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≪ **Research Paper** ≫

Investigation of Strength Characteristics of Ferrous Slag and Waste Concrete in Water Contacting Environment by Exposure to Raining Events

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ABSTRACT

Ferrous slag is a by-product from steel making process and waste concrete is generated from construction activities. Large part of ferrous slag and waste concrete are recycled as construction materials. However, Ca^{2+} leaching out of ferrous slag and waste concrete in the water-contacting environment can cause a strength change. Strength can be reduced due to the dissolution of solid form of CaO which is one of the main contents of ferrous slag and waste concrete. On the other hand, strength can be enhanced due to the pozzolanic reaction of cementitious components with water. In this study, steelmaking slag, blast furnace slag, and waste concrete were aged by exposure to raining events, and the change of their compaction and shear strength characteristics was investigated. Optimum moisture content of all materials used in this study increased with aging period while maximum dry unit weight slightly decreased, implying that the relative contents of fine particles increased as the CaO solid particles were dissolved. Internal friction angle and shear strength of recycled materials also increased with aging period, indicating that the materials became denser by the decrease of void ratio attributed to the fine particles generated during the weathering process and the development of cementitious compounds increasing the bonding and interlocking forces between the particles. The results of this study demonstrated that mechanical strength of recycled materials used as construction materials has little chance to be deteriorated during their service life.

Key words : Steelmaking slag, Blast furnace slag, Waste concrete, Harvard miniature compaction test, Direct shear test

1. Introduction

Ferrous slag which is a by-product from steel making process and waste concrete generated from construction activities have been recycled as construction materials. Reuse of ferrous slag and waste concrete is desirable for economic and environmental aspect by reducing the amount of materials to be disposed. Blast furnace slag is employed as the concrete admixture and the cement raw materials for its cementitious characteristic as a pozzolanic material (Shi et al., 2004). Steel slag contains useful resources such as Fe, C, CaO and waste concrete has been found to have little harmful effects on environment. Numerous researches for recycling the ferrous slag and waste concrete have been carried out all around the world, including application of composite slag for roadbed material (Kim et al., 2003), comparative study of mixed soils with paper fly ash and blast furnace slag (Lee and Lee, 2003), investigation on the engineering and environmental properties of reclaimed concrete materials as road materials (Lee et al., 2005), and estimation on the performance of recycled aggregate concrete (Limbachiya et al., 2004; Arulrajah et al., 2011; Jin et al., 2003). It has been known that the long-term strength of concrete increase when blast furnace slag powder is added (Gengying and Xiaohua, 2003) and the overall strength can be increased by pozzolanic reaction (Kim et al., 2009).

However, Ca^{2+} can be leached out of ferrous slag and waste concrete during the materials contact with water for a long time, resulting in the change of their engineering properties like mechanical strength. Strength can be reduced due to the dissolution of solid form of CaO which is one of the main contents of ferrous slag and waste concrete. On the

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other hand, strength can be enhanced due to the pozzolanic reaction of cementitious components with water. Change of the mechanical strength of recycled materials could be critical because it might cause deterioration of the structure which those are supporting.

In this study, the change of strength characteristics of recycled materials including ferrous slag and waste concrete were estimated by exposure to raining events. The scope of target materials is limited to ferrous slag and waste concrete themselves.

2. Materials and Methods

2.1. Materials

Steelmaking slag and blast furnace slag were obtained from G steelworks in Korea. Blast furnace slag could be categorized as two types by cooling method as granulated BF slag and air-cooled BF slag. Air-cooled BF slags generally recycled as road construction materials were used in this study.

Waste concrete was collected from a reconstruction site in Seoul National University. Most of the waste concrete were composed of cement hydrate, unhydrated cement, and granite powder.

All materials were air-dried for a week and passed through #4 sieve for Harvard miniature compaction test (Peter et al., 1987). XRF (X-ray Fluorescence Spectrometry, Shimadzu model XRF-1700) analysis was performed to determine the chemical composition.

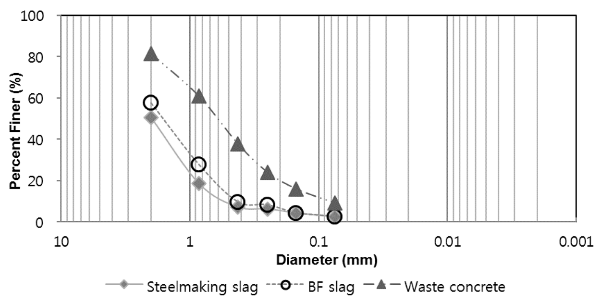


Fig. 1. Particle size distributions of recycled materials.

Fig. 1 shows the particle size distribution of ferrous slag and waste concrete, and compositional and geotechnical characteristics are summarized in Table 1 and Table 2, respectively. Uniformity coefficient (C_u) and coefficient of curvature (C_c) of steelmaking slag are 4.0 and 1.09, respectively, representing the poor particle size distribution. Uniformity coefficient (C_u) and coefficient of curvature (C_c) of blast furnace slag are 4.89 and 0.91, respectively. In case of waste concrete, uniformity coefficient (C_u) and coefficient of curvature (C_c) are 11.11 and 1.78, respectively, indicating the well graded particle size distribution. As shown in Table 1, all materials contain high CaO contents.

2.2. Experimental Methods

2.2.1. Aging of materials

Steelmaking slag, blast furnace slag, and waste concrete were exposed to raining environment for inducing natural weathering. A column with 5.5 cm of diameter and 20 cm of height was manufactured by acrylic material. The upper end was opened to allow the rainfall percolating sample in column and the lower end was closed by perforated cap and a porous was installed directly above the hole to prevent runoff of samples. A sampling bottle was placed below the lower hole of column to collect effluents. A schematic diagram of test column is shown in Fig. 2.

The column was filled with steelmaking slag, blast furnace slag, and waste concrete with their optimum moisture content, respectively. The optimum moisture contents were carried out from Harvard miniature compaction test. Exposure was started on June 16th, 2011 and weathering periods were 30 days, 90 days and 150 days. The number of raining days and average daily precipitation were 19 days (39.3 mm), 48 days (35.0 mm), and 60 days (29.2 mm), respectively. Based on the raining information, the amounts of rainfall infiltrated through column are about 1.77 L,

Table 1. Chemical composition of recycled materials

Composition	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	S	MnO	TiO_2
Steelmaking slag (%)	13.8	44.3	1.5	17.5	6.4	0.07	5.3	1.5
Blast furnace slag (%)	33.8	42.0	14.4	0.3	6.7	0.8	0.3	1.0
Waste concrete (%)	18.1	58.7	4.9	2.9	2.3	0.3	0.2	12.8

Table 2. Geotechnical characteristics of recycled materials

	Specific gravity	C_u	C_g	W/P	Percentage of passing through #200 [%]
Steelmaking slag	3.51	4.00	1.09	Poorly graded	2.27
Blast furnace slag	2.97	4.89	0.91	Poorly graded	2.56
Waste concrete	2.54	11.1	1.78	Well graded	5.9

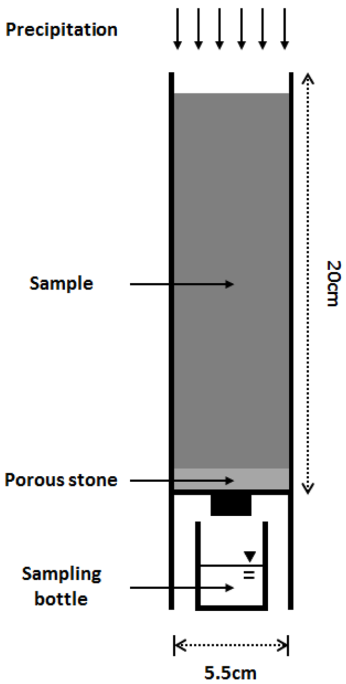


Fig. 2. A schematic diagram of test column.

3.99 L, and 4.16 L, respectively. The weather information was obtained from the data provided by Korea Meteorological Administration.

2.2.2. Measurement of chemical characteristics of effluents

The effluents were collected regularly from the sampling bottle and filtered out through 0.45ìm membrane filter (Millipore, USA). The pH was measured using pH meter (Orion 5 Star, Thermo scientific), and calcium ion concentration was analyzed by ICP-AES (ICP-Atomic Emission Spectrometer, PerkinElmer, Optima-4300 DV).

2.2.3. Assessment of mechanical characteristics of materials

Samples in column after each exposure period (30, 90, 150 days) were collected and tested to assess geotechnical characteristics of each weathered material.

Harvard miniature compaction test using a mold with 3.3 cm diameter and 7.15 cm height was conducted to determine the change of the compaction properties with aging time. Three layers at 25 tamps per layer were performed. Tap water was used for preparing samples. Harvard miniature compaction test was selected since the quantity of sample obtainable from exposure test is relatively small to perform other compaction tests such as standard proctor compaction test. Harvard miniature compaction test is known to effectively duplicate the compaction with small amount of soil sample.

Direct shear test was conducted by following ASTM D 3080 to investigate the variation of shear strength properties with aging time. Size of shearing box having the dimension of 6.6 cm in diameter and 3.3 cm in height was operated at with the shearing rate of 0.4mm/min. Shear stress (τ) can be obtained from the cohesion (c’) and internal friction angle (Φ’).

$$\tau = c' + \sigma\tan\Phi' \quad (1)$$

Specimens were sheared until no more increment of shear stress was observed, and the shear stress at this point was considered as the maximum shear stress. The time for consolidation was relatively short because of the short drainage path, but volume change or pore pressure cannot be measured in the direct shear test.

3. Results and Discussion

3.1. Variation of pH and Ca^{2+} concentration

Variation of pH and Ca^{2+} concentration with aging time are shown in Fig. 3(a) and 3(b), respectively. The pH of effluents were high in the range of 10~13 in the initial stage of aging, but gradually decreased with time. The strong alkaline property of effluents at the initial stage might be contributed to the reactions described by the following equations.

$$\text{Free-CaO} + H_2O \rightarrow Ca(OH)_2 \quad (2)$$

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- \quad (3)$$

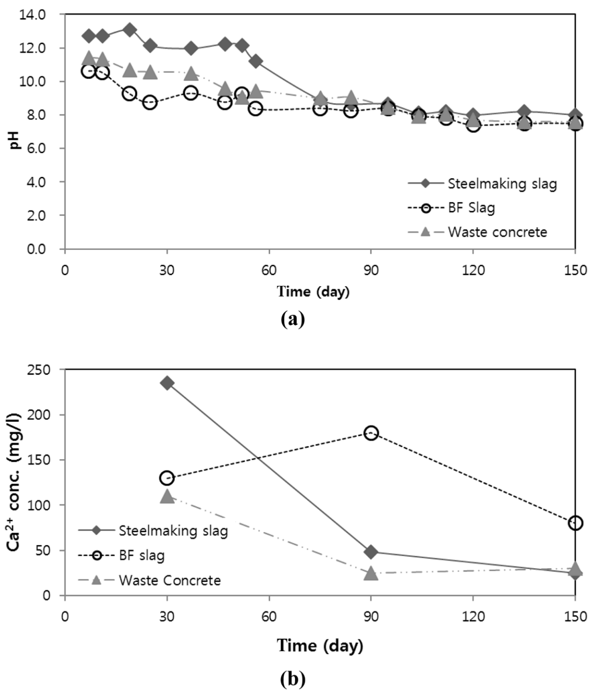


Fig. 3. Variation of (a) pH and (b) Ca^{2+} concentration with time.

Reaction of free-CaO and H_2O produces $Ca(OH)_2$ (Equation 2) which should be subsequently dissolved in water as shown in Equation 3. Hydroxyl ions derived from $Ca(OH)_2$ dissolution might result in the high pH of effluents. The rate of dissolution was presumed to gradually decrease based on results of the Ca^{2+} concentration of effluents (Fig. 3(b)). The decrease tendency of pH also supports the estimation.

Steelmaking slag and blast furnace slag have large amount of CaO, SiO_2 and Al_2O_3.as shown in Table 1. These components can produce calcium silicate hydrate (CSH, CaO-SiO_2-H_2O) and calcium aluminate hydrate (CAH, CaO-Al_2O_3-H_2O) by hydration and pozzolanic reaction in the ground (Mostafo et al., 2001). It is expected that similar reaction might occur in waste concrete because CaO and SiO_2 are abundant in waste concrete. Since Ca^{2+} is consumed by the hydration and pozzolanic reaction, the decreasing tendency of Ca^{2+} can be explained during the weathering proceeds.

3.2. Compaction characteristics with aging period

Harvard miniature compaction tests were performed to investigate effect of weathering on the compaction properties and the results are shown in Fig. 4.

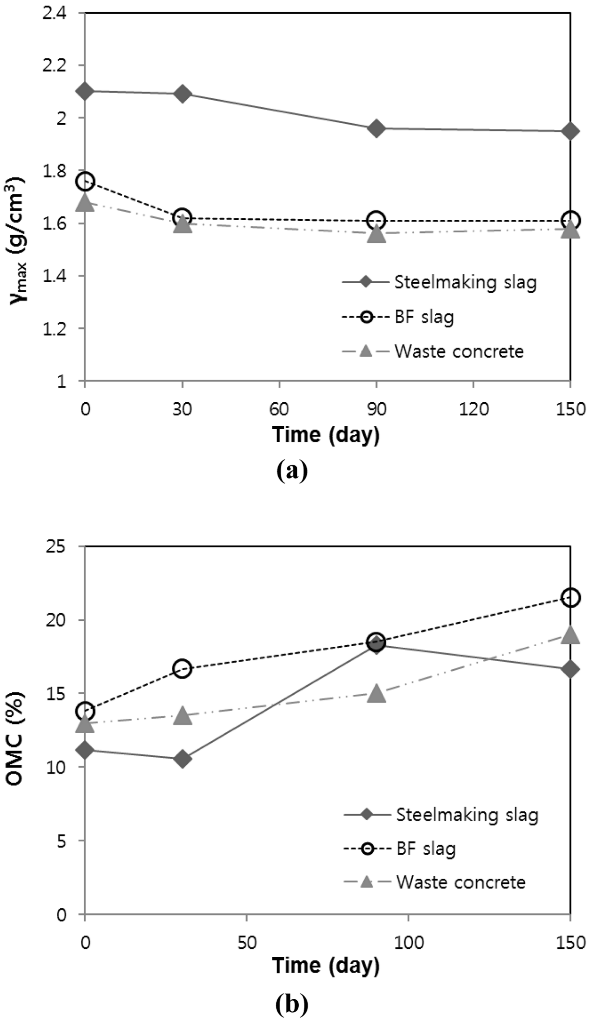
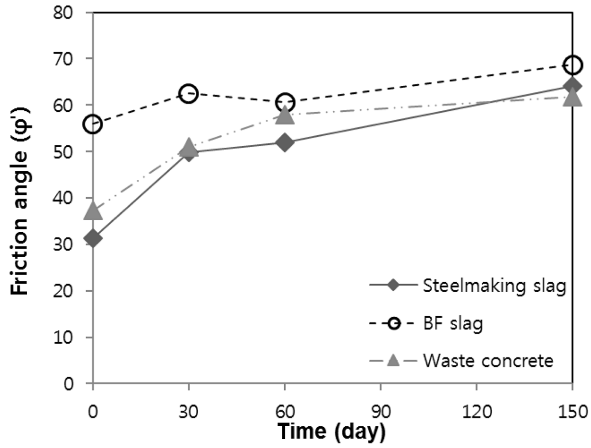


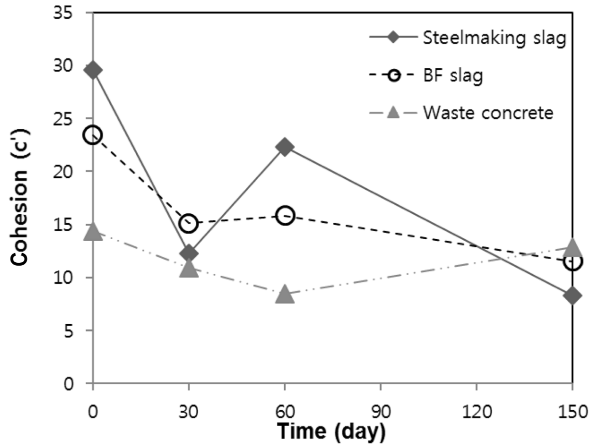
Fig. 4. Variation of compaction characteristics of (a) Maximum dry unit weight (γ_{max}) and (b) Optimum moisture content (OMC) with aging period.

Maximum dry unit weight of steelmaking slag was highest while blast furnace slag and waste concrete had similar value of maximum dry unit weight. However change of maximum dry unit weight was not significant with aging period.

Optimum moisture content of all materials increased with aging period; from 11.15% to 16.64% for steelmaking slag, from 13.8% to 21.5% for blast furnace slag, and from 13.1% to 18.8% for waste concrete. Osinubi (2006) reported that optimum moisture content should be increased as the hydration of material proceeds because more water is needed for the hydration of lime and slag applied in soil improving. For the same reason, the optimum moisture content of



(a)



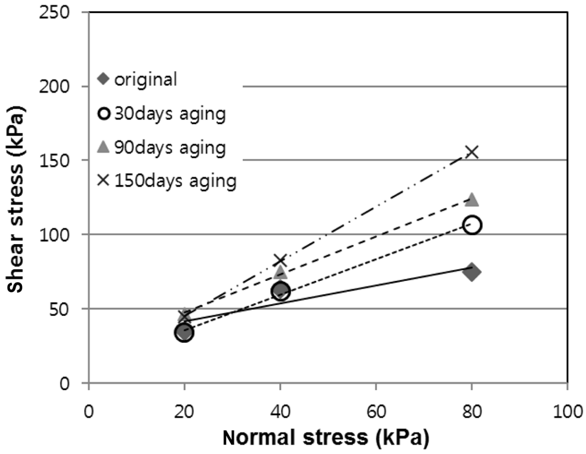
(b)

Fig. 5. Variation of shear strength characteristics of (a) internal friction angle and (b) cohesion with aging period.

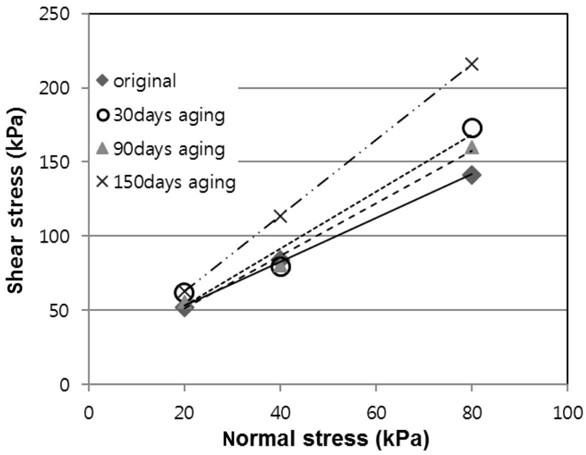
materials estimated in this study increased because hydration should further proceed with aging period. The maximum dry unit weight was slightly decreased while optimum moisture content was increased which imply that the relative contents of fine particles were increased. This phenomenon is assumed that the size of CaO solid particles were gradually decreased by dissolution reactions.

3.3. Shear strength characteristics with aging period

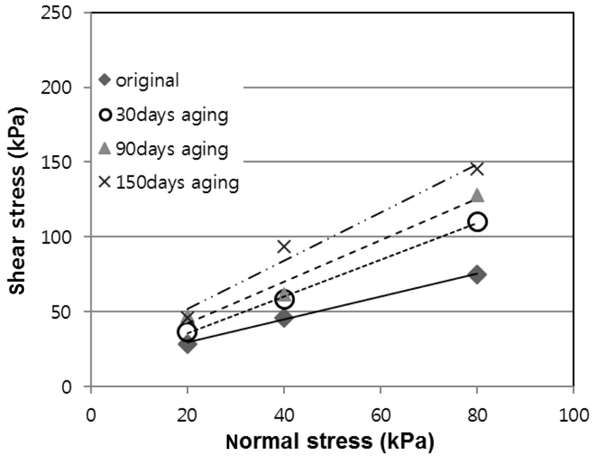
Shear strength characteristics of materials exposed to raining conditions are shown in Fig. 5 and 6. Fig. 5(a) shows variation of internal friction angle with aging period and Fig. 5(b) shows that of cohesion. Internal friction angle of original steelmaking slag, blast furnace slag and waste



(a)



(b)



(c)

Fig. 6. Variation of shear stress of (a) steelmaking slag, (b) blast furnace slag, and (c) waste concrete aged during different period with normal stress.

concrete were 31.26°, 55.93°, and 37.28°, respectively. Internal friction angle increased with aging period to 64.13° for steelmaking slag, 68.63° for blast furnace slag, and 61.79° for waste concrete and those values are higher than that of Joomunjin sand (Korean standard sand) (30° ~ 45°). The original materials of steelmaking slag, blast furnace slag and waste concrete had higher cohesion than aged materials but there were no consistent changes with aging period.

Fig. 6 shows the shear stress under the normal stress condition with aging time. At normal stress of 80 kPa, the shear stress of all materials increased with aging period. Maximum shear stress of blast furnace slag having highest internal friction angle was 216.02 kPa, and those of steelmaking slag and waste concrete were 155.54 kPa and 145.45 kPa. The ratio of 150 day aged materials to original materials was 1.70 for steelmaking slag, 1.46 for blast furnace slag and 1.93 for waste concrete, indicating that the shear strength of materials increased during the weathering.

The enhanced shear strength of the materials during the exposure to raining events might be attributed to the formation of hydrates formed by the reaction of cementitious compounds such as C3S($3CaO{\cdot}SiO_2$), C2S($2CaO{\cdot}SiO_2$), C3A ($3CaO{\cdot}Al_2O_3$) and C4AF($4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$) with water (Bujang et al., 2003; Chang et al., 2001; Hajiali et al., 1992). Since hydration of cementitious compounds is complicated and time-consuming process, it is hard to represent these reactions with simple reaction formula. However the hydration of cementitious compounds could be roughly described with the following equations.

$$2(3CaO{\cdot}SiO_2)+6H_2O \rightarrow 3CaO{\cdot}SiO_2{\cdot}3H_2O+3Ca(OH)_2 \quad (4)$$

$$2(2CaO{\cdot}SiO_2)+4H_2O \rightarrow 3CaO{\cdot}2SiO_2{\cdot}2H_2O+Ca(OH)_2 \quad (5)$$

$$2(3CaO{\cdot}Al_2O_3)+27H_2O \rightarrow 4CaO{\cdot}Al_2O_8{\cdot}19H_2O+2CaO{\cdot}Al_2O_8{\cdot}8H_2O \quad (6)$$

$$4CaO{\cdot}Al_2O_3{\cdot}19H_2O+2CaO{\cdot}Al_2O_3{\cdot}8H_2O \rightarrow 2(3CaO{\cdot}Al_2O_8{\cdot}6H_2O)+15H_2O \quad (7)$$

The compounds such as $3CaO{\cdot}SiO_2$, $2CaO{\cdot}SiO_2$, $3CaO{\cdot}Al_2O_3$, and $4CaO{\cdot}Al_2O_3{\cdot}19H_2O$ in the materials might react with water and produce calcium hydroxide ($Ca(OH)_2$), calcium silicate (CSH, $CaO\text{-}SiO_2\text{-}H_2O$) and calcium aluminate (CAH, $CaO\text{-}Al_2O_3\text{-}H_2O$) which could make their structures denser. Some pores in the materials are filled with these precipitates which also lead to the increments in the bonding and interlocking forces between the particles. Consequently, the effect of Ca^{2+} leaching out of the materials was not significant when compared to the pozzolanic reaction, resulting in the increase of internal friction angle and shear strength.

4. Conclusions

Assessments of strength characteristics of industrial wastes such as steelmaking slag, blast furnace slag, and waste concrete were performed in this study. The materials was aged by exposure to raining events and the consequent change of shear strength and compaction properties were investigated by harvard miniature compaction test and direct shear test, respectively. The findings from this study could be summarized as:

(1) The pH of effluent from the materials decreased from the high initial alkaline value above 10 with aging period, indicating that a large amount of Ca^{2+} might be leached out in the initial stage of aging, and the leaching amount decrease with time. It is expected that calcium silicate hydrate and calcium aluminate hydrate are could be formed by pozzolanic reaction in the materials.

(2) Maximum dry unit weight slightly decreased with time, and optimum moisture content of all materials increased with aging period because the relative contents of fine particles increased as the CaO solid particles were dissolved.

(3) Shear strength of the materials increases with weathering. Namely, internal friction angle increased with aging period indicating that the materials became denser by the decrease of void ratio attributed to the fine particles generated during the weathering process and the development of cementitious compounds leads to the increments in the bonding and interlocking forces between the particles.

(4) The results of this study demonstrated that mechanical strength of recycled materials used as construction materials has little chance to be deteriorated during their service life.

(5) The waste materials are not solely used in field appli-

cation, so the geotechnical behavior of sand mixture or concrete mixture using waste materials need to be further investigated.

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References

Arulrajah, A., Piratheepan, J., Aatheesan, T., and Bo, M. W., 2011, Geotechnical properties of recycled crushed brick in pavement applications, *Journal of Materials in Civil Engineering*, **23**(10), 1444-1452.

Bujang, B.K.H., Shukri, M., and Thamer, A.M., 2003, Effect of chemical admixtures on the engineering properties of tropical peat soils, *American Journal of Applied Sciences*, **2**(7), 1113-1120.

Chang, P., Park, Y., Song, C., Woo, C., and Lee, S., 2001, Compaction and strength characteristics of reinforced soil for building divider, *Geosynthetics-2001 conference.*

Gengying, L. and Xiaohua, Z., 2003, Properties of concrete incorporating fly ash and ground granulated blast-furnace slag, *Cem. Concr. Res.*, **25**, 293-299.

Hajiali, A., Adnan, A., and Chew, K.C., 1992, Geotechnical properties of a chemically stabilized soil from Malaysia with rice husk ash as an additive, *Journal of Geotechnical and Geological Engineering*, **10**(2), 117-134.

Jin, S., Lee, H., Hwang, J., Jin, C., and Park, H., 2003, An experimental study to determine the mechanical properties of recycled aggregate separated from demolished concrete and recycled aggregate concrete, *The Journal of Engineering Geology*, **3**(3), 345-358.

Kim, D., Lee, J., Lee, H., and Son, J., 2003, A study on application of composite slag for roadbed material, *J. Korea Soc. Waste Manag.*, **17**(4), 374-383.

Kim, Y. and Kang, H., 2009, Shearing properties of waste tire powder-added lightweight soil by direct shear test, *Journal of the Korean Society of Ocean Engineering*, **23**(3), 20-29.

Lee, K. and Lee, J., 2003, Comparative study of mixed soils with PFA and blast furnace slag, *2003 Annual Conference of Korean Society of Civil Engineering*, 3445-3450.

Lee, Y., Kwan, Y., and Hyun, J., 2005, The engineering and environmental properties of reclaimed concrete materials as road materials, *J. Korea Geo-Environ. Soc.*, **6**(3), 17-23.

Limbachiya, M.C., Koulouris, A., Roberts, J.J., and Fried, A.N., 2004, Performance of recycled aggregate concrete, *RILEM International Symposium on Environment-Conscious Materials and System for Sustainable Development*, 127-136.

Mostafa, N.Y., El-Hemaly, S.A.S, Al-Wakeel, E.I., El-Korashy, S.A., and Brown, P.W., 2001, Characterization and evaluation of the hydraulic activity of water-cooled slag and air-cooled slag, *Cem. Concr. Res.*, **31**, 899-904.

Osinubi, K.J., 2006, Influence of compactive efforts on lime-slag treated tropical black clay, *J. Mater. Civ. Eng.*, **18**(2), 175-181.

Peter, J.B. and Carlos, O.G., 1987, Frictional properties between sand and various construction materials, *Journal of Geotechnical Engineering*, **113**(9), 1035-1039.

Shi, C., 2004, Steel slag-its production, processing, characteristics, and cementitious properties, *Journal of Materials in Civil Engineering*, **16**(3), 230-236.