access the pH change over time, the pH of leachates measured at 7, 14, 28 days after immersion.

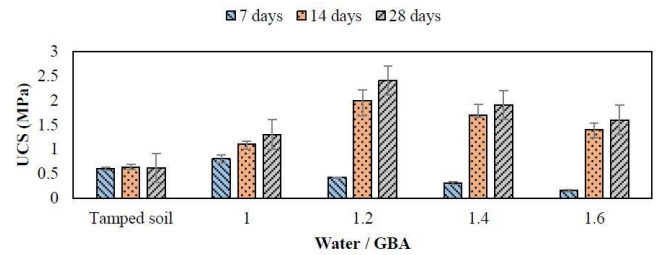


Fig. 4 Effects of water/GBA ratio and curing time on unconfined compressive strength of soil stabilized with ground bottom ash

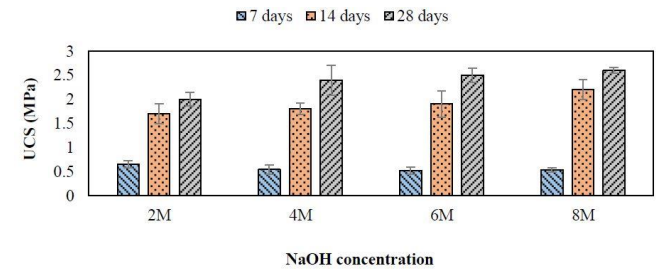


Fig. 5 Effects of NaOH concentration and curing time on unconfined compressive strength of soil stabilized with ground bottom ash

## 3. Results and discussion

### 3.1 Unconfined compressive strength

#### 3.1.1 GB binder groups

Fig. 4 shows the effect of water/GBA ratio on the unconfined compressive strength of the soil stabilized with ground bottom ash. The figure shows the compressive strength of the untreated soil specimen in comparison with that of ground bottom ash-stabilized soils. For specimens cured for 28 days, as water/GBA ratio increases, the compressive strengths of initially increase significantly and then decreases. The highest compressive strength is achieved at the water/GBA ratios of 1.2. This means that there is considerable improvement in the mechanical behavior of bottom ash-stabilized soil when the water/GBA ratio is 1.2. As noted by Davidovits (1994), water plays an important role as a medium for dissolution and transport of dissolved ions. When extra water is added, it dilutes the alkaline activator and attenuates the carbonation and pozzolanic reactions. Furthermore, extra water increases pore space and decreases inter-cluster cementation bonding, resulting in low mechanical performance. Fig. 4 also demonstrates that the rate of compressive strength gain depends on the curing time: the significant strength development is achieved during the period of 7 to 14 days, which is more prominent for the specimens with higher water/GBA ratio.

Fig. 5 shows the influence of NaOH concentration on the unconfined compressive strength of the soil stabilized with ground bottom ash. For specimens cured for 7 days, the compressive strength slightly decreases as the NaOH concentration increases. For specimens cured for 14 and 28 days, however, the compressive strength increases with an



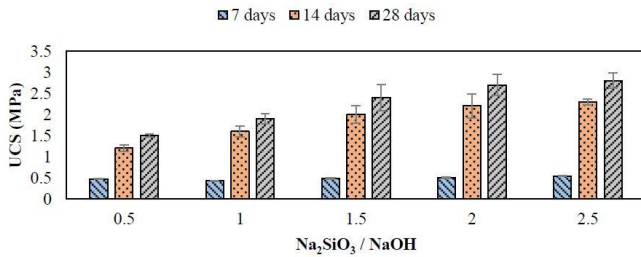


Fig. 6 Effects of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio and curing time on unconfined compressive strength of soil stabilized with ground bottom ash

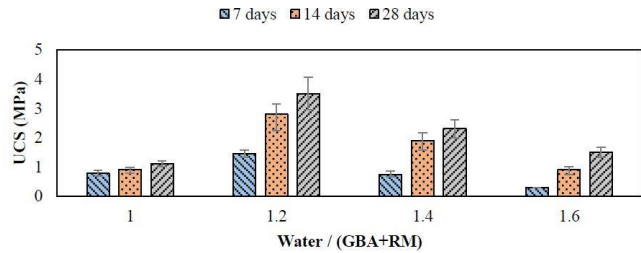


Fig. 7 Effects of water/(GBA+RM) ratio and curing time on unconfined compressive strength of soil stabilized with ground bottom ash and red mud

increase of NaOH concentration. For example, the compressive strength of 28 days curing is 2, 2.4, 2.5 and 2.6 MPa, respectively, when the NaOH concentration is 2, 4, 6 and 8M for a water/GBA ratio of 1.2. Sathonsaowaphak *et al.* (2009) stated that the increase in compressive strength of bottom ash-based mortar by the addition of NaOH is primarily due to the great amount of silica and alumina ions leached from aluminosilicate material and high level of  $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$  ratio in mortar. Strength improvement by adding NaOH to nonclinker cements was also reported in Wang *et al.* (2007).

Fig. 6 shows the effect of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio on the unconfined compressive strength of the soil stabilized with ground bottom ash. The compressive strength of specimens cured for 7 days is insensitive to the  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio. However, the compressive strength increases with increasing  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio for both 14 and 28 days of curing. The increase in compressive strength with increasing  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio can be explained by the increase of soluble  $\text{SiO}_2$  content contributing to the formation of cementitious compounds. This is accordance with the previous works (Hardjito *et al.* 2005; Yahya *et al.* 2015), in which higher  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio leads to higher compressive strength of cementitious compounds. Xu and Van Deventer (2000) demonstrated that the high concentration of silicon in activator accelerates the dissolution of aluminosilicate material, resulting in forming long chain silicate oligomer and Al-O-Si complexes. The existence of such products causes better setting and higher compressive strength of the geopolymer.

### 3.1.2 GRB binder groups

Fig. 7 shows the effect of water/(GBA+RM) ratio on the unconfined compressive strength of the soil stabilized with ground bottom ash and red mud. For a given curing day, the

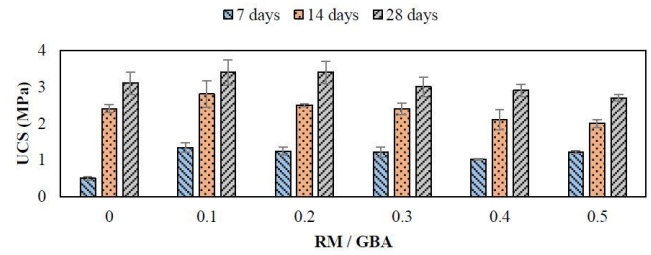


Fig. 8 Effects of RM/GBA ratio and curing time on unconfined compressive strength of soil stabilized with ground bottom ash and red mud

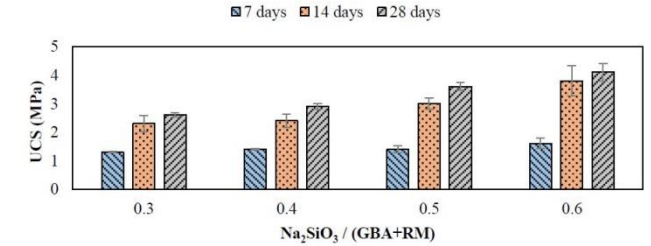


Fig. 9 Effects of  $\text{Na}_2\text{SiO}_3/(\text{GBA}+\text{RM})$  ratio and curing time on unconfined compressive strength of soil stabilized with ground bottom ash and red mud

compressive strength increases with increasing water/(GBA+RM) ratio. A water/(GBA+RM) ratio of 1.2 gives the maximum value of compressive strength. Compressive strength decreases when the water/(GBA+RM) ratio increases to 1.6, thus, indicating that 1.2 is the optimum water/(GBA+RM) ratio for compressive strength of the soil with stabilized with ground bottom ash and red mud. According to Liu and Wu (2012), alkaline-activated cements made with red mud improve compressive strength as well as possess good resistance against sulfate attack and freezing-thawing cycles.

Fig. 8 shows the influence of RM/GBA ratio on the unconfined compressive strength of the soil stabilized with ground bottom ash and red mud. The ground bottom ash-treated soil specimens (i.e., RM/GBA=0) cured for 7, 14 and 28 days fail at the compressive strengths of 0.5, 2.4 and 3.1 MPa, respectively. The replacement of ground bottom ash by red mud causes the strength improvement. At 0.1 RM/GBA ratio, the compressive strengths are maximum at all curing times. The compressive strength continuously decreases with further increase in RM/GBA ratio, indicating that 0.1 is the optimum RM/GBA ratio for compressive strengths in soil stabilized with ground bottom ash and red mud. The compressive strength of stabilized soil increases to a certain limit with the use of red mud in the mixture can be explained by the characteristics of red mud. Firstly, red mud has high alkalinity (pH=11.6) so it can replace the role of NaOH solution which dissolves ions from aluminosilicate materials. Secondly, red mud has fine particles that make specimens become high packing density and low porosity (Liu and Zhang 2011). Lastly, red mud has higher  $\text{CaO}/\text{SiO}_2$  ratio compared to bottom ash, as seen in Table 2. Tastan *et al.* (2011) indicated that the  $\text{CaO}/\text{SiO}_2$  ratio is indicator of the potential for pozzolanic reactions and that the binders with higher  $\text{CaO}/\text{SiO}_2$  ratio is likely to be

Table 5 Element concentrations of leachates from stabilized soils (unit: mg/L)

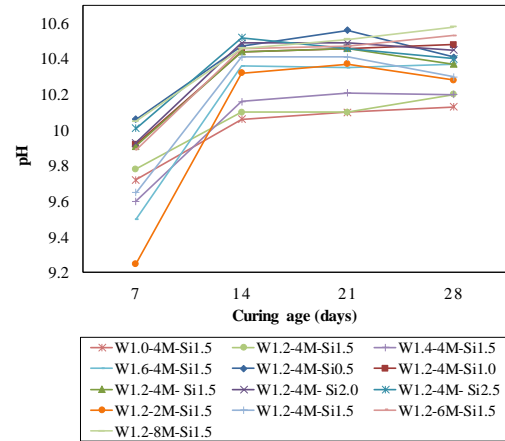
Notation	Cd	Cr	Cu	Ni	Pb	Zn
W1.0-4M-Si1.5	N.D	0.0013	0.1340	0.0034	0.0011	0.0052
W1.2-4M-Si1.5	N.D	0.0016	0.1384	0.0038	0.0011	0.0050
W1.4-4M-Si1.5	N.D	0.0015	0.1371	0.0037	0.0011	0.0045
W1.6-4M-Si1.5	0.0500	0.0014	0.1719	0.0045	0.0012	0.0042
W1.2-2M-Si1.5	0.0000	0.0021	0.5083	0.0066	0.0013	0.0045
W1.2-4M-Si1.5	0.0000	0.0024	0.6220	0.0070	0.0020	0.0055
W1.2-6M-Si1.5	0.0000	0.0026	0.7694	0.0152	0.0016	0.0055
W1.2-8M-Si1.5	0.0000	0.0028	0.8762	0.0269	0.0015	0.0067
W1.2-4M-Si0.5	0.0001	0.0041	0.4280	0.0191	0.0007	0.0059
W1.2-4M-Si1.0	0.0000	0.0028	0.9282	0.0133	0.0007	0.0062
W1.2-4M-Si1.5	0.0000	0.0026	0.9341	0.0097	0.0011	0.0047
W1.2-4M-Si2.0	0.0001	0.0030	0.7840	0.0100	0.0018	0.0066
W1.2-4M-Si2.5	0.0001	0.0029	0.6458	0.0076	0.0018	0.0068
W1.0-R0.2-Si0.5	0.0000	0.0197	0.2123	0.0066	0.0012	0.0060
W1.2-R0.2-Si0.5	0.0001	0.0225	0.2596	0.0071	0.0037	0.0128
W1.4-R0.2-Si0.5	0.0001	0.0189	0.2426	0.0064	0.0034	0.0111
W1.6-R0.2-Si0.5	0.0002	0.0191	0.2646	0.0052	0.0039	0.0095
W1.2-R0.0-Si0.5	N.D	0.0012	0.1068	0.0024	0.0036	0.0245
W1.2-R0.1-Si0.5	0.0002	0.0094	0.1989	0.0059	0.0050	0.0121
W1.2-R0.2-Si0.5	0.0000	0.0149	0.2131	0.0060	0.0018	0.0083
W1.2-R0.3-Si0.5	0.0000	0.0207	0.2090	0.0060	0.0014	0.0073
W1.2-R0.4-Si0.5	0.0001	0.0306	0.2556	0.0066	0.0016	0.0088
W1.2-R0.5-Si0.5	0.0001	0.0361	0.3283	0.0077	0.0018	0.0096
W1.2-R0.2-Si0.3	0.0000	0.0178	0.2110	0.0060	0.0016	0.0078
W1.2-R0.2-Si0.4	0.0000	0.0257	0.2323	0.0063	0.0015	0.0080
W1.2-R0.2-Si0.5	0.0000	0.0149	0.2131	0.0060	0.0018	0.0083
W1.2-R0.2-Si0.6	0.0000	0.0269	0.2696	0.0068	0.0017	0.0087
USEPA (1993)	0.005	0.1	1.3	-	0.015	-
MOE (2015)	0.005	0.05	1	-	0.01	3

more effective stabilizers. Accordingly, the increase in CaO/SiO<sub>2</sub> ratio with the inclusion of red mud improves the strength development.

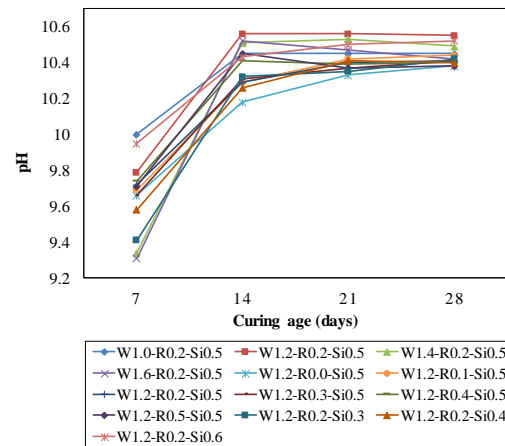
Fig. 9 shows the effect of Na<sub>2</sub>SiO<sub>3</sub>/(GBA+RM) ratio on the unconfined compressive strength of the soil stabilized with ground bottom ash and red mud. With the exception of specimens cured for 7 days, the compressive strength increases with an increase of Na<sub>2</sub>SiO<sub>3</sub>/(GBA+RM) ratio. This result supports the idea that higher Na<sub>2</sub>SiO<sub>3</sub> content provides more reactive silica and hence promotes a larger extent of stabilization of the soil mixture. Duxson *et al.* (1994) demonstrated that higher concentration of soluble silica in geopolymer induces an increase of silicon in its structure, leading to higher compressive strength.

### 3.2 Leachate concentration and pH

Table 5 summarizes the trace element concentrations in the leachate from the specimens. In general, the highest concentration is achieved for Cu, followed by Zn, Ni, Cr, Pb and Cd. The measured concentrations are compared to drinking water maximum contamination levels suggested by the United States Environmental Protection Agency (USEPA 1993) and the Ministry of Environment, South



(a) Leachate pH of soil stabilized by GB binder



(b) Leachate pH soil stabilized by GBR binder

Fig. 10 Leachate pH versus curing time

Korea (MOE 2015). As shown, the concentrations of trace elements are below the permissible level, indicating that the heavy metals present in the bottom ash and red mud may not leach beyond critical limits. Consequently, the stabilized soils studied have no detrimental impact on the environmental. It is noteworthy that the leach concentrations of trace metals obtained from this study may differ from those from batch water test or column test that provides realistic leaching characteristics (Mofarrah *et al.* 2012).

Fig. 10 shows the variations of pH of leachates from specimens against curing time. The pH increases rapidly in 14 days and then approach equilibrium with further increase in curing time. More importantly, the pH of leachates ranges between 9.3 and 10.6, which falls within upper and lower bounds ( $2 < \text{pH} < 12.5$ ) of USEPA criteria. This result indicates that the soil stabilized with bottom ash and red mud would be an environmentally friendly material.

## 4. Conclusions

The following conclusions may be drawn from the present work:

- Industrial solid wastes (ground bottom ash and red

mud) can be used to stabilize the weathered soils. For all studied specimens, the rate of strength improvement was more pronounced at the later age than at the early age.

- With regard to the unconfined compressive strength, the water/binder of 1.2 was found to be optimum ratio for both the GB binder and GBR binder groups. For 28 days of curing, the compressive strengths of soils stabilized with alkaline-activated GB binder and GBR binder were 2.8 MPa and 4.1 MPa, respectively.

- For a given ratio of solid waste and soil (0.33), the replacement of ground bottom ash by red mud increased the unconfined compressive strength of the stabilized soils. At all curing times, the compressive strength increased when the RM/GBA ratio was increased from 0 to 0.1. However, the compressive strength decreased when the RM/GBA ratio was increased to 0.5, indicating 0.1 was the optimum RM/GBA ratio for soils stabilized with ground bottom ash and red mud.

- The addition of the chemical activators (NaOH and  $\text{Na}_2\text{SiO}_3$ ) increased the unconfined compressive strength of the stabilized soils. Moreover, based on the results obtained with GBR binder, it can be concluded that red mud can replace the role of NaOH in the formation of cementitious and pozzolanic gels due to its own alkalinity.

- The metal concentrations and pH of the leachates from the stabilized soils after 28 days of curing showed minimum environmental impacts within the permissible limits.

The laboratory investigation of this study revealed that the ground bottom ash and red mud are recyclable and can be utilized as soil stabilizer or fill material for geotechnical engineering applications.

## Acknowledgments

This research was supported by a grant (No. 16-RDRP-B076564-03) from Regional Development Research Program funded by the Ministry of Land, Infrastructure and Transport of Korean government.

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