Invited paper

Improvement of Concrete Properties using Granulated Blast Furnace Slag Sand

Toshiki Ayano¹* and Takashi Fujii²

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Abstract

A high volume of ground granulated blast furnace slag (GGBS) or granulated blast furnace slag (BFS) can enhance the resistance of concrete to freezing and thawing without the use of air-entraining (AE) agents. Furthermore, it can also enhance the resistance of concrete to chloride ion penetration and sulfuric acid attack, although the mechanism of improvement differs. In particular, BFS can reduce time-dependent strains, such as drying shrinkage strain and creep strain. The use of granulated blast furnace slag, either GGBS or BFS, promotes the durability of concrete structures by improving the mechanical properties of cementitious materials. Some of the concrete properties that are improved by the incorporation of BFS are presented in this paper. The detailed improvement mechanism of BFS has not yet been clarified. However, it is clear that it depends on the chemical reactions involving BFS and thus a critical time is required for BFS to hydrate in order to improve concrete properties. It takes four weeks to achieve high resistance to freezing and thawing by using BFS without the addition of an AE agent; use of a thickening agent can further shorten this curing period to one week. This paper is an English translation from a previous work by the authors [Ayano et al., 2014]. “Resistance to freezing and thawing attack of concrete with blast furnace slag fine aggregate.” Journal of Japan Society of Civil Engineers, Ser. E2 (Materials and Concrete Structures), 70(4), 417-427 (in Japanese)] and [Jariyathitipong et al., (2013). “Improvement of resistance to sulfuric acid attack of concrete by use of blast furnace slag sand.” Journal of Japan Society of Civil Engineers, Ser. E2 (Materials and Concrete Structures), 69(4), 337-347 (in Japanese)].

1. Introduction

Earlier-than-expected deterioration of concrete structures is not uncommon. For example, concrete deck slabs of bridges often deteriorate earlier than expected under the influence of heavy traffic and freeze–thaw cycles (Fukunaga et al., 2014; Mitamura et al., 2008). The use of road salt in winter further accelerates the deterioration of concrete (Honjo et al., 2014; Ishikawa et al., 2010). Some reports estimate that the length of Japanese highway roads that requires maintenance, that is, the renewal of deteriorated concrete slabs, exceeds 230 km. Inspection of field slabs containing a large amount of ground granulated blast furnace slag (GGBS) has revealed signs of damage by salt scaling (Bleszynski et al. 2002). However, granulated blast furnace slag (BFS) does not contribute to damage by salt scaling. Furthermore, BFS can improve the resistance of concrete to freezing and thawing.

Besides bridges, sewerage facilities are another type of concrete structures that are also prone to serious damage, in this case by sulfuric acid. Sewage pipes have been reported to collapse at over 3000 locations per year in Japan. The cause of these collapse accidents is the erosion of concrete by sulfuric acid. It is known that the higher the concrete strength, the greater the damage caused by sulfuric acid (Uomo 2007; Mizukami 1986; Kurashige and Uomoto 2000). However, this fact is not accounted for in practical guidelines and manuals (JSWA 2007). The damage to concrete by sulfuric acid is not a problem peculiar to Japan. It occurs throughout the world because sulfuric acid is produced by bacteria common in sewage. Fundamental research on such deterioration has been conducted (Atto et al. 1988). Ceramic waste powder used as a cement replacement is reported to be effective at improving the resistance of the material to sulfuric acid attack (Shariši et al. 2020). Mineral admixtures, which have latent hydraulic activity (Alapour et al. 2017) or pozzolanic activity (Najimi et al., 2019; Saha et al., 2019), can also be expected to enhance the resistance of the material to sulfuric acid attack to some degree because they reduce the amount of calcium hydroxide produced by cement hydration. The effects of several types of sand have been examined (Mardani-Aghabaglou et al., 2016), but BFS without sand has a conspicuous effect on improving the resistance of the material to sulfuric acid attack.

Granulated blast furnace slag has been used as both the binder and sand of concrete for a long time (NSA 2009; JSCE 1997; Saito et al., 2009; ACI 1995). Granulated blast furnace slag is produced during the smelting process of pig iron. In this process, the quality of not only pig iron but also blast furnace slag is strictly controlled
in order to increase pig iron production productivity. Both GGBS and BFS are reliable as constituent materials of concrete based on the long history of their usage. Since BFS does not have a negative effect on concrete (Rakesh et al. 2017), it has been used as a part of ordinary sand in a restricted amount and has been regarded as an alternative to ordinary sand.

The purpose of this study is to experimentally show that BFS has a significant effect on improving concrete properties. Unfortunately, the effect of BFS on the improvement of concrete performance is not well known, although it is safe to say that the reaction of BFS with cement paste affects the improvement of concrete properties. Therefore, the effect of BFS depends on the reactivity of BFS. Moreover, the particle size distribution of BFS also indirectly affects the properties of concrete (Yüksel et al. 2006). The experimental results presented in this paper offer some clarification on the beneficial effects of BFS. BFS can enhance the resistance of the material to freezing and thawing without the addition of air-entraining (AE) agents. When both GGBS and BFS are used, the chloride ion penetrates at three months of immersion. Creep and drying shrinkage can be reduced, and the effect of BFS is significant, especially when the concrete strength is low. The resistance of the material to sulfuric acid attack is improved. Generally, when the strength of the concrete is high, its resistance to sulfuric acid is low. However, when BFS is used, even when the strength of the concrete is high, its resistance to sulfuric acid attack is not diminished.

The use of BFS does not always result in enhanced concrete properties. GGBS, whose quality conforms to JIS A 6206 (Ground granulated blast furnace slag for concrete) and BFS whose quality conforms to JIS A 5011-1 (Slag aggregate for concrete, Part 1: Blast furnace slag aggregate) were used in this study. When some types of mineral admixtures are used as binders, the beneficial effects of BFS are not always imparted to the resulting material (Yüksel et al. 2007; Yüksel and Genc 2007; Fujii and Ayano 2017). Therefore, GGBS, not mineral admixtures, was used in this study as a binder of concrete to obtain the test results.

2. Resistance to freezing and thawing

2.1 Effect of salt

Salts, such as sodium chloride and calcium chloride, accelerate damage to concrete by freezing and thawing (Takeda and Sogo 2001). Figure 1 shows the test method used to examine the resistance of small mortar pieces to freezing and thawing (Oyamada et al. 2011, 2015). This test method, prescribed by the Japan Society of Civil Engineers Standard JSCE-C 507, was developed to evaluate the quality of BFS by freezing and thawing in a sodium chloride solution using small mortar pieces. Five to seven mortar pieces, 10 × 10 × 10 mm in size, were soaked in the solution. The bottle containing the mortar pieces and solution was alternately frozen at −20°C for 16 hours and thawed at 20°C for 8 hours. The concentration of the sodium chloride solution was 5% by mass, in accordance with the JSCE-C 507 standard.

When freshwater was used as the solution, the mass retention of the mortar pieces was almost 100% at 14 cycles, as shown in Fig. 2. However, when the concentration of the sodium chloride solution was greater than 3%, the mass retention of the mortar pieces was 0% at 7 cycles, and most of the mortar pieces were broken. Therefore, the effect of salt on damage to cementitious materials by freezing and thawing is considerable.

Figure 3 shows a comparison of the mass retention between the mortar pieces with crushed sandstone sand (CSS) and that with BFS. The concentration of the sodium chloride solution was 5% by mass. Although the mortar pieces with CSS were broken at 7 cycles, the mass retention of the mortar pieces with BFS remained 100% after 14 cycles. The effect of BFS on the resistance of mortar in a sodium chloride solution to freezing and thawing is clear from this figure. The test mortars used to obtain the results shown in Figs. 2 and 3 were cured in water for 28 days.

2.2 Effect of granulated blast furnace slag

Figures 4 and 5 respectively show the effects of GGBS...
and BFS on the freezing and thawing of concrete. The experiments followed the guidelines of the Japanese Industrial Standards Number JIS A 1148: 2010 (Method A). However, sodium chloride solutions were used for the freezing and thawing tests because the damage to concrete in a sodium chloride solution is much larger, as shown in the previous section. The specimens in a sodium chloride solution of 10% concentration by mass were alternately exposed to $-18^\circ C$ and $5^\circ C$ every 5 hours. The water-to-binder ratio of each concrete specimen was 40%. The water curing period was 28 days. AE agents were not used. The constituents were as follows: the cement was ordinary Portland cement (OPC; density: 3.15 g/cm$^3$; Blaine fineness: 3350 cm$^2$/g), the admixture was GGBS (density: 2.89 g/cm$^3$; Blaine fineness: 4150 cm$^2$/g), the fine aggregates were crushed sandstone sand (CSS; density in saturated surface dry condition: 2.65 g/cm$^3$; water absorption: 1.70%; fineness modulus: 3.04) and BFS (density in saturated surface dry condition: 2.69 g/cm$^3$; water absorption: 0.61%; fineness modulus: 2.51), the coarse aggregate was crushed sandstone (maximum size: 20 mm; density in saturated surface dry condition: 2.74 g/cm$^3$; water absorption: 0.64%), and the high range water reducing agent was a polycarboxylate type water reducing agent.

The longitudinal axis of both figures is the relative dynamic modulus of elasticity. In general, the concrete is assessed as broken when the relative dynamic modulus of elasticity is less than 60%. As shown in Fig. 4, the concrete without GGBS broke at 50 cycles. However, as the GGBS content increased, the number of cycles at which the concrete broke also increased. When the GGBS-to-binder ratio was 60%, the relative dynamic modulus of elasticity was approximately 90% even though an AE agent was not added. The effect of GGBS on improving the resistance to freezing and thawing is remarkable.

BFS can also enhance the resistance of concrete to freezing and thawing, as shown in Fig. 5. As the binder-to-cement ratio of each concrete specimen in this figure was 40%, the concrete without BFS was broken at approximately 250 cycles. As the BFS content increased, the resistance of the concrete to freezing and thawing also increased. Therefore, BFS can also steadily enhance the resistance of concrete to freezing and thawing.

2.3 Effect of thickening agent

Figure 6 shows the effect of curing time on the resistance of the concrete specimens to freezing and thawing. The binder-to-cement ratio was 40%. The sand was entirely composed of BFS. AE agents were not used. The concrete test specimens were cured in water until the start of the test. When the water curing period was 28 days, the relative dynamic modulus of elasticity was maintained at 100% until 300 cycles. However, when the curing period was 7 days, the concrete was broken before 100 cycles. Therefore, a long curing period is required before the beneficial effects of BFS are activated. It is well known that a critical curing time is necessary for concrete, especially when slag is used (Sanjayan et al. 2000).

The durability factor is the index used to express the resistance of concrete to freezing and thawing. The durability factor is the index used to express the resistance of concrete to freezing and thawing. The durability factor is the index used to express the resistance of concrete to freezing and thawing.
Durability factor $DF$ is defined as follows:

$$DF = \frac{P \times N}{M}$$  \hspace{1cm} (1)

where $DF$ is the durability factor, $P$ is the relative dynamic modulus of elasticity at $N$ cycles of freezing and thawing (%), $N$ is the number of cycles at which $P$ reaches 60% or 300 cycles when the relative dynamic modulus elasticity is over 60%, and $M$ is 300 cycles. The concrete is assessed to be good when the durability factor is over 60.

As shown in Fig. 6, the relative dynamic modulus of elasticity of concrete after 7 days of water curing was 60% at 90 cycles. Therefore, $N$ in Eq. (1) is equal to 90. As $P$ is 60% and $M$ is 300 cycles, the $DF$ of concrete with 7 days of water curing is equal to 18. However, the relative dynamic modulus of elasticity of concrete after 28 days of water curing was 100% until 300 cycles. Therefore, $N$ is equal to 300 cycles when $P$ is equal to 100%. The $DF$ of concrete after 28 days of water curing was equal to 100.

Figure 7 shows the durability factor $DF$ of the concrete cured for 7 days. The sand was entirely composed of BFS. When a thickening agent was not used, the durability factor $DF$ was almost 18 regardless of the GGBS-to-binder ratio. However, when a thickening agent was used, the durability factor $DF$ of every concrete was 100 even though the curing period was only 7 days. It is well known that the resistance of ordinary AE concrete to freezing and thawing is deteriorated by the use of a thickening agent (Sudo et al. 1992). However, the resistance of concrete with BFS to freezing and thawing, especially when the curing period is relatively short, can be enhanced by a thickening agent, although the improvement mechanism has not been clarified.

### 3. Corrosion inhibition effect

#### 3.1 Resistance to penetration of chloride ion

Figures 8, 9, 10, and 11 show the chloride penetration profile of the mortar specimens soaked in sodium chloride solutions at a concentration of 10% by mass. The experiments followed the guidelines of the Japan Society of Civil Engineers Standard JSCE-G 572-2003. This test method was used to determine the apparent diffusion coefficient of the chloride ion in concrete by immersion in a sodium chloride solution. The water-to-binder ratio...
of the mortar specimens was 50%. The unit water content of the mortar was 270 kg/m³. The mix proportion of the mortar specimens is shown in Table 1. The constituents were as follows: the cement was OPC (density: 3.15 g/cm³; Blaine fineness: 3350 cm²/g), the admixture was GGBS (density: 2.89 g/cm³; Blaine fineness: 4150 cm²/g), and the fine aggregates were CSS (density in saturated surface dry condition: 2.64 g/cm³; water absorption: 1.78%; fineness modulus: 2.93) and BFS (density in saturated surface dry condition: 2.72 g/cm³; water absorption: 0.58%; fineness modulus: 2.32).

Figure 8 shows the chloride penetration profiles of the mortar containing OPC and CSS. Three years after the start of immersion in the sodium chloride solution, the chloride ions reached a depth of 100 mm. The apparent diffusion coefficient was 2.65 cm²/year.

When the GGBS content was 60% of the total binder content, as shown in Fig. 9, chloride penetration was restricted, and the depth of chloride immersion was approximately 30 mm after three years of immersion in the sodium chloride solution. The apparent diffusion coefficient was 0.26 cm²/year, which was approximately one-tenth that of the mortar containing OPC and CSS. Therefore, the effect of GGBS on the resistance of mortar to chloride ion penetration is considerable, as reported by other researchers (Song et al. 2010; Guneyisi et al. 2011; Lim et al. 2016). The high resistance to chloride ion penetration due to GGBS has also been demonstrated for concrete blocks exposed daily to seawater for approximately 25 years (Thomas et al. 2008; Riding et al. 2013). Although the effects of concrete porosity were examined (McCarter et al., 2000), the distinct mechanism has not yet been clarified.

Figure 10 shows the chloride penetration profiles of the mortar containing OPC and BFS. GGBS was not used. The depth of chloride immersion was approximately 30 mm at three years after the start of immersion in the sodium chloride solution, which is almost the same result as that shown in Fig. 9. The apparent diffusion coefficient of mortar containing OPC and BFS was 0.32 cm²/year. Therefore, chloride penetration can be restricted by BFS as well as GGBS.

Figure 11 shows the chloride penetration profiles of the mortar containing GGBS and BFS. The depth of chloride immersion was approximately 10 mm at three years after the start of immersion in the sodium chloride solution. The apparent diffusion coefficient of mortar with OPC and BFS was 0.05 cm²/year. Importantly, chloride ions did not penetrate the mortar after three months of immersion in the sodium chloride solution when both GGBS and BFS were used.

Figure 12 shows the interface between the cement paste and CSS. A gap can be clearly seen along the interface. However, there is no such gap at the interface of the mortar with BFS, as shown in Fig. 13. It is assumed that the absence of a gap at the interface is due to the reaction of BFS with some cement constituents as well as GGBS. As no gap through which chloride ions can easily pass exists in the mortar with BFS, BFS seems to be able to enhance the resistance of mortar to chloride penetration.

Table 1 Mix proportion of the mortar specimens.

| W/B (%) | GGBS/B (%) | BFS/S (%) | Air (%) | Unit content (kg/m³) |
|---------|------------|-----------|---------|----------------------|
|         | OPC        | GGBS      | CSS     | BFS                  | B  | S  |
| 50.0    | 0.0        | 0.0       | 100.0   | 2.0                  | 270|    |
| 100.0   | 0.0        | 1465      | 1397    | 0                    |    |    |
| 60.0    | 0.0        | 324       | 1397    | 0                    | 1440|    |

W: water; B: binder; S: sand
3.2 Steel corrosion protection ability of BFS

It is well known that an increase in the GGBS proportion decreases the amount of corrosion of the reinforcement (Pal et al. 2002; Al-Yaqout et al. 2020). In this section, BFS is demonstrated to exhibit the same effect. Figure 14 shows a schematic of the mortar specimen with an embedded steel rod of 13 mm in diameter. The specimen was alternately exposed to drying conditions and soaked in a sodium chloride solution in order to accelerate the corrosion of the steel rod embedded in mortar. The age of the mortar at the start of the test was 14 days. One cycle of this test consisted of a three-month soaking period in 10 mass% sodium chloride solution and one month of drying in a chamber at 40°C. Therefore, one cycle lasted four months.

The mortar used in the preparation of the specimen was wet-screened concrete from which coarse aggregates with sizes greater than 5 mm were removed. The mix proportion of the concrete is shown in Table 2. The water-to-cement ratio was 65% and the unit water content was 175 kg/m³. The constituents were as follows: the cement was OPC (density: 3.15 g/cm³; Blaine fineness: 3350 cm²/g), the fine aggregates were CSS (density in saturated-surface dry condition: 2.64 g/cm³; water absorption: 2.00%; fineness modulus: 3.02) and BFS (density in saturated-surface dry condition: 2.77 g/cm³; water absorption: 0.69%; fineness modulus: 2.32), and the coarse aggregate was crushed sandstone (maximum size: 20 mm; density in saturated-surface dry condition: 2.72 g/cm³; water absorption: 0.53%).

Figures 15 and 16 show the mortar specimens and the embedded steel rods in the mortar at 10 cycles, that is, at 3 years and 4 months after the start of testing. Figure 15 shows the results when CSS was used, and Fig. 16 shows the results when BFS was used. The difference between the two cases is apparent. The steel embedded in the mortar containing CSS was highly corroded, whereas the steel embedded in the mortar containing BFS hardly corroded and did not show any staining.

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rods. The amount of corrosion was obtained by the difference between the mass of the steel before the removal of the corrosion products and after the removal of the corrosion products. The corrosion products were removed using a 10% aqueous solution of diammonium citrate. As shown in this figure, the mortar containing BFS is effective at inhibiting the corrosion of steel.

4. Composite degradation test

4.1 Test procedure

Deterioration of concrete in bridge deck slabs is a significant problem in society. Fatigue due to increased loading is a major cause, but it is not the only cause. Another contributing factor is the freeze-thaw effect, which clearly promotes damage inside concrete, with the presence of water significantly accelerating concrete deterioration under fatigue loading (Farooq et al. 2017). This phenomenon is called “composite degradation” in this paper. Tests to investigate the effect of BFS in composite degradation were conducted using reinforced concrete (RC) and precast concrete (PC) beam specimens made of concrete with BFS as fine aggregate. Some results shown in this section are from the authors’ previous work (Ayano et al. 2017).

Figure 18 shows the RC and PC small beams used in the combined deterioration test. The dimensions of the test beams were 1350 mm length, 125 mm cross section, and 200 mm height.

The mix proportion of the concrete used in the beams is listed in Table 3. One set used CSS (density in saturated-surface dry condition: 2.67 g/cm³, water absorption: 1.49%, fineness modulus: 3.08) as a fine aggregate with a design compressive strength of 50 N/mm². The other set adopted BFS (density in saturated-surface dry condition: 2.72 g/cm³, water absorption: 1.12%, fineness modulus: 2.24), and the design compressive strength was the same. The cement used was HPC, with density of 3.13 g/cm³ and Blaine fineness of 4600 cm²/g. The coarse aggregate used was crushed sandstone, with maximum particle size of 20 mm, density of 2.74 g/cm³ in the saturated surface-dry state, and water absorption rate of 0.60%. The other additives used were polycarboxylate-type high-range water-reducing agent, AE agent, defoaming agent, alkyl aryl sulfonate, and alkylammonium salt thickener. The composite degradation test was carried out on four beam specimens consisting of two RC beams and two PC beams. CSS was used for the concrete of one RC beam specimen and one PC beam specimen, while BFS was used for the concrete of each of the other beam specimens.

Deformed rebars with nominal diameter of 13 mm (yield strength: 402 N/mm²; Young’s modulus: 200 kN/mm²) were used as reinforcement for the RC beams, and two rebars were placed in each RC beam. For the PC tendon of the PC beams, a prestressing steel bar with nominal diameter of 11 mm (yield strength: 125 N/mm²; Young’s modulus: 200 kN/mm²) was used, and one bar was placed in each PC beam. The design ultimate flexural strength of the RC and PC beams was considered to be almost the same. Table 4 shows the physical properties of the concrete. Steam curing was applied for curing the test beams at the maximum temperature of 50°C.

In the composite degradation test, 30 freeze-thaw cycles and 200,000 cycles of fatigue loading were con-
bined to reproduce the composite degradation. This combination was repeatedly applied to the test beams until failure. The freezing and thawing tests used throughout this study followed the guidelines of JIS A 1148: 2010 (Method A), except that a 10% sodium chloride solution was used instead of fresh water. The specimens in the sodium chloride solution of 10% concentration by mass were alternately exposed every 5 hours to −18°C and 5°C.

Figure 19 shows the fatigue loading test situation. The beam specimen was simply supported with a span length of 1200 mm, and the load was applied at two symmetrical points in the middle of the beam with an arm length of 450 mm. The fatigue tests were conducted at the loading frequency of 5 Hz and the minimum loading load of 15 kN. These values were chosen to take the possibility of flexural cracking in the RC beams into consideration. At the maximum load of 45 kN, the tensile stress acting on the RC beam’s reinforcing bars was equal to twice the allowable stress. The RC beams failed due to fatigue failure of the reinforcing bars after approximately 2 million cycles of cyclic loading. At that point, the maximum stress acting on the rebars in the RC beam reached a value equal to the allowable stress. The estimated fatigue life of the rebar was calculated according to Eq. (2), which is specified in Standard Specifications for Concrete Structures – 2017: Design, issued by the Japan Society of Civil Engineers:

\[
f_{\text{rd}} = 190 \times 10^6 \left(1 - \frac{\sigma_{\text{op}}}{f_{\text{sd}}}\right) \gamma_s
\]

where \(f_{\text{rd}}\) is the design fatigue strength (N/mm²), \(N\) is the fatigue life, equal to or less than 2 million (cycles), \(\sigma_{\text{op}}\) is the stress of the rebar under dead load, \(f_{\text{sd}}\) is the design tensile strength of the rebar (N/mm²), \(\alpha\) is an exponent equal to \(k_{\text{ef}}(0.81 - 0.003 \phi)\), where \(k_{\text{ef}} = 1.0\) and \(\phi\) is the diameter of the rebar (mm), \(k\) is the coefficient of fatigue life (0.12), and \(\gamma_s\) is the coefficient of the rebar material (1.05).

The stresses (stress strength ratio) the concrete and steel of the PC and RC beams were subjected to are shown in Fig. 20. The statically calculated stresses at the span center for the minimum and maximum loads are shown in the figure. The structural differences between the RC and PC beams account for ample differences in the stress conditions that apply to their concrete and reinforcement. When a load of 45 kN was applied to each beam, the concrete stress in the PC and RC beams was 30.0 and 19.0 N/mm², respectively. When a load of 15 kN was applied to each beam, the concrete stress in the PC and RC beams was 7.4 and 3.7 N/mm², respectively. Figure 20 shows that the amplitude of concrete stress in PC beams exceeds that in RC beams. On the other hand, the amplitude of the steel stress is smaller in the PC beam than in the RC beam. The reason is that the centroid position of the compressive stress acting on the concrete due to the bending moment in the PC beam changes more widely than that of the RC beam. This difference in the structural properties between PC and RC beams may lead to the conclusion that RC bridge deck slabs may fail due to reinforcement fatigue. However, it is known that existing RC bridge deck slabs tend to fail due to fatigue degradation of concrete accelerated by the presence of water. On the other hand, from Fig. 20, it can be concluded that the possibility of fatigue

| Type of sand | Air content (%) | Compressive strength (N/mm²) | Young’s modulus (×10³ N/mm²) | Design bending strength (kN·m) |
|--------------|-----------------|------------------------------|-------------------------------|-------------------------------|
|              |                 | 18 h | 7 d | 18 h | 7 d |                                    |
| CSS          | 5.1             | 40.3 | 57.5 | 36.8 | 38.1 | 15.6                                |
| BFS          | 2.6             | 42.7 | 54.8 | 36.2 | 40.0 |                                    |

### Table 4 Main physical properties of concrete.

**Fig. 19 Fatigue loading test.**

**Fig. 20 Stress applied to the concrete and steel bars in the RC and PC beams.**
failure of prestressing steel in PC bridge deck slabs is low. However, the stress state of concrete in PC bridge deck slabs is more severe than that of RC bridge deck slabs. Therefore, the possibility of failure due to fatigue degradation of concrete accelerated by water is considered to be much higher. Thus, preventing the failure of PC bridge deck slabs due to fatigue degradation of concrete accelerated by water contributes to their longevity.

Figure 21 shows the relative dynamic modulus of elasticity of the concrete used for the test beams measured according to JIS A 1148: 2010 (Method A). The freezing and thawing resistances of AE concrete with crushed sand and non-AE concrete with BFS as fine aggregate are comparable. Both types of concretes could withstand more than 400 freeze-thaw cycles.

4.2 Damage by cyclic loads

Figures 22, 23, 24, and 25 show the beam specimens’ conditions after completing the composite degradation tests. Figure 22 is the PC beam with AE concrete using CSS, Fig. 23 is the PC beam with non-AE concrete using BFS, Fig. 24 is the RC beam with AE concrete using CSS, and Fig. 25 is the RC beam with non-AE concrete using BFS.

Figure 22 shows a PC beam made of AE concrete containing CSS that failed after 360 freeze-thaw cycles and 2.4 million load cycles owing to fatigue degradation of the concrete accelerated by the presence of water. Figure 24 shows an RC beam made of AE concrete containing CSS that failed due to steel fatigue after 240 freeze-thaw cycles and 1.6 million load cycles. On the other hand, Figs. 23 and 25 show the condition of PC and RC beams made with non-AE concrete using BFS. Neither of the beams failed even after undergoing the composite degradation test of 600 freeze-thaw cycles and 4 million load cycles. In fact, both specimens remained intact and could withstand more than twice the number of cycles as the specimens using concrete with crushed sand. The difference is more pronounced in the test results of beam specimens. These results indicate that concrete with BFS as fine aggregate has higher resistance to composite degradation due to the combination of freeze-thaw and thawing, and fatigue.

5. Time-dependent strain

5.1 Drying shrinkage strain

The size of the prism specimens used to measure the drying shrinkage strain was 100 × 100 × 400 mm. Two pairs of gage points were attached symmetrically on the surfaces other than the casting surface and the opposite side to measure the drying shrinkage strain. The strain measuring device was a Whittemore strainmeter with minimum reading accuracy of 1/1000 mm. The specimens were stored in a climatic chamber to keep them in a constant temperature and humidity environment (temperature: 20 ± 1°C, relative humidity: 60 ± 3%).
OPC (density: 3.15 g/cm\(^3\), Blaine fineness: 3350 cm\(^2\)/g) was used as the cement. A polycarboxylate-type high-range water-reducing agent and an AE agent were used as additives.

Table 5 shows the density in the saturated-surface dry condition, water absorption, and fineness modulus of the crushed sandstone gravel and each sand. The mix proportion of the concrete used in the experiment to obtain the results shown in Fig. 26 are listed in Table 6.

Figure 26 is a plot of the shrinkage strain of the concrete with time. The regression curve was obtained by fitting the data to the hyperbolic equation shown in Eq. (3):

\[
\varepsilon(t) = \frac{\varepsilon \times t}{\beta + t}
\]

where \(\varepsilon(t)\) is the drying shrinkage strain at drying period \(t (\times 10^{-6})\), \(t\) is the drying period (days), \(\varepsilon\) is the ultimate drying shrinkage strain \((\times 10^{-6})\), and \(\beta\) is the term that expresses the evolution of the drying shrinkage strain (non-dimensional). The drying shrinkage strain of the concrete containing BFS was smaller than that containing CSS. Moreover, with a decrease in the water absorption of BFS, the drying shrinkage of the concrete with BFS also decreased.

The values of the ultimate drying shrinkage strain \(\varepsilon_{\text{ave}}\) were obtained from the regression curve according to Eq. (2) and plotted in Fig. 27. The unit water content of each concrete was 175 kg/m\(^3\). The binder was OPC. When BFS was used, especially those with low water absorption, the drying shrinkage strain decreased. The reducing effect of BFS on the drying shrinkage strain is particularly significant when the water-to-cement ratio is high.

Ordinarily, the effect of GGBS on the ultimate drying shrinkage strain is small (Rashad et al. 2016). However, GGBS with a large particle size is known to reduce shrinkage strain and shrinkage cracking (Topcu et al. 2010). Although the water absorption of BFS was considered in this test, the particle size of BFS can also affect the drying shrinkage strain.

### 5.2 Creep strain

The size of the prism specimen used for measuring the creep strain was 100 \(\times\) 100 \(\times\) 400 mm. Two pairs of gage points were attached symmetrically on the surfaces other than the casting surface and the opposite side. The strain measuring device was a Whittemore strainmeter with minimum reading accuracy of 1/1000 mm. The specimens were stored in a climatic chamber to keep them in a...
constant temperature and humidity environment (temperature: 20 ± 1°C, relative humidity: 60 ± 3%). The stress yield in the specimen was 25% of the concrete strength at the age of the first load application and was kept constant during the test. The creep strain was obtained by subtracting the drying shrinkage strain from the strain under constant stress. The mix proportion of the concrete used in the experiment to obtain the results shown in Fig. 28 is listed in Table 6.

Figure 28 shows a plot of the creep strain of the concrete with time. The regression curve was obtained by fitting the data to the logarithmic equation shown in Eq. (4):

\[ \varepsilon_c(t) = A \cdot \log(t+1) \]  

(4)

where \( \varepsilon_c(t) \) is the creep coefficient at loading time \( t \) (non-dimensional), \( t \) is the loading time (days), and \( A \) is the nominal creep coefficient (non-dimensional). The creep strain of the concrete containing BFS was also smaller than that containing CSS. Moreover, with the decrease in water absorption of BFS, the creep coefficient of the concrete with BFS also decreased.

The values of the nominal creep coefficient \( A \) were obtained from the regression curve according to Eq. (3) and plotted in Fig. 29. The concrete used in this experiment was the same as that used to measure the drying shrinkage strain. When BFS was used, especially those with low water absorption, the nominal creep coefficient decreased. The reducing effect of BFS on creep is particularly significant when the water-to-cement ratio is high.

6. Resistance to sulfuric acid attack

6.1 Erosion of cementitious material by sulfuric acid attack

Figure 30 shows the erosion cycle of cement paste by sulfuric acid attack, based on the sulfuric acid immersion test results of cementitious materials. Figure 30(b) shows that a gypsum coat is formed as soon as the cement paste is immersed in sulfuric acid. The pH of the sulfuric acid solution is very low and the pH of the cement paste is very high, thus creating a pH gradient across the gypsum layer. The metal ions move towards the point where the pH stabilises the metal ions. Gradually, gypsum changes to ettringite by the reaction between gypsum and concentrated aluminium ions [Fig. 30(c)]. Ettringite is stable when the surrounding pH is high. However, when the pH is low, ettringite changes to gypsum in a paste layer [Fig. 30(d)]. As increasing amounts of gypsum are generated in the paste, the gypsum layer slides off the solid concrete not exposed to attack by sulfuric acid. The ettringite near the solid concrete gets exposed to a low pH environment and eventually all the ettringite left in the paste changes to gypsum. In this manner, the gypsum in the paste is easily removed from the solid concrete, the new concrete surface becomes exposed to sulfuric acid attack, and a new cycle of erosion begins [Fig. 30(a)].

A cylindrical specimen of \( \phi 50 \times 100 \) mm in dimension was used for the sulfuric acid immersion test of the mortar. After their casting, the specimens were cured in water for 7 days, and then immersed in a 5% mass concentration sulfuric acid solution. The results of spraying phenolphthalein solution on the split surfaces of the mortar specimens containing CSS after immersion in sulfuric acid for 56 days are shown in Fig. 31. The mortar specimens did not contain white sections that did not react with the phenolphthalein solution. The lower the water-to-cement ratio, the greater the erosion of the mortar. The fact that erosion occurs in mortar or concrete with high strength exacerbates the problems associated with the maintenance of sewerage facilities because of the common misconception that resistance to sulfuric acid attack is high in the case of high concrete strength.

In contrast, as shown in Fig. 32, when BFS was used, the mortar specimens contained white sections that were not affected by the phenolphthalein solution. As shown in these photographs, the mortar with a gypsum coating exhibited high resistance to sulfuric acid attack even when the water-to-cement ratio of the mortar was low.
6.2 Prediction of mortar erosion depth by sulfurous acid attack

The depth of mortar erosion by sulfurous acid was plotted with the product of the soaking time and sulfurous acid concentration, as shown in Figs. 33 and 34, in which the relationship between these parameters was revealed to be linear. The results shown in Figs. 33 and 34 were obtained using mortars containing CSS and BFS, respectively. The cement was an OPC, and no mineral admixture was used. The slope of the line for the mortar with water-to-cement ratio of 25% is 13.0 mm/day and that for the mortar with water-to-cement ratio of 60% is 9.4 mm/day. The diagrams show the erosion cycle of cementitious material by sulfurous acid attack.
mm/day, as shown in Fig. 33. Evidently, as the water-to-cement ratio decreased, the erosion of the mortar containing CSS increased. However, in the case of BFS, the slope of the line for the mortar with water-to-cement ratio of 25% is 2.6 mm/day and that for the mortar with water-to-cement ratio of 60% is 3.0 mm/day. When BFS was used, the erosion of the mortar was smaller when the water-to-cement ratio was low. Notably, the resistance to sulfuric acid attack of the mortar containing BFS was five times higher than that containing CSS when the water-to-cement ratio was 25%.

7. Practical applications of precast elements with BFS concrete

Some PC elements manufactured with BFS are shown in Figs. 35, 36, 37, and 38. Hereafter, the concrete whose whole sand is BFS is called BFS concrete. The precast RC box culverts shown in Fig. 35 were constructed under the sea. They were adopted with the expectation that BFS concrete is highly resistant to chloride ion permeation. The precast element lifted by the marine crane shown in Fig. 36 is a RC deck slab of the jacket-type pier. The size of the deck slab is 8.0 × 4.0 × 0.4 m, and 140 deck slabs were used to construct the pier. The high resistance of BFS concrete to chloride ion permeation does not require the use of epoxy rebar. BFS concrete was adopted in this construction because not using epoxy rebar reduces construction costs. Figure 37 shows construction for highway renewal. BFS concrete was used to manufacture the deck slabs. In this area, salt spray occurs during winter. BFS concrete was adopted to prevent the early deterioration of the concrete deck slabs by heavy traffic and freeze–thaw cycles. The precast elements shown in Fig. 38 are for overhang roads in the valley. Cold wind blows through the precast elements during winter. BFS concrete was used for these precast elements to enhance their resistance to damage by freeze–thaw cycles.

8. Conclusions

Concrete deterioration can be caused by a variety of factors, including freeze–thaw cycles, road salt, increased heavy traffic, and poor waterproofing. New or renewed concrete members used in cold climates need to be made of especially durable concrete. When replacing deteriorated members with new concrete slabs, the use of PC elements is necessary to minimize traffic restrictions during the construction period. This study showed that BFS can be used to produce precast PC and RC elements with higher durability. The following main conclusions can be drawn from the test results.

1) BFS can enhance the resistance of concrete to freezing and thawing even without the addition of AE agents. When a thickening agent is used, the curing time at
which BFS is effective can be shortened.

2) BFS can suppress the penetration of chloride ions and inhibit the corrosion of steel.

3) BFS can reduce time-dependent strains, such as drying shrinkage strain and creep strain.

4) BFS can improve the resistance of cementitious materials to sulfuric acid attack. For ordinary concrete or mortar containing CSS, the greater the strength of the concrete or mortar, the greater the erosion by sulfuric acid. However, when BFS is used, the effect of strength on erosion by sulfuric acid is small; rather, high-strength concrete or mortar becomes more durable owing to enhanced capacity to withstand sulfuric acid.

5) Based on the findings presented in this paper, guidelines on the design, manufacture, and construction methods of PC with BFS sand were issued as Concrete Library 155 by the Japan Society of Civil Engineers in March 2019.

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