Time-dependent characteristics of permeability due to crushed and aged granulated blast furnace slag

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1. Introduction

Granulated blast furnace slag (hereinafter abbreviated as GBFS) can be used as an alternative material for civil usages, such as sand compaction pile (SCP). SCP was developed to prevent geotechnical disasters, such as liquefaction, by draining and compacting the ground. In other words, the SCP method provides a drainage path for water while inducing self-consolidation to the ground. It is one of the cheapest and fastest ground improvement methods; however, there are some drawbacks. SCP method has low stiffness, thus a large percentage replacement with the soft ground is needed to have efficient stiffness. Besides, GBFS increases in stiffness when undergoing the hydration process, which is similar to Portland cement. Therefore, the use of GBFS for sand compaction pile increases stiffness over time, which can decrease the percentage replacement with soft ground. GBFS is prone to crushing and undergoing pozzolanic reaction and carbonization; thus, there are crushed and aged (pozzolanic reaction and carbonation) GBFS when used as a material for SCP. The pH value is neutralized from 11 to about 7 during the carbonization due to the chemical equation, (Ca, Mg) $SiO_3 + CO_2 \rightarrow$ (Ca, Mg)$CO_3 + SiO_2$. To enhance the civil engineering utilization of GBFS, this study conveys basic research on the permeability characteristics of GBFS when crushed and aged over time.

2. Material

GBFS is a by-product produced during the iron-making process that is rapidly cooled by water. Due to this cooling process, the entrapped air forms a highly porous and sand-like granule. The physical properties of GBFS are shown in Table 1. Based on the data, GBFS is classified as sandy to sandy with gravel soil. Moreover, the void ratio of GBFS is 1.159 according to Sakata. Thus, hydraulic conductivity claimed to be high.

Table 1. Physical properties of GBFS

Soil particle density	ρ_s (g/cm^3)	2.82
Minimum dry density	ρ_{dmin} (g/cm^3)	0.805
Maximum dry density	ρ_{dmax} (g/cm^3)	1.185
Mean grain size	D_{50} (mm)	0.85
Coefficient of uniformity	U_c	2.63

3. Experimental Apparatus

Tests were conducted using three different apparatus: rotary crushing and mixing machine, single-particle strength test apparatus, and constant head permeability test apparatus.

3-1. Rotary crushing and mixing machine

This machine was used to prepare crushed GBFS. In this experiment, TM500 with 500 mm of cylinder diameter was utilized. The inner layout of the cylinder is separated into three floors with each containing 4 flexible chains. These chains rotate with a given speed (revolution per minute or rpm) that crushes and mixes the material, which is added into the cylinder; an increase in rpm produces smaller particle size.

3-2. Single-particle strength test apparatus

The same apparatus with the unconfined compression test is used for the single-particle strength test. The test was operated with a load of 0.2475 N/mm and a speed of 0.1 mm per minute. The mean grain sizes obtained from sieve analysis test was used.

3-3 Constant head permeability test apparatus

Since the GBFS specimens were cured in a 5 by 10 cm cylindrical mold, the apparatus and the mold size are equivalent. Furthermore, cured specimens are sealed with bentonite to prevent water flow between the specimen and the apparatus.

Table 2. The test program of crushed and aged GBFS for constant head permeability test

Test ID	Crushing Condition (rpm)	Curing Condition	Curing time (day)
C0w	0	Distilled water	0, 7, 28
C3w	1200		
C0c	0	Carbonized water (250g CO_2 in a 500ml water)	0, 7, 14, 28
C1c	400		
C2c	800		
C3c	1200		

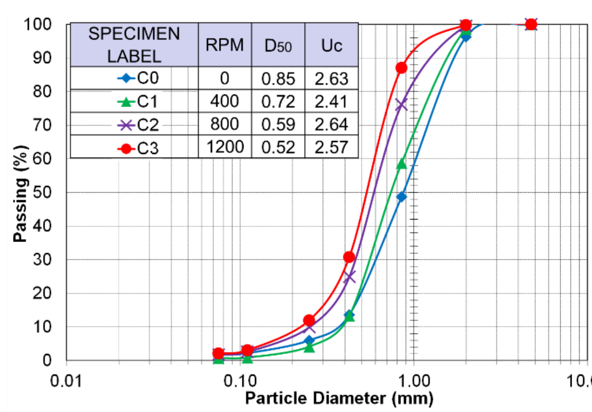

Fig. 1. The particle distribution curve of crushed GBFS

4. Methodology

To examine the permeability characteristics of crushed and aged GBFS, the test utilized model experiments. The samples were first crushed into four different particle sizes by using rotary crushing and mixing machine with an rpm of 0 (non-crushed), 400, 800, and 1200. From these samples, single-particle tests were carried out using mean grain sizes of 0.85, 0.72, 0.59, and 0.52 accordingly to observe the particle characteristics. Then, the specimens were poured into the 5 by 10 cm cylindrical mold into three layers and struck 50 times each. Curing was conducted by 500ml of distilled and carbonized water for 0 and 1200 rpm and only carbonized water for 400 and 800 rpm, with curing days of 0, 7, 14, and 28 days. Before the permeability test, an aging observation test was conducted using litmus paper by checking the pH value to observe the neutralization of specimens. The specimens were removed from the mold and installed into the permeability apparatus with bentonite sealing. Soon after, the specimens were placed into the deaerator for 24 hours to remove the air entirely. The constant head permeability test is then conducted for each specimen. The test program is presented in Table 2.

5. Results and discussion

The sieve analysis data after crushing GBFS is illustrated in **Fig. 1**. The mean grain size has decreased as the rpm increased, which determined the GBFS has been successfully crushed overall. Stress obtained from a single particle strength test is shown in **Fig. 2**. Stress was obtained from a single particle strength divided by the area which is $\sigma=F_{max}/A$. Since the particle size is very small, the particle is assumed as a square in which the area is calculated by $A=(D_{50})^2$. As the rpm increased, the stress (MPa) increased. Crushing GBFS formed fractures in the particle; during the application of loading, the fractures expanded which crushed the particle into several pieces. The result conveys that larger particle size illustrates lower stress. By crushing the particle, a fresh surface was exposed, thus the pH value increased for crushed GBFS, which is shown in **Fig. 3**. Moreover, curing in carbonized water allowed the pH value to appear more neutralized than curing in distilled water. In clarification, curing GBFS in carbonized water succeeded in aging. From these crushed and aged GBFS, the permeability test was conducted to observe the hydraulic conductivity over curing days; and the results are conveyed in **Fig. 4**. During curing day 0, the difference between water curing and carbonized water curing specimens cannot be seen since no chemical reactions have occurred due to no curing. On the other hand, crushing has caused a huge difference since smaller particle sizes might have caused a smaller void ratio, which affected the hydraulic conductivity. Both crushed and aged GBFS showed lower hydraulic conductivity than non-crushed and non-aged GBFS as time elapsed. Specifically, smaller particle size provides a more specific surface area in which reaction rate increases. Thus, the formation of calcium silicate hydrate and calcium carbonate from pozzolanic reaction and carbonization increases that decrease the hydraulic conductivity.

6. Conclusion

The main conclusions are as follows:

1. The single particle stress decreased as particle size increased, and the results showed a linear decrease.
2. Permeability characteristics for crushing and aging GBFS exhibit a drastic decrease in hydraulic conductivity at seven days curing. The process of pozzolanic reaction and carbonization might have decreased the void ratio due to the formation of calcium silicate hydrate and calcium carbonate.

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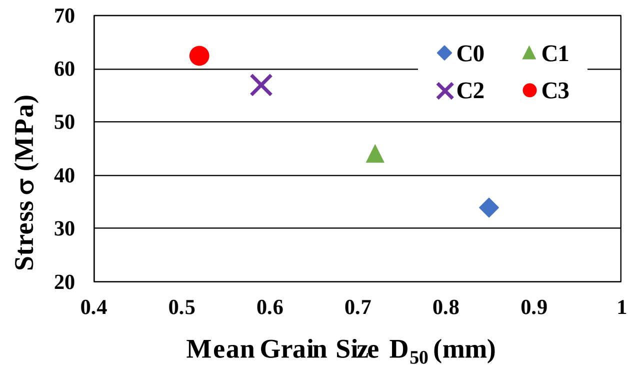

Fig. 2. Stress obtained from single particle strength test for crushed GBFS

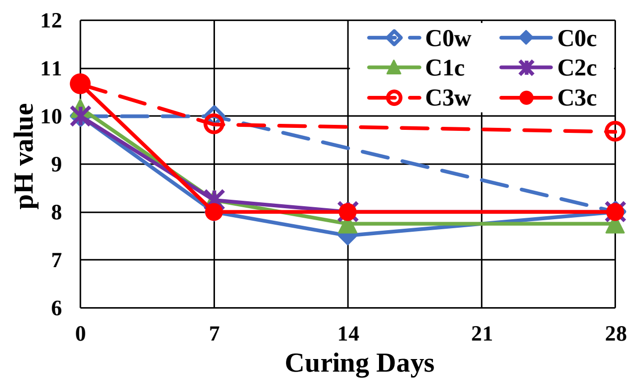

Fig. 3. Aging observation of crushed and aged GBFS

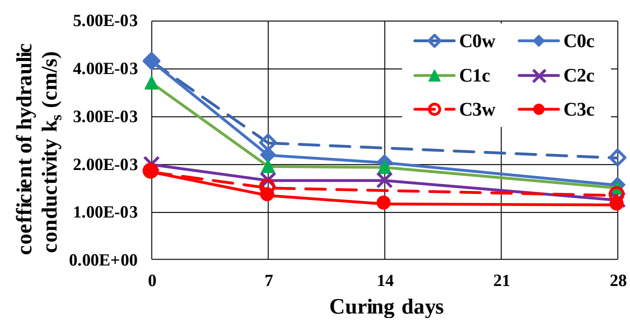

Fig. 4. Coefficient of hydraulic conductivity of crushed and aged GBFS

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