Geotechnical characteristics of soils with refractory waste

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ABSTRACT: In Korea, about 10% of steel industrial byproducts are discarded by landfill. Among the materials, hydration of magnesia refractory (mainly composed of MgO) is known to increase the volume due to density change which can cause severe damages to structures. This study aims to study modified geotechnical characteristics of soils with different amount of magnesia refractory waste due to hydration of MgO. One-dimensional swelling test and direct shear test are performed with specimen prepared by compacting mixture of sand and crushed refractory brick (MR) with weight ratio = 0, 30, 50, 70 and 100%. Swelling pressure and volumetric strain increased with increment of MR contents. However, MR swell index indicates the critical MR contents that can reinforce the mixture. Residual friction angle decreased with increment of MR contents for before and after hydration as contact friction of MR-to-MR and sand-to-MR are smaller than sand-to-sand. Dramatic decrement has been observed for pure MR due to mineralogy and morphology change of MR after hydration reaction.

Keywords: industrial waste, MgO hydration; 1-D swelling test; residual friction angle

1. Introduction

In Korea, approximately 10% of generated byproducts from a steel industry including slag, sludge, dust and refractory materials amounted steel production are discarded by landfill [1]. Among refractory materials, magnesia refractory, where dead-burned magnesium oxide (MgO) predominantly consists the refractory, is known to have vulnerability because a hydration of MgO to magnesium hydroxide ($Mg(OH)_2$) is occurred when the materials are in contact with humid air, water or stream (Eq (1)). The hydration results in a volume expansion up to 200% of its original volume due to density change [2, 3].

$$MgO + H_2O = Mg(OH)_2 \quad (1)$$

Hydration of buried magnesia refractory waste causes a soil movement leading serious damages to structures. Especially for foundation structures, novel approach is needed to consider the upward pressure applied by MgO hydration. This study aims to investigate the swelling characteristics (i.e., swelling strain and pressure due to MgO hydration) of MgO and modified geotechnical characteristics of soils with magnesia refractory.

2. Experimental Procedure

2.1. Materials

Crushed magnesia refractory bricks were used in this study to generate homogeneous mixture of soil-magnesia refractory (MR) as shown in Figure 1. The median diameter (D_{50}) of MR and crushed sand was 0.22 mm and 0.18 mm, respectively. Both MR and sand were classified as SP according to USCS. Table 1 summarizes basic properties of the MR and sand.

Figure 1. Shredded magnesia refractory bricks (MR)

Table 1. Basic properties of crushed MR and sand

Types	G_s	D_{10}(mm)	D_{30}(mm)	D_{50}(mm)	C_u	C_c	USCS
Crushed MR	3.41	0.05	0.11	0.22	7.35	0.82	SP
Sand	2.64	0.09	0.14	0.18	2.24	1.21	SP

2.2. Specimen preparation

MR was initially mixed with sand at 5 different weight ratio (%) = 0, 30, 50, 70, 100. Specimens were prepared by compacting the dry mixture with compaction energy

60 kN-m/m^3. Then the specimens were saturated to initiate hydration of MgO and hydration reactions processed for 20 days. To accelerate the hydration reaction of MgO, 0.1 molL^{-1} and 70°C hydration agent, magnesium acetate, ($(CH_3COO)_2Mg$), was used [4, 5].

2.2.1. One-dimensional swelling test

Specimens were prepared at a cylindrical mold with diameter of 50mm and height of 30mm. A load cell was installed on the top of the mold to measure the vertical swelling pressure of sand-MR mixture directly under contant volume [6]. Furthermore, free-swell tests were performed to measure the swelling of sand-MR mixture. Swelling amount was measured with time.

2.2.2. Direct shear test

Shear resistance of sand-MR mixture was measured by using a direct shear device. The diameter of the shear box was 60mm, and initial height of the mixture was 45mm. The vertical and horizontal displacements are measured by using LVDT. Strain-controlled shearing were conducted for all shear tests. The applied horizontal strain is fixed at 1mm/min (ASTM D5321). For speciemns after hydration reaction, preconsolidation pressure 50kPa was applied for 24 days before shearing. The residual friction angle was decided with effective stresses of 100,200 and 300kPa.

2.2.3. Mineralogy and morphology analysis

To access the mineralgy diffrence before and after the reaction, X-ray diffraction (XRD) patterns were recorded for before and after the reaction over the 2θ range from 10˚ to 90˚. Also, the morphology was compared via scanning electron microscope (SEM).

3. Results and Analysis

3.1. Basic properties

3.1.1. Specific gravity

Specific gravity (G_s)of the mixtures was measured following ASTM D854 for before and after hydration reaction. To avoid further hydration, vacuum system was applied. Figure 2 shows the variation of specific gravity of mixture ($G_{s,mix}$) with MR contents. It is shown that measured $G_{s,mix}$ matches well with the estimated $G_{s,mix}$, that is calculated by considering weight fraction of MR based on the specific gravity of sand ($G_{s,sand}$ =2.64) and MR after hydration reaction ($G_{s,MR(after)}$ = 2.42). Since the hydration reaction could be changed the density of MR [2, 3], it can be assumed that MR in all sand-MR mixtures after reaction have similar hydration rate which will not affect further behavior difference.

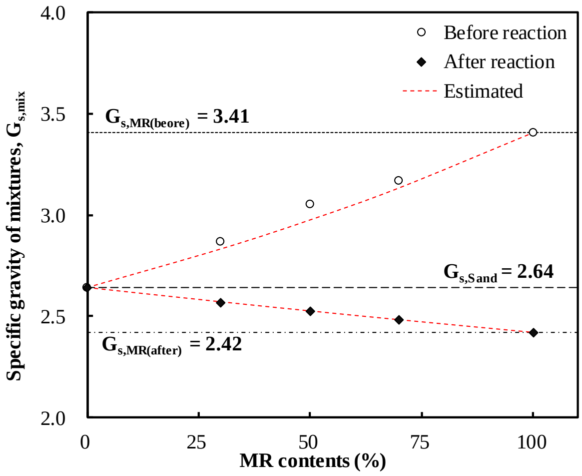

Figure 2. Specific gravity of sand-MR mixture ($G_{s,mix}$) with different MR contents compared with estimated value

3.1.2. XRD and SEM analysis

Figure 3 (a) shows the XRD pattern of MR=100% specimen before and after the reaction. Pure MR specimen before reaction showed characteristics of pericalse structured MgO, while, after the reaction , it showed brucite phase of $Mg(OH)_2$.This corresponds to past studies [7, 8], meaning the hydration reaction has been successfully occurred in the sand-MR specimens. Figure 3 (b) and (c) show the SEM image of MR=100% before and after the reaction. As shown in Figure 3, morphology of MgO has been changed to hexagonally shaped morphologies which represents brucite crystallites [9].

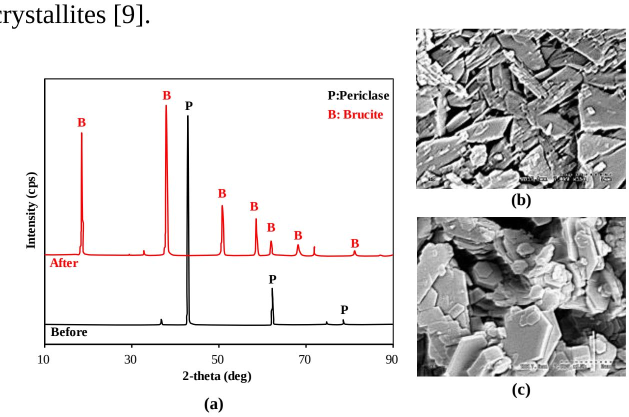

Figure 3. (a) XRD patterns of MR=100% before and after reactions; SEM image of MR=100% (b) before and (c) after reactions

3.2. One-dimensional swelling test

Swelling pressure (SP) and volumetric strain (VS) increased with rection time and converged at day 20. Figure 4 only shows SP and VS of two cases: MR=100% and MR=30% as other sand-MR mixtures shows similar development trends. It is noticeable that the VS converges faster than that of SP. This may be due to energy dissipation occurred by movement of sand-MR mixture along the side of cells, however, further study is needed.

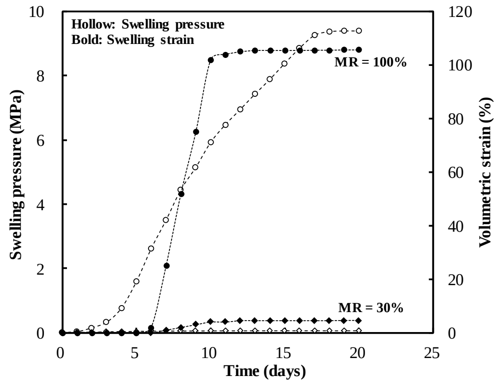

Figure 4. One-dimensional swelling test for sand-MR mixture

Table 2 summarizes SP and VS of the mixtures at day 20. It is obvious that increment of MR in the mixture increased SP and VS. Furthermore, the relationship of SP and VS are summarized with power function: SP (MPa) = $0.00003(\text{VS }(\%))^{2.760}$ with $R^2 = 0.90$.

To analyze the pure effect of MR hydration on soil swelling, the term MR swell index is defined as total swell amount (mL) divided by weight of MR (g) in the mixture. MR swell index indicates the ability of 1g of MR to swell in the sand-MR mixture. As shown in Figure 5, the mixture with MR=30% shows the least MR swell index, and when MR >30% MR the swell index shows trivial differences.

Table 2. Swelling pressure and volumetric strain of sand-MR mixture at 20 days

MR contents (%)	100	70	50	30	0
Swelling pressure (MPa)	9.39	4.89	1.57	0.07	0.00
Volumetric strain (%)	105.7	77.7	55.2	4.6	0.0

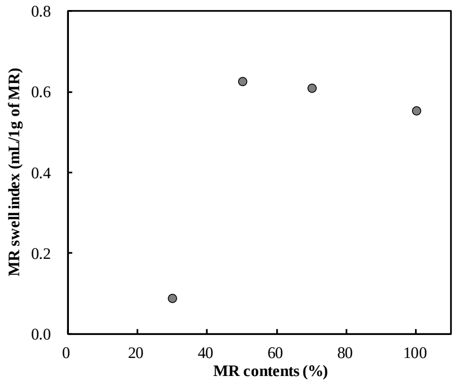

Figure 5. Swell amount divided by MR weight in the mixture at different MR contents (%)

The least value of MR swell index for MR=30% can be explained with the porosity. The dry density of MR=100% after reaction was measured, and for different sand-MR mixtures the total weight of mixtures was estimated considering weight ratio of sand and MR. Table 3 summarizes porosity of before and after reaction of sand-MR mixture. Porosity after reaction normally increased (i.e. the void increased), however, MR=30% mixture clearly showed porosity decrement (i.e. the void decreased). This is expected due to void filling effect of MR after hydration. In other words, MR=30% mixture becomes denser as swollen of MR fills the voids and consequently the porosity decreases. However, for higher MR contents, the swelling of MR exceeds initial void volume of mixture and results in porosity decrement. This suggests the existence of critical MR contents that can reinforce the sand-MR mixture. Except that range of MR contents, hydration of MR causes density and volume change of total mixture at same time and consequently swollen soils can cause serious damages to structures.

Table 3. Porosity of sand-MR mixtures before and after reaction

MR (%)		0	30	50	70	100
Porosity, n	Before	0.432	0.401	0.424	0.426	0.439
	After	0.432	0.281	0.459	0.470	0.461

3.3. Direct shear test

Figure 6 shows direct shear results of sand-MR mixture before and after hydration reactions. Before hydration reactions occurs, residual friction angle($\varphi_{mix,res}$) of the mixtures decreases with increment of MR contents. Residual friction angle generaly depends on mineralogy, gradation, particle characteritics and rate of shear [10]. The particle characteritics of sand-MR mixtures would be decided by three contact types: (a)sand-to-sand contact (b)sand-to-MR contact and (c)MR-to-MR contact. Decrement of $\varphi_{mix,res}$ with increment of MR contents referd that sand-to-sand particle contact has high friction compared with sand-to-MR or MR-to-MR contacts.

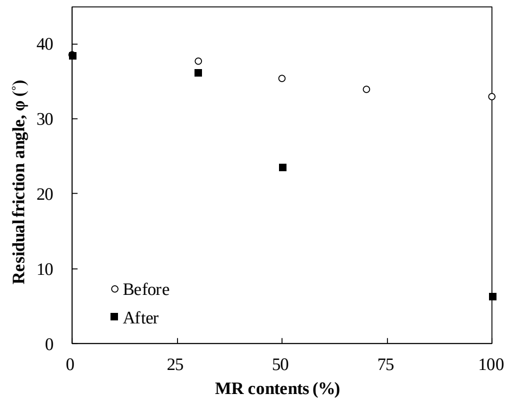

Figure 6. Direct shear results of sand-MR mixture before and after hydration reaction

After hydration occurs, the trands of $\varphi_{mix,res}$ with MR contetns shows similar trends with that of before hydration; $\varphi_{mix,res}$ decrease with increase of MR contents. Compared with before and after hydration reaction, $\varphi_{mix,res}$ of pure MR showed dramatic changes: 37.5˚ to 3.26˚. This is predominantly due to mineralogy and morphology change of MR shown in figure 3. Furtheremore, it is interesting to note that the trends of $\varphi_{mix,res}$ with MR contents after hydration reactions corresponds to the variation of residual friction angle of kaolinite-quartz mixtures where the morphology of clay minerals are platy [10-12]. Interestingly, kaolinite is composed of hexagonal sheets of clay minerals [13] similar to pure MR after hydration reaction (Figure 3 (c)). This provide a direction for further study.

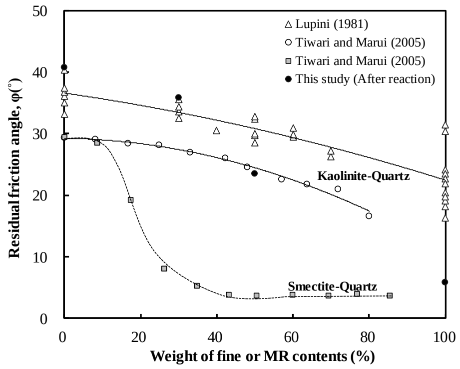

Figure 7. Variation of residual friction angle of clay-sand mixture and sand-MR mixture

4. Conclusions

In this study sand and crushed magnesia refractory bricks was mixed with 5 different weight ratios (0,30,50,70 and 100%) for sand-MR mixture and modified geotechnical behaviors were observed. One dimensional swelling test and direct shear test were performed. The hydration of magnesium oxide in magnesia refractory changed total behavior of sand-MR mixtures which includes:

1. XRD analysis showed that hydration of MR changed the particle morphology from periclase structured MgO to brucite phase of $Mg(OH)_2$ with hexagonally shaped morphology.
2. Swelling pressure and volumetric strain increased with MR contents. However, MR=30% mixture showed the least value of MR swell index (mL/1g of MR). With porosity decrement after hydration of MR=30% mixture, this suggests critical MR contents to reinforce soil mixture.
3. Residual friction angle decreased with increment of MR contents for before and after hydration reactions. Furthermore, comparing pure MR, dramatic decrement of residual friction angle was observed. This refers that the contact friction between sand-to-sand particles are higher than sand-to-MR and MR-to-MR contact friction before and after hydration reaction. Also, MR-to-MR particle friction after hydration reaction gets smaller due to morphology and mineralogy change.

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