Evaluation of self-restoration characteristics of GBFS by using hydration reaction

Hiroshi Matsuda i), Hiroyuki Hara ii), Naoyuki Igawa iii) and Shoya Nakamura iv)

i) Professor, Graduate school of Science and Engineering, Yamaguchi University, 2-16-1, Tokiwadai, Ube 755-8611, Japan.
ii) Assistant Professor, Graduate school of Science and Engineering, Yamaguchi University, 2-16-1, Tokiwadai, Ube 755-8611, Japan.
iii) Yachiyo Engineering Co. Ltd, 2-18-12, Nishiochiai, Shinjuku 161-8575, Japan.
iv) Master course Student, Graduate school of Science and Engineering, Yamaguchi University, 2-16-1, Ube 755-8611, Japan.

ABSTRACT

Granulated Blast Furnace Slag (GBFS) is expected to be a useful earthwork material because GBFS increases in shear strength due to its hydration reaction under the natural environment. Authors have already clarified the physical and mechanical properties in the process of hardening by laboratory tests and in-situ case studies. When the earth structures consisted of GBFS which was hardened by a long-term curing are collapsed by external factors such as earthquake, the shear strength is considered to be recovered by its self-restoration due to generation of hydrates at collapsed boundaries. In this study, the self-restoration characteristics induced by the hydration reaction were investigated by observing the hardening process of GBFS which was taken from the in-situ embankment constructed 11 years ago. In addition, a method to estimate the increase of shear strength of GBFS with time was proposed.

Keywords: granulated blast furnace slag, unconfined compressive strength, self-restoration, hydration reaction

1 INTRODUCTION

Granulated Blast Furnace Slag (GBFS) is produced in a manufacture process of iron and the production is about 204.1MN (2013) in Japan, Nippon slag association(2014). GBFS has a latent hydraulic property and expected to become a non-liquefied material after hardening. GBFS has also some advantages such as lightweight, high internal friction angle, high permeability and has already been used as a backfill material of the quay wall, landfill and lightweight embankment, etc. Authors have already clarified the physical and mechanical properties in the process of hardening for various environmental conditions and also in-situ case studies, Shinozaki(2008), Matsuda(2008).

After GBFS is hardened, even if the GBFS-used earth structure is collapsed by such an earthquake motion, the shear strength of GBFS is considered to be recovered without any additives. The geotechnical properties including the recoverable shear strength, however, are not clarified yet. In this study, the self-restoration characteristics due to the hydration reaction were investigated by observing the hardening process of GBFS, which were taken from the in-situ embankment constructed 11 years ago and re-cured after shearing in the laboratory. Then, the estimation method of shear strength was proposed.

2 MATERIALS AND HYDRATION REACTION TEST

2.1 GBFS for laboratory test

In this study, two different samples of GBFS were used in laboratory tests. One is the virgin sample of GBFS without a hydration history. The other is the block samples of GBFS taken from in-situ test embankment at December, 2012. The in-situ embankment was constructed at November, 2001, therefore, the GBFS has a history of 11 years left in the natural environmental condition and so the hydration reaction is considered to be proceeded remarkably. Hereinafter, the former GBFS is referred to as the un-hydrated GBFS and the latter one as the embankment GBFS, respectively.

2.2 Hydration reaction test

In this study, in order to evaluate the degree of hardening of GBFS, the hydrates generated on GBFS were measured by hydration reaction test. Salicylic acid, acetone and methanol mixed solution have a characteristics to dissolve only a hydrate in GBFS. Kondo and Ohsawa (1969) proposed the test method to measure the rate of hydration reaction of GBFS. By this method, the rate of hydration reaction can be obtained as a ratio of the mass of hydrates on the GBFS particles to the total mass of GBFS including hydrates. Although this method is usually applied to the fine particle of GBFS,
in this study, GBFS was used as a granular material for the hydration reaction test, because it is considered that the hydrates on the surface of GBFS are the dominant factor of the strength. In addition, when the particle size of GBFS is small, it may take a long time at the filtration process in the hydration reaction test.

Procedure of the hydration reaction test is as follows. Firstly, GBFS sample is heated in the oven at 110ºC, then 1g of sample and compound solution composed of salicylic acid 5g, acetone 70mL and methanol 30mL are put into the stoppered Erlenmeyer flask. Secondly, the sample and compound solution were agitated for an hour and the mixture is left for one day and then separated by a suction filtration using quantitative filter paper with a pore diameter of 1.0 µm. The residues obtained by filtration are put into a crucible together with the filter paper, and heated at 850ºC for about an hour in order to incinerate the filter paper. Thirdly, the weight of the residues was measured with crucible. Then the hydration reaction ratio can be obtained by following equations.

\[ R_i = \frac{m_i}{m_j \times (1/L/100)} \]  

\[ R = 100 - R_i \]  

where, \( R_i \) (%) is un-hydrated ratio, \( m_i \) (g) is mass of GBFS after heating, \( m_j \) (g) is mass of GBFS before immersed in compound solution, \( IL \) (%) is loss on ignition of GBFS before curing and \( R \) (%) is the hydration reaction ratio. In this study, seawater was also used as a curing solution for GBFS. In this case, there is a possibility that the hydration reaction ratio obtained by the above mentioned method is overestimated due to the dissolution of salinity sticking to the surface of GBFS. For this reason, when seawater is used as a curing solution, un-hydrated ratio is obtained by using equation (3) in which the effect of salinity is minimized, and then hydration reaction ratio is obtained by equation (2).

\[ R_i = \frac{m_i}{m_j \times (1/L/100) - m_{sa}} \]  

where, \( m_{sa} \) is the mass of salinity in GBFS sample.

### 3 EFFECT OF CURING CONDITION ON THE STRENGTH AND HYDRATION CHARACTERISTICS OF GBFS

In order to investigate the hardening property of GBFS, unconfined compression test and hydration reaction test were performed for GBFS specimens using un-hydrated GBFS. Physical properties and grain size distribution of un-hydrated GBFS are shown in Table 1 and Fig. 1, in which, results of Toyoura sand and Genkai sand are also shown for the comparison. Test procedure is as follows. Specimens are poured into a plastic mold with a relative density 80% by the air pluviation method, and immersed in solutions together with the plastic mold. The solid-liquid ratio for the specimen and solutions was set in the range from 1 to 1.4. Ca(OH)₂ solution was used to accelerate hydration reaction of GBFS. In the case of plain water and seawater, specimens were cured in the oven with the constant temperature of 80°C. In a series of test, curing duration was set as 0, 3, 7, 14, 28, 56, 84 and 112 days. After curing, unconfined compression test and hydration reaction test were conducted.

Fig. 2 shows the change in unconfined compressive strength \( q_u \) with curing time. In the figure, plots on the zero value line of \( q_u \) mean the specimen cannot stand by itself. For the specimen cured in Ca(OH)₂, \( q_u \) increases rapidly compared with other case of solutions. In the case of solutions with the temperature of 80°C, the strength cured in seawater increases more rapidly than plain water. Fig. 3 shows the change in the hydration reaction ratio with curing time. Ca(OH)₂ solution reaches to the highest hydration reaction ratio after 40days of curing, followed by seawater and plain water. Therefore, it is considered that Ca(OH)₂ solution and seawater can accelerate the hydration of GBFS, significantly. Fig. 4 shows relationships between \( q_u \) and the hydration reaction ratio. \( q_u \) increases with the hydration reaction. It can be seen when the rate of hydration reaction exceeds about 0.8%, \( q_u \) starts to increase almost linearly. However, \( q_u \) is different due to the curing condition, even if their hydration reaction ratio indicates almost the same. It is considered that the hydrate which is generated on the surface of the GBFS is different due to the curing condition and its contribution to the strength of GBFS is also different.

<table>
<thead>
<tr>
<th>Soil particle density ( \rho_s ) (g/cm³)</th>
<th>Maximum void ratio ( \theta_{max} )</th>
<th>Minimum void ratio ( \theta_{min} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-hydrated slag</td>
<td>2.643</td>
<td>1.510</td>
</tr>
<tr>
<td>Genkai sand</td>
<td>2.678</td>
<td>0.872</td>
</tr>
<tr>
<td>Toyoura sand</td>
<td>2.646</td>
<td>0.999</td>
</tr>
</tbody>
</table>

![Fig. 1. Grain size distribution of GBFS.](image-url)
In order to evaluate the self-restoration characteristics of GBFS under seawater environment, unconfined compression test and hydration reaction test were performed for GBFS with unraveled and re-cured in seawater. Un-hydrated GBFS which was cured for predetermined duration in the seawater with the temperature of 80°C and the embankment GBFS taken from in-situ test embankment were used as a sample. At first, samples were unraveled carefully so as to prevent a particle from crushing, and prepared specimens in the same way as shown before and re-cured in the seawater with 80°C. In this study, the first curing duration and the second re-curing duration are referred to the primary re-curing time and curing time, respectively, and the sum of the both durations is referred to total curing time. In this study, the primary curing time was set as 0, 14, 28, 56 days and 11 years, in which 11 years of primary curing time means hydrated at the in-situ embankment. Re-curing time was set as 0, 3, 7, 14, 28, 56, 84 and 112 days. After re-curing, unconfined compression test and hydration reaction test were conducted for each specimen.

Fig. 5 shows the change in hydration reaction ratio with total curing time. The tendency of the hydration reaction ratio is almost the same irrespective of the primary curing time and this means the effect of unravels is not significant on the hydration property of GBFS. Figs. 6 (a) and (b) show the change in the unconfined compressive strength $q_u$, where the horizontal axis corresponds to the total curing time and the re-curing time, respectively. In Fig. 6 (a), $q_u$ increases with total curing time for all specimens. This means that the strength of GBFS is recovered, even if GBFS is once collapsed. In Fig. 6 (b), although $q_u$ of specimens having a hydration history are small compared with un-hydrated GBFS (primary curing time: 0 day), $q_u$ increases, even if 11 years already passed after the start of hydration. Fig. 7 shows the relationships between $q_u$ and the re-curing time. Plots in the figure show observed results and broken lines show calculated ones obtained by the following equation.

4 SELF-RESTRIATION CHARACTERISTICS OF GBFS UNDER SEAWATER

In order to evaluate the self-restoration characteristics of GBFS under seawater environment, unconfined compression test and hydration reaction test were performed for GBFS with unraveled and re-cured in seawater. Un-hydrated GBFS which was cured for predetermined duration in the seawater with the temperature of 80°C and the embankment GBFS taken from in-situ test embankment were used as a sample. At first, samples were unraveled carefully so as to prevent a particle from crushing, and prepared specimens in the same way as shown before and re-cured in the seawater with 80°C. In this study, the first curing duration and the second re-curing duration are referred to the primary re-curing time and curing time, respectively, and the sum of the both durations is referred to total curing time. In this study, the primary curing time was set as 0, 14, 28, 56 days and 11 years, in which 11 years of primary curing time means hydrated at the in-situ embankment. Re-curing time was set as 0, 3, 7, 14, 28, 56, 84 and 112 days. After re-curing, unconfined compression test and hydration reaction test were conducted for each specimen.

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where, $t$ is re-curing time and $A_n$ is experimental constant. Subscription $n$ in $A_n$ denotes the primary curing time. In each case, approximated curves agree well with observed results, then the correlation coefficient $R$ shows close to 1.0. Fig. 8 shows the relationships between $A_n/A_0$ and primary curing time. $A_0$ means the value of $A_n$ when the primary curing time is 0 day. The broken line in Fig. 8 shows the average value of $A_n/A_0$ excluding the results of primary curing time 0 day. It can be seen from this figure that the strength recovery of GBFS having the hydration history shows about 60% of un-hydrated GBFS.

5 STRENGTH ESTIMATION OF GBFS CONSIDERING SELF RESTORATION

As described before, strength of GBFS increased with progress of hydration, even if GBFS has a hydration history. In this study, strength estimation method for GBFS which has a hydration history was proposed based on aforementioned experimental results. For the hydration reaction ratio on un-hydrated GBFS cured in three types of solutions (80°C seawater, 80°C plain water, 20°C Ca(OH)$_2$ solution), approximation by using equation (5) were performed as shown in Fig.9.
where, \( r \) is experimental constant and \( t_m \) is the time when the hydration reaction begins to start considerably. In the case of 80°C plain water, the hydration reaction ratio increases rapidly after about 90 days, and for this case, equation (5) is applicable. Relationships between the unconfined compressive strength and the hydration reaction ratio were obtained as shown in Fig. 4. Fig. 10 shows the regression lines obtained by using equation (6).

\[
R = r \sqrt{t - t_m} \quad (5)
\]

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\[
q_u = m \cdot R + C \quad (6)
\]

where, \( m \) and \( C \) are experimental constants. Equation (7) was derived from equation (5) and (6).

\[
q_u = m \cdot r \sqrt{t - t_m} + C \quad (7)
\]

Furthermore, this equation can be expressed as follows by summarizing the experimental constants as \( \alpha = m \cdot r \).

\[
q_u = \alpha \sqrt{t - t_m} + C \quad (8)
\]

Experimental constants in equation (8) are shown in Table 2. In addition, the average of \( A_u/A_0 \) of GBFS which has a hydration history is 0.628 as shown in Fig. 8. When the average value of \( A_u/A_0 \) for all results excluding un-hydrated GBFS is defined as self-restoration coefficient \( k_{re} \), the equation for estimating the strength of GBFS including the self-restoration can be expressed by equation (9).

\[
q_{u, re} = k_{re} \cdot \alpha \sqrt{t - t_m} + C \quad (9)
\]

where, \( q_{u, re} \) is the unconfined compressive strength for once collapsed GBFS and \( k_{re} \). Fig. 11 shows the comparison between observed and calculated results for unconfined compressive strength. The calculated values are in good accordance with the observed ones.

6 CONCLUSIONS

In this study, strength of GBFS under several conditions was investigated focusing on a hydration reaction. In addition, self-restoration characteristics of GBFS were also examined by using un-hydrated GBFS and in-situ embankment GBFS. The main conclusions are as follows:

1) The strength of GBFS increases with its hydration reaction.
2) The strength of GBFS is recovered by curing, even if GBFS is once collapsed, and the strength shows approximately 60% of GBFS without the hydration history.
3) Hydration reaction ratio and unconfined compressive strength of GBFS increases in proportion to the square root of curing time regardless of curing conditions.
4) An estimation equation for the strength of GBFS including the self-restoration was proposed.

REFERENCES

