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Application of a Method to Accelerate Granulated Blast Furnace Slag Solidification

Une méthode de solidification accélérée des granulats issus de laitier de haut fourneau

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ABSTRACT: On-site observations indicate that granulated blast furnace slag (GBFS) solidifies over time, but the entire mass solidifies quite slowly. This means that if GBFS is to be relied upon to be solid, it must be treated in order to accelerate the solidification process. Adding blast furnace slag in micro powder form to GBFS effectively speeds GBFS solidification in seawater. To improve the material's resistance to separation, we recommend Prior Homogeneous Mixing Treatment (PHMT), which reduces the amount of separation of the material during pouring but does not interfere with the speed of the mixture's accelerated solidification. PHMT-treated GBFS tends to solidify better when inundated in seawater than in fresh water. It is strong enough to protect against liquefaction if it remains in seawater for about two months.

RÉSUMÉ : les observations in-situ indiquent que les granulats issus de laitier de haut fourneau (GLHF) se solidifient dans le temps, avec néanmoins une vitesse de prise assez lente. L'utilisation de GLHF solidifiés implique donc que ces derniers fassent l'objet d'un traitement afin d'accélérer ce processus de prise. L'ajout sous forme de poudre fine issue de laitiers accélère de manière efficace cette solidification sous l'eau. Afin de limiter la ségrégation, il est recommandé d'effectuer au préalable un mélange homogène avec la poudre. Cela réduit la ségrégation entre les matériaux durant le déversement du mélange tout en n'influençant pas l'augmentation de la vitesse de prise. Les GLHF traités avec de la poudre de laitier tendent après un mélange homogène à se solidifier de manière plus efficace lorsqu'il sont plongés dans de l'eau de mer plutôt que dans de l'eau douce. Ce mélange a alors assez de résistance pour résister à la liquéfaction si celui-ci reste immergé dans l'eau de mer plus d'une année et demi.

KEYWORDS: granulated blast furnace slag, solidification, backfill, quay wall

1 INTRODUCTION

Granulated blast furnace slag (GBFS) solidifies when it reacts with water. This property is known as latent hydraulicity. However, this characteristic of GBFS was ignored in the Japanese handbook for port construction engineers published in 1989 (CDIT, 1989) due to the lack of adequate information on the solidification of GBFS used in port construction. If used as a self-solidifying material, GBFS holds great promise for use in protecting against liquefaction and for earth pressure reduction.

Most GBFS used to backfill quay walls does solidify, but a post-construction follow-up survey showed that GBFS solidification is a lengthy process, it never solidifies uniformly, and some may remain unsolidified (Kikuchi et al. 2005). As a result, some treatment is necessary before GBFS can be used as a self-hardening material.

In this study, we examine a method to accelerate the solidification of GBFS and propose a practical way to apply that method.

2 PREVIOUS RESEARCH

GBFS is vitreous, and the silicate SiO_4 it contains is in an unstable condition compared with crystalline material (NSA 1980). GBFS has high chemical reactivity and therefore solidifies in the presence of water and under high pH conditions where the pH exceeds 11.

Nishi et al. (1982) concluded that the latent hydraulicity of GBFS is high in highly alkaline water but low in seawater, which has a pH of about 8.
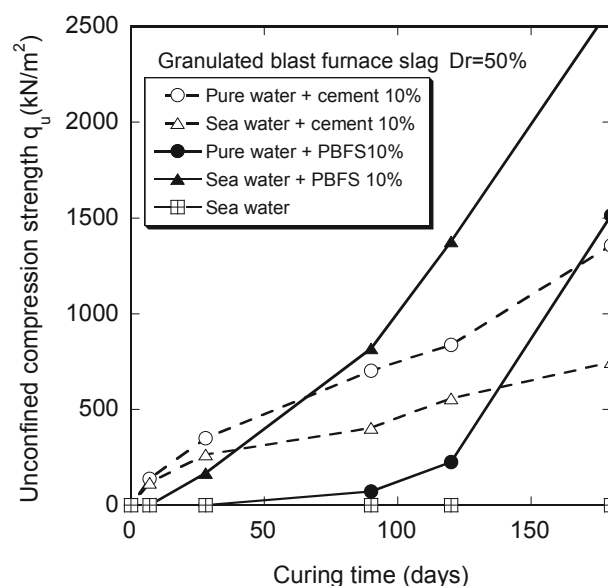

Figure 1. Acceleration of solidification achieved by mixing cement or PBFS with GBFS and by varying pore water type.

These facts suggest that solidifying GBFS in seawater is difficult because seawater acts as buffer solution with a very high buffering capacity (Christian 1986), and adjusting the pH of seawater is impractical.

A site investigation of GBFS placed as backfill 6-12 years previously showed that most of the GBFS had solidified, but its strength varied greatly (Kikuchi et al. 2006).

Kikuchi et al. (2011) tested various combinations of pore water and additives, attempting to speed GBFS solidification.

Figure 1 shows part of their results. Seawater and fresh water were tested with Portland cement and powdered blast furnace slag (PBFS) as additives. When fresh water was used, cement was more effective than PBFS in solidifying GBFS. But when seawater was used, PBFS was more effective than cement. Using seawater and PBFS was the most effective combination.

3 ISSUES REGARDING APPLYING THE GBFS SOLIDIFICATION ACCELERATION METHOD IN THE FIELD

There are several issues to consider when determining the most appropriate mixture of GBFS and PBFS for accelerating GBFS solidification: (1) the material can separate during construction, (2) it may separate after construction because of water flow (3) separation of the mixture is likely to affect how the GBFS solidifies, (4) the flow of pore water can affect solidification, and (5) GBFS may solidify differently when the pore water changes from sea water to fresh water (Kikuchi et al. 2010).

In the present study, we examine issues (1) to (5). First, we present experimental results regarding issues (2), (3), and (4). We then explain a way to prevent issue (1), and finally consider issue (5).

3.1 *Possibility of material separation after construction*

The physical properties of the GBFS used were ρ_s = 2.845 g/cm^3, ρ_{dmin}= 1.175 g/cm^3, ρ_{dmax}= 1.508 g/cm^3, D_{15} = 0.28 mm, and D_{50} = 0.38 mm. The physical properties of the PBFS used were ρ_s = 2.890 g/cm^3, with 5000 to 7000 cm^2/g of specific surface area. Artificial seawater was used as pore water.

The diameter of the PBFS was about 4 μm assuming spherical particles with no small holes. Thus, the GBFS and PBFS may separate when the mixture is poured onto the seabed. The ratio of D_{15} for GBFS to D_{85} for PBFS is more than 50. This ratio is an indicator of the possibility of material separation due to water flow through the material (Ishihara 2001).

We conducted experiments on the separation of the PBFS from the mixture. In this series of experiments, specimens with two layers were prepared. The lower layer of the specimen was a mixture of GBFS with 20% PBFS by weight. The upper layer was only GBFS. The relative density of each layer was 50%.

Water flowed from the bottom of the specimen with a hydraulic gradient of from 10 to 40. This test was conducted in a triaxial apparatus at a confining pressure of 50 kN/m^2 to prevent boiling. The outlet velocity of the water at a hydraulic gradient of 40 was 120 m/day. The total outlet water volume from the specimen was 6 times the void volume of the specimen.

Figure 2 shows close-up X-ray CT images of the boundary between the layers of the specimen, where the contrast reflects the density of the material. Comparing the images before and after water flow, small differences can be observed. This means that although there may be a little separation when the peak velocity of the water flow is 120 m/day, complete separation of the material does not occur under these conditions.

In practice, the water flow velocity in GBFS used as backfill for gravity quay walls is around several m/day. Thus, GBFS and PBFS will never separate after construction.
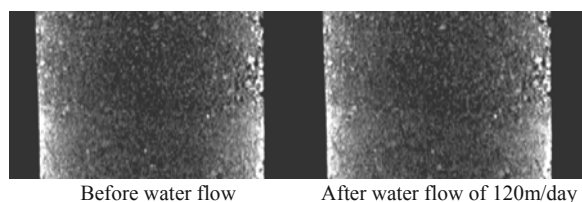

Before water flow   After water flow of 120m/day
Figure 2. Close-up X-ray CT images at mid-height of the specimen.

3.2 *Solidification of GBFS after material separation*

The effect of material separation on the solidification characteristics of the material is examined in this section.

The GBFS and PBFS used here were the same as those used in section 3.1. The relative densities of the specimens were 50%. The pore water used was artificial sea water. In each specimen, 7.5% PBFS by weight was added to the GBFS. We tested four experimental mixing regimes: (1) GBFS and PBFS were mixed homogeneously (HMT), (2) PBFS was mixed with GBFS, then artificial sea water was added to achieve a 10% water content ratio and the mixture was cured in air for a week (prior homogeneous mixing treatment or PHMT), (3) One PBFS layer was sandwiched between two layers of GBFS, and (4) Two PBFS layers were sandwiched between three GBFS layers.

Each specimen was saturated with artificial sea water and sealed, then cured for a designated period at a constant temperature of 20 degrees centigrade. Each specimen's unconfined compression strength was measured after the designated curing period.

Figure 3 shows the relationship between the curing duration and unconfined strength. The unconfined compression strengths using HMT and PHMT exceeded 200 kN/m^2 after 14 days of curing. These strengths increased as the curing time lengthened. When the materials were separated, such as in cases (3) and (4), the unconfined compression strengths were very low. Figure 4 shows examples of the failure states for each case.
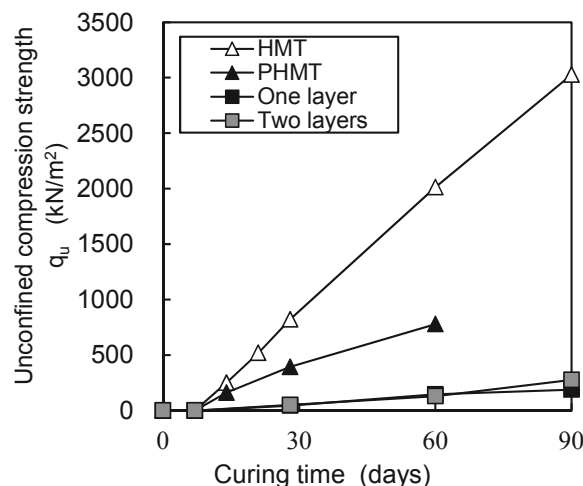

Figure 3. Change of unconfined compression strength with curing time.

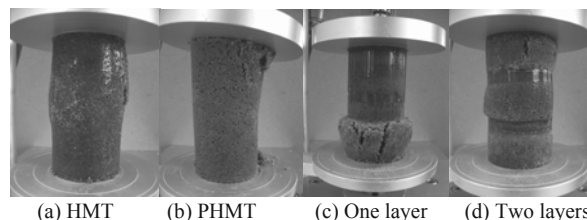(a) HMT   (b) PHMT   (c) One layer   (d) Two layers
Figure 4. Failure modes of specimens in each mixing regime

These results show the importance of thoroughly mixing the GBFS and PBFS in accelerating the solidification of the GBFS.

3.3 *Solidification of GBFS underground with flowing water*

In previous research, movement of pore water has been shown to prevent GBFS solidification (Kitayama 2003). In this section, we examine how pore water flow effects GBFS solidification. In this series of experiments, two water flow conditions and two mixing conditions were tested.

We used the same GBFS and PBFS as in section 3.1, and the HMT (1) and PHMT (2) mixing regimes from section 3.2.

In this series, sand boxes 30 cm wide, 30 cm long, and 50 cm high were fitted with a bulb for supplying water, located 3 cm from the bottom. Model ground 30 cm high was constructed of a mixture of GBFS and PBFS with 50% relative density. This was saturated with artificial sea water at the beginning of the test. Tests were run under static water and flowing water conditions. In the static water case, the pore water was never changed during the experiment. In the flowing water case, a volume of water equal to the volume of the voids in the ground was supplied slowly from the bottom of the ground once every three days. Curing continued for two months at a constant temperature of 20 degrees centigrade. After curing, the bearing strength distribution of the ground was measured using a soil hardness meter, and was converted to unconfined compression strengths.

The results show that the HMT-treated material subjected to static water conditions was the strongest. The material that had undergone HMT was weaker when cured in flowing water. However, for the PHMT-treated material, the opposite was true. With flowing water the PHMT material was stronger than the HMT material, meaning that PHMT has a higher potential to solidify GBFS than HMT under non-static water conditions.

3.4 *Improving resistance to separation during construction using PHMT*

For this series of experiments, we used GBFS with the following physical properties: ρ_s = 2.808 g/cm^3, ρ_{dmin}= 1.199 g/cm^3, and ρ_{dmax}= 1.562 g/cm^3. The median particle diameter (D_{50}) was 0.74 mm. The physical properties of the PBFS were ρ_s = 2.890 g/cm^3, with 5000 to 7000 cm^2/g of specific surface area. Artificial seawater was used as pore water.

As the GBFS and PBFS may separate when the mixture is poured onto the seabed, PHMT was used to counter this problem. With PHMT, some of the PBFS attaches to the GBFS granules, making the mixture more resistant to separation and decreasing the turbidity the mixture causes in water.

We mixed 10% seawater and 7.5% by weight of PBFS with GBFS and cured the mixture for a designated period in air. We measured the turbidity it caused after 0, 3, 7, 10, and 14 days of curing. In each test, about 0.460 N of the PHMT mixture was poured into 1000 ml of pure water and stirred well, then left to sit for 30 min. A turbidity meter was used for measurements.
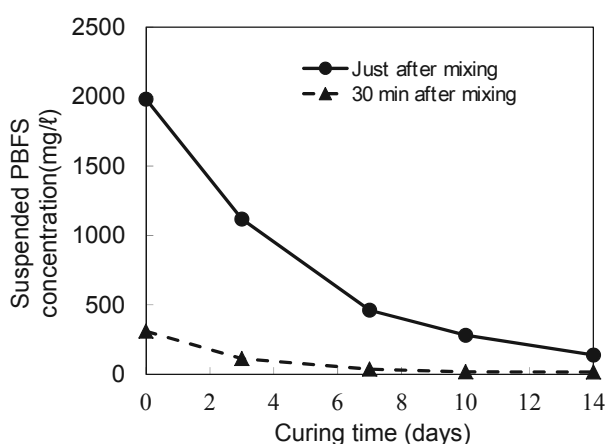

Figure 5. Change in suspended PBFS concentration with curing time.

Figure 5 shows how the suspended material concentration changed with curing time. The level just after mixing decreased to one-fourth of its initial value after 7 days of curing. The concentration 30 min after mixing became negligible after 7 days of curing.

A mixture of GBFS and PHMT is thus shown to be effective in reducing the amount of material separation during construction.

3.5 *Effects of changing from sea water to fresh water on the solidification of PHMT-treated GBFS*

Here, we address issue (5) described above. The follow-up survey about GBFS used as backfill noted in the introduction revealed that the pore water in the GBFS layer changed completely from seawater to fresh water over a period of 4 months (Kikuchi et al. 2005). This phenomenon occurs because the mean ground water level is higher than the mean sea level and rainfall supplies fresh water. Figure 1 shows that GBFS mixed with PBFS in seawater solidified in a month. With this in mind, we checked the effect of a pore water transition in a series of laboratory experiments.

Figure 6 shows how the experiment was set up. The box holding the sand was 800 mm long, 500 mm high, and 500 mm wide. We used PHMT cured for 7 days, made following the procedure described in section 3.2. The PHMT layer was made when wet and was covered by the sand layer. We used silica sand #4 (ρ_s = 2.644 g/cm^3, ρ_{dmin} = 1.342 g/cm^3, and ρ_{dmax}= 1.618 g/cm^3). The relative densities of the PHMT and sand were 50%. The water used to make the layers was artificial seawater, except for case 4 (Table 2.), in which fresh water was used. The shape of each layer is shown in Fig. 6. After making the model ground, 6 standpipes were installed at the positions marked No. 1, No. 2, and No. 3 to collect pore water. Two pipes were installed at each location to collect water from different depths. The open circles in Fig. 6 show the points where pore water was collected. Water was supplied as shown in the upper right part of the figure at a rate of 6 *l* per day. Effluent flowed from the bottom of the apparatus as shown in the figure. Since the void space in the model ground layer was about 84 *l*, the hydraulic retention time of the water in the apparatus was 14 days. Each experiment was conducted at 20 degrees centigrade. As the room was not perfectly temperature-controlled, its temperature was somewhat affected by the outside temperature.
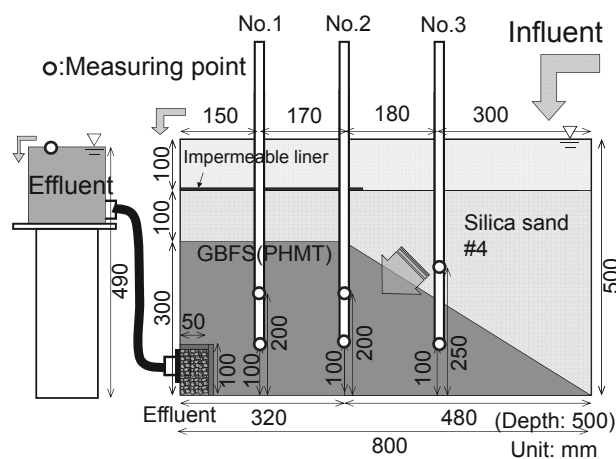

Figure 6. Experimental setup

During the experiment, pore water was collected from each point at designated times, and pH and salinity were measured. After 8 weeks, the strength of the PHMT-treated GBFS was measured with a Yamanaka soil hardness meter (Kikuchi et al. 2010). About 2000 strength measurements were made in each case. The data collected were converted to unconfined compression strengths using a relationship between strength and hardness determined before the experiment.

Table 1 shows the types of water supplied in each case.

Table 1. Experiment conditions

Case	Condition
Case 1	Sea water supplied for 8 weeks
Case 2	Sea water supplied for 6 weeks, then pure water supplied for 2 weeks

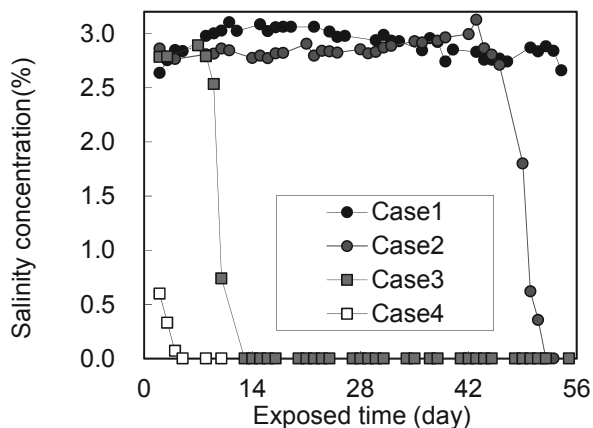| Case 3	Pure water supplied for 8 weeks
Case 4	Pure water used for making the model ground and Pure water supplied for 8 weeks

Figure 7. Change in salinity during the experiment (sampling location No. 1-100).

Figure 7 shows how the salinity changed during the experiments in standpipe No. 1, 100 mm from the bottom of the sand box. As shown in Table 1, fresh water was introduced starting at 42 days of exposure time in case 2. The salinity began to drop within about 1 week after the change and had almost vanished within 3 or 4 days after that point.

Figure 8 shows the converted unconfined compression strength distribution in each case. Table 2 shows the maximum and average strengths and the standard deviation for each case. The highest strength was observed in case 1, followed by cases 2 and 4, which were similar, and the lowest was in case 3. From these results, we see that about 2 months of curing time in seawater is important for accelerated solidification.
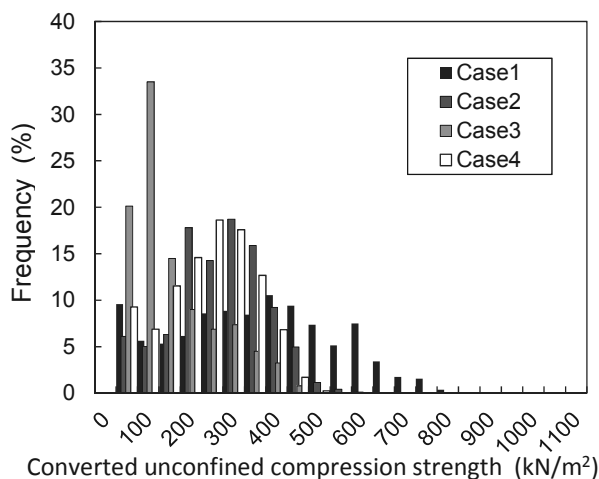

Figure 8. Distribution of converted unconfined compression strength.

An unconfined compression strength of more than 100 kN/m^2 is enough to prevent the liquefaction of sandy soil (Zen et al. 1990). The fractions of data below this level were 15%, 11%, 54%, and 16% in cases 1, 2, 3, and 4, respectively. This indicates that 80% of PHMT-treated GBFS cured in seawater for more than 2 months is strong enough to protect against liquefaction. This conclusion cannot be used to predict solidification levels in the field, but the results show that this technique can be used to accelerate the solidification of GBFS.

Finally, a series of permeability tests was conducted on solidified GBFS specimens in triaxial cells. After the permeability tests, the samples' unconfined compression strength was measured. These tests showed that the coefficient of permeability decreased with increasing strength. However,

the coefficient of permeability was about 10^{-4} cm/sec even when the unconfined compression strength was about 1000 kN/m^2, indicating that the permeability of solidified PHMT-treated GBFS is about the same as that of ordinary sand.

Table 2. Converted unconfined compression strength (kN/m^2)

Case	Maximum	Average	Standard deviation
1	1060.2	331.4	189.4
2	550.8	244.9	107.9
3	500.7	130.5	99.5
4	493.9	213.4	102.9

4 CONCLUSION

The solidification of GBFS used in port structures can be accelerated by adding PBFS. However, mixing PBFS with GBFS presents some issues when used in actual construction sites. To overcome these problems, we subjected the GBFS to PHMT treatment. This paper demonstrates the superiority of this process. PHMT reduces the amount of separation of the GBFS/PBFS mixture and produces sufficient unconfined compression strength after about 2 months of curing in seawater, which occurs automatically when GBFS is used to backfill quay walls. We conclude that PHMT-treated GBFS solidifies at an accelerated rate and can be used to prevent liquefaction.

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