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Paper:

Improvement of Durability of Precast Concrete Member by Granulated Blast Furnace Slag Sand

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Concrete deck slabs of bridges are often deteriorated by heavy traffic and freezing and thawing actions. Spraying salt during the winter further promotes the deterioration of concrete. Some reports estimate that the length of highway roads requiring the renewal of deteriorated concrete slabs exceeds 230 km. In order to extend the lifespan of damaged bridge girders, the load for these girders must not be increased. This means that prestressed concrete (hereafter, PC) members are desirable to sustain bridge life, because they can be thinner than reinforced concrete (hereafter, RC) members. In addition, to shorten the period of traffic regulation during renewal construction, precast members should be applied. One problem in manufacturing durable precast concrete is steam curing. When the temperature, period, or both of the steam curing process are inadequate, the effect of air-entraining (hereafter, AE) agents is lost because the warmed air trapped by the AE agent expands and escapes from the concrete. Another problem is concrete fatigue. It is well known that the fatigue lives of concrete slabs in wet conditions are much shorter than those in dry conditions. Concrete slabs are waterproofed immediately after construction, but the waterproofing can be fractured soon after opening bridges, and water can reach the concrete surface. The lifespan of concrete slabs in contact with water often depends on the fatigue of the concrete. Granulated blast furnace slag sand (hereafter, BFS) can enhance the resistance to freezing and thawing actions without using AE agents. Therefore, the resistance to freezing and thawing of concrete mixed with BFS is not damaged by steam curing. The fatigue of concrete in water is also improved by the addition of BFS. Furthermore, BFS can reduce the drying shrinkage of concrete. It is advantageous to restrict the loss of prestress in PC. This study shows that precast PC members with high durability can be manufactured when granulated blast furnace slag is used as a fine aggregate in the concrete. BFS reacts with cement hydrates. It is well known that the carbonation of concrete with ground granulated blast furnace slag (hereafter, GGBF) is much greater than that with ordinary binder. However, BFS does not accelerate the carbonation of concrete. When using granulated blast furnace slag as a fine aggregate, no disadvantage in the concrete properties is detected.

Keywords: BFS, resistance to freezing and thawing, fatigue in water condition, precast member, PC slab

1. Introduction

Bridges constructed in the high-growth era of the 1970s have already served for more than 40 years since their opening in Japan. The deterioration of bridges caused by fatigue from issues such as increases in the number and load of vehicles, salt damage by airborne chloride ions, and the spraying of anti-freezing agents has become a major problem [1]. Damage to concrete deck slabs is particularly serious. One of the main causes of this damage is fatigue, and the damage is exacerbated when the concrete slabs are in contact with water. In such cases, the surface of concrete deck slabs can be crushed and ground into sand and fine particles (hereafter, "fatigue deterioration of concrete accelerated by water"). Freezing and thawing actions with salt accelerate this phenomenon [2, 3].

Concrete deck slabs in which damage has become advanced are generally removed and replaced with new concrete slabs. Precast prestressed concrete (PC) deck slabs are necessarily used for replacement because the bridges must remain in service during maintenance; therefore, the period of traffic regulation must be minimized [4]. Precast PC deck slabs are also advantageous in requiring lower thickness relative to conventional concrete deck slabs reinforced with rebar, thereby reducing the dead load. Therefore, damaged concrete deck slabs in a bridge can be replaced without additional strengthening by steel girders by using precast PC deck slabs.

The requirements for concrete used in replacement members are as follows. 1) Fatigue deterioration of

Table 1. Mix proportions of concrete.

No.	W/C (%)	Design Air (%)	s/a (%)	Unit content (kg/m^3)					HRWRA (C×%)	Thickener (C×%)	AE (C×%)	DF (C×%)	Measured air (%)	Comp. strength (N/mm^2)
				W	C	S		G						
						CS	BFS							
1	65.0	4.5	48.0	170	262	885	0	967	0.4	0.00	0.003	0.00	3.6	34.7
2	40.0	2.0	43.0	153	383	0	839	1,065	1.1	0.04	0.000	0.03	2.7	84.6

CS: Crushed sand, BFS: Granulated blast furnace slag sand, HRWRA: High-range water-reducing agent, DF: De-forming agent, Comp. strength at 28 days

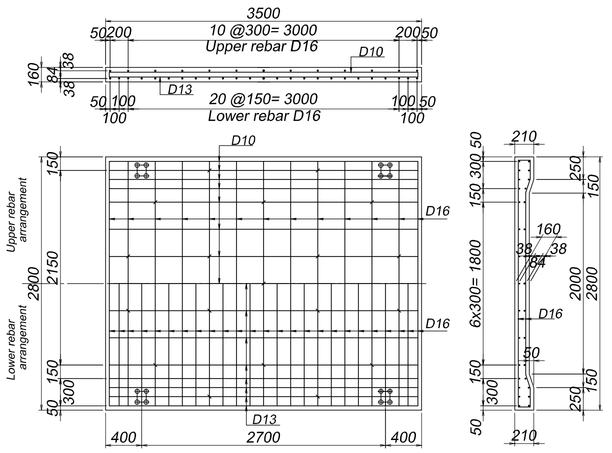


Fig. 1. Size and dimension of slab.

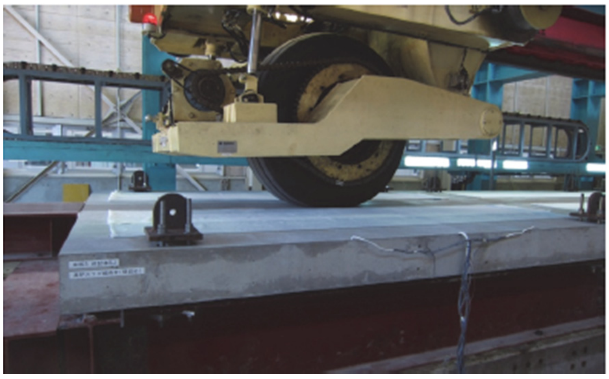


Fig. 2. Wheel running fatigue test.

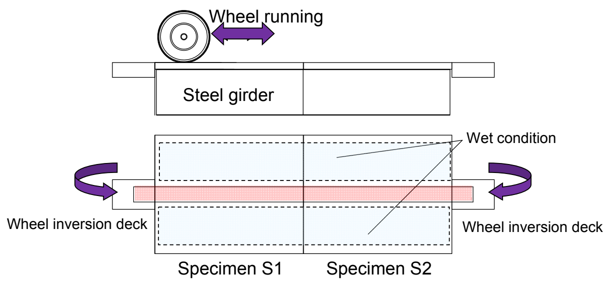


Fig. 3. Schematic of the test set-up.

concrete accelerated by water should not occur easily; namely, concrete used in replacements should have high resistance to freezing and thawing attacks and fatigue in water. 2) Concrete is suitable for PC members; namely, the creep and shrinkage degrees are small and the Young's modulus is high. 3) Concrete should protect reinforcing steel from corrosion; namely, it should be highly resistant to carbonation and the penetration of chloride ions. It is well known that the addition of GGBF significantly reduces the penetration of chloride ions, while increasing carbonation speed [5, 6]. However, concrete that meets all the above requirements can be produced by using BFS instead of conventional fine aggregate materials. BFS formerly experienced hardening during storage. Sodium polyacrylate, a retarding agent, mitigates this problem of BFS without affecting the properties of the concrete, so BFS can be used easily as a replacement for conventional fine aggregate.

2. Wheel Running Fatigue Test

2.1. Test Specimens

In order to investigate the resistance characteristics of concrete to fatigue while in contact with water, wheel running fatigue tests were performed on two test specimens. The sizes, dimensions, and rebar arrangements of the specimens are shown in **Fig. 1**. The test specimens simulate a bridge deck slab designed according to the specification for road bridges published in 1964 [7]. The thickness of the specimen is 160 mm.

The mix proportions of the concrete used for the test specimens are shown in **Table 1**. The mix proportion No.1 is concrete using crushed sand (density in saturated-surface dry condition: 2.60 g/cm^3, water absorption: 0.93%, fineness: 2.83) with the design compressive strength of 35 N/mm^2. The mix proportion No.2 is concrete using BFS (density in saturated-surface dry condition: 2.77 g/cm^3, water absorption: 0.22%, fineness: 2.11) instead of crushed sand with the design compressive strength of 70 N/mm^2. High-early-strength Portland cement (hereafter, HPC) (density: 3.13 g/cm^3, Blaine fineness: 4,600 cm^2/g) is used. As a coarse aggregate, crushed sandstone (maximum size: 20 mm, density in saturated-surface dry condition: 2.65 g/cm^3, water absorption: 0.43%) is used.

The test specimens S1 and S2 were cast with concretes No.1 and No.2. The two test specimens are otherwise equal in size, dimension, and rebar arrangement.

2.2. Outline of Experiment

The machine used for the wheel load running test is shown in **Fig. 2**. The machine has a self-running pneumatic tire that applies load via an oil jack [8].

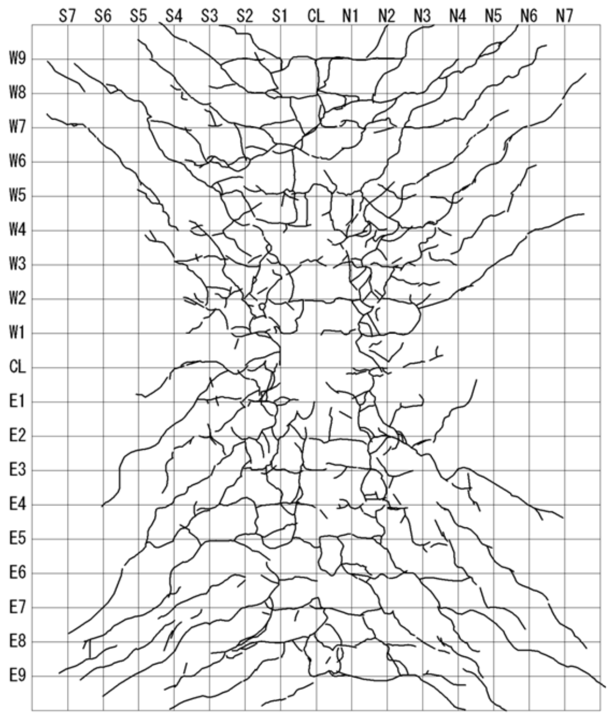


Fig. 4. Cracking pattern of S1 (50,000 times).

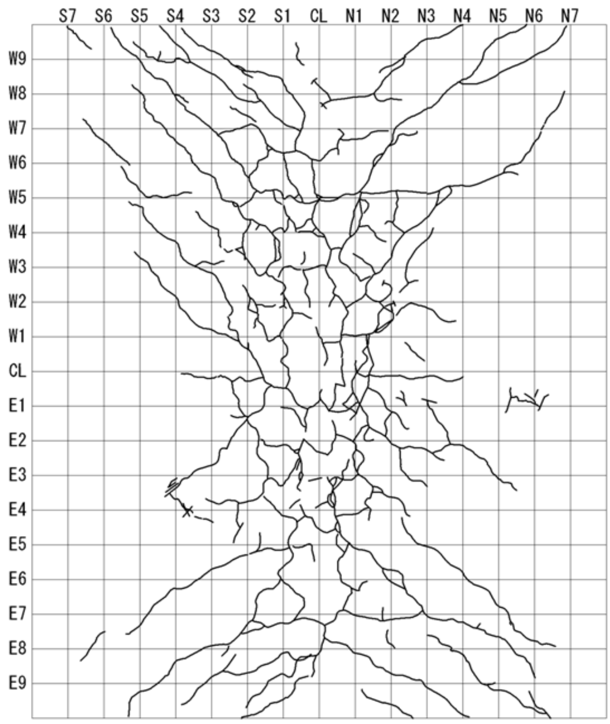


Fig. 5. Cracking pattern of S2 (50,000 times).

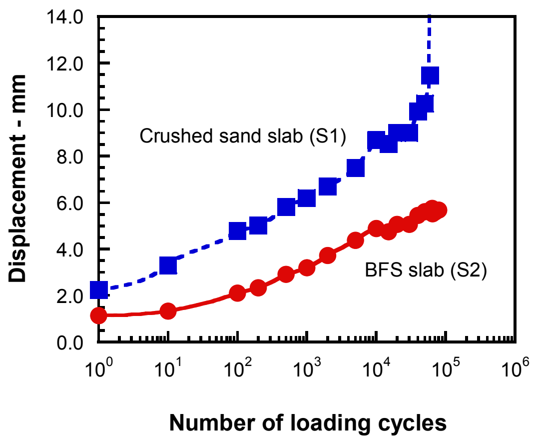


Fig. 6. Displacements of the specimens.

Figure 3 shows a schematic of the test. Two specimens are placed side-by-side on steel girders and steel crossbeams. The specimens are supported on four sides. The span lengths are 3,300 mm in the longitudinal direction and 2,500 mm in the perpendicular direction. Lift-preventing devices are set at the four corners of each specimen. The applied constant load is 200 kN, which is about 3.6 times of design load. The wheel runs from one wheel-inversion deck to the other repeatedly with a velocity of approximately 2 km/h. In order to simulate water in contact with the upper surface of the concrete, curing sheets are placed on the specimens as shown in **Fig. 3**, and water is scattered and resupplied every day.

Displacements at the center of the specimens are measured after 1, 10, 100, 200, 500, 1,000, 2,000, 5,000, and 10,000 cycles, and statically every 10,000 cycles afterward. Cracks in the concrete specimens are observed on the bottom surfaces; the cracking patterns are sketched at each instance of static measurement.

2.3. Test Results

The test specimen S1 broke by fatigue after 64,189 loading cycles, while the test specimen S2 did not break even after 88,475 loading cycles, which was the machine-determined limit of loading.

Figures 4 and **5** show the cracking patterns of specimens S1 and S2 on the bottom surfaces after 50,000 loading cycles. Early during loading, cracks occur longitudinally. Radial cracks extending from the four corners to the center of the specimen follow, before cracks in the direction perpendicular to the longitudinal axis form. As the loading cycles are increased, cracks develop in a grid-like pattern with increasing density. In comparing the cracking patterns of S1 and S2 after 50,000 cycles, it is obvious that the density of cracks in S2 is lower than that in S1. This indicates that a higher compressive strength correlates to fewer occurrences of cracking.

Displacements at the center of the specimens are plotted in **Fig. 6**. The displacements of the two specimens are increased as the number of loading cycles increases, and the final displacement of S1 approaches 12 mm at the failure of the specimen by fatigue. The displacement of S2 at 88,475 loading cycles is less than 6 mm, which is one-half of the final displacement of S1. This means that S2 maintains sufficient load-bearing ability at the end of loading. Leakage of water through cracks occurs in specimen S1 after 20,000 loading cycles. However, no leakage is observed in S2.

From these test results, it can be said that increases in

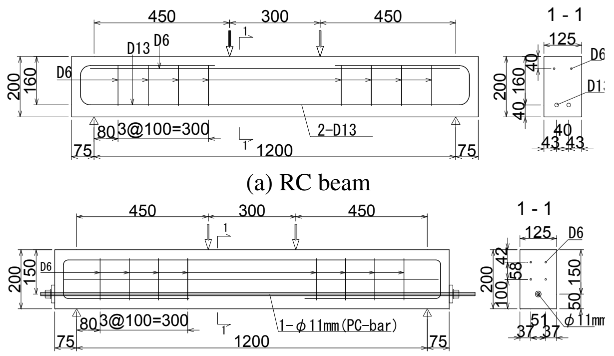
Table 2. Mix proportions of concrete.

W/C (%)	Air (%)	s/a (%)	Unit content (kg/m^3)					HRWRA (C×%)	Thickener (C×%)	AE (C×%)	DF (C×%)
			W	C	S		G				
					BFS	CSS					
35.0	4.5	49.0	155	443	0	863	921	0.8	0.00	0.01	0.0
	2.0	42.0			782	0	1,088		0.04	0.00	0.7

CSS: Crushed sandstone sand, BFS: Granulated blast furnace slag sand, HRWRA: High-range water-reducing agent, DF: De-forming agent

Table 3. The main physical properties of concrete.

Fine aggregate	Concrete					Type	Design bending strength (kN・m)
	Air content (%)	Compressive strength (N/mm^2)		Young's modulus (×10^{3}N/mm^2)			
		18hr	7days	18hr	7days		
CSS	5.1	40.3	57.5	36.8	38.1	RC	15.640
						PC	
BFS	2.6	42.7	54.8	36.2	40.0	RC	15.643
						PC	



(a) RC beam

(b) PC beam

Fig. 7. Size and dimension of test beams.

the compressive strength of concrete can improve the resistance to fatigue and reduce the occurrence of cracks.

3. Composite Degradation Test

Deterioration of concrete in bridge deck slabs related to fatigue by increased load is a significant problem. Typically, damage to concrete increases when freezing and thawing actions occur simultaneously, with fatigue deterioration of concrete accelerated by water. Hereafter, this phenomenon is described as "composite degradations" in this paper. It was found that when BFS was used as a fine aggregate of concrete, resistance to freezing and thawing can be improved even without an air-entraining (AE) agent [9, 10, 11].

In order to investigate the resistance of concrete using BFS as a fine aggregate, composite degradation tests were performed using RC and PC beams [12].

3.1. Outline of Experiment

Small beams of RC and PC, as shown in **Fig. 7**, are used in the composite degradation test. The cross-sections of the beams are 125 mm in width and 200 mm in height, and the lengths of the beams are 1,350 mm.

The mixing proportions for the concrete used in the beams are shown in **Table 2**. One uses crushed sand (density in saturated-surface dry condition: 2.67 g/cm^3, water absorption: 1.49%, fineness: 3.08) as a fine aggregate with the design compressive strength of 50 N/mm^2. The other uses BFS (density in saturated-surface dry condition: 2.72 g/cm^3, water absorption: 1.12%, fineness: 2.24) with the same design compressive strength. As a cement, HPC (density: 3.13 g/cm^3, Blaine fineness: 4,600 cm^2/g) is used. As a coarse aggregate, crushed sandstone (maximum size: 20 mm, density in saturated surface dry condition: 2.74 g/cm^3, water absorption: 0.60%) is used. A polycarboxylate-type high-range water-reducing agent, AE agent, de-forming agent, and alkyl aryl sulfonate and alkylammonium salt thickeners are used as additives [14, 15]. Four beams, two RC and two PC, were employed for the composite degradation tests. One RC and PC beam each was cast with concrete using crushed sand, while the other was cast with concrete using BFS.

The RC and PC beams were designed with almost equal ultimate bending strengths. As tensile steel, two deformed rebars with the nominal diameter of 13 mm (yield strength: 402 N/mm^2, Young's modulus: 200 kN/mm^2) were placed in each RC beam. One prestressing steel bar with the diameter of 11 mm, (yield strength: 1,125 N/mm^2, Young's modulus: 200 kN/mm^2), was placed in each PC beam. The main physical properties of the concrete are listed in **Table 3**.

3.2. Test Procedures

The test beams were steam-cured at the highest temperature of 50°C. Afterward, the beams were kept indoors until they reached the age of seven days.

The composite degradation test combined 30 cycles of

Fig. 8. Fatigue loading test.

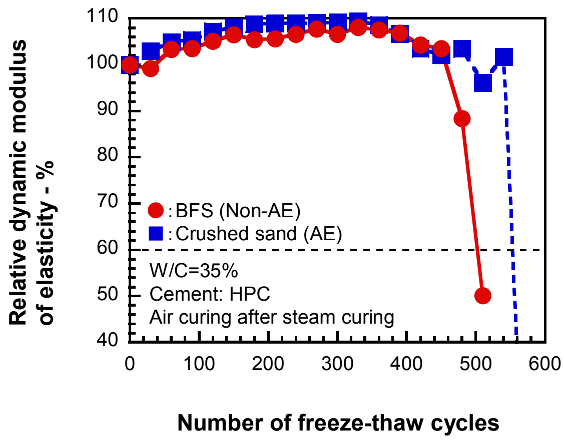


Fig. 10. Resistance to freezing and thawing attack.

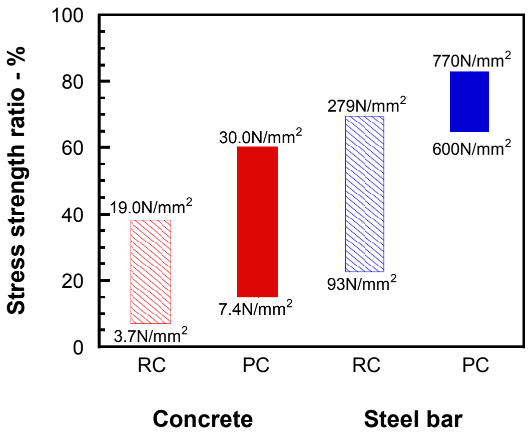


Fig. 9. Stress applied to concrete and steel in beams.

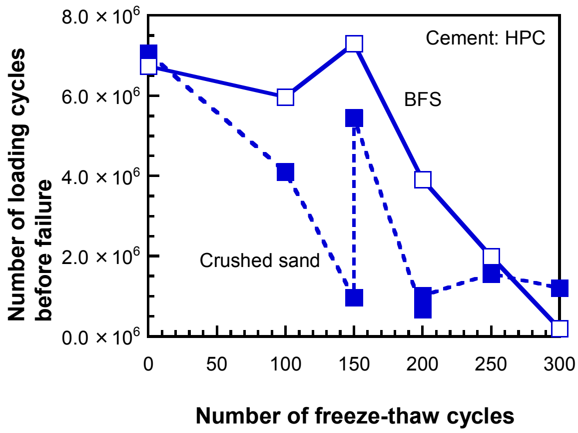


Fig. 11. Fatigue in water.

freezing and thawing with 200,000 cycles of fatigue loading. This combination was repeated until the failure of the test beams. The freezing and thawing tests throughout the experiments reported in this study followed the guidelines of JIS A 1148: 2010 (Method A) [13], except that 10% salt water was used instead of fresh water.

For fatigue loading, the beams were simply supported with span lengths of 1,200 mm, as shown in **Fig. 8**. The load is applied at two points symmetrically with an arm length of 450 mm. The loading frequency is 5 Hz. The minimum applied load was 15 kN. This is selected to cause bending cracks in the RC beam. The maximum load is 45 kN, at which point the tensile stress of the rebar in the RC beam reaches twice the allowable stress. The rebar of the RC beams broke by fatigue after about 2 million cycles when the maximum stress by cyclic loading is equal to the allowable stress. The estimated fatigue life of the rebar is calculated according to equation (1) indicated in the standard specifications [16].

$$f_{srd} = 190\frac{10^a}{N^k}\left(1-\frac{\sigma_{sp}}{f_{ud}}\right)/\gamma_s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where f_{srd} is the design fatigue strength (N/mm^2), N is the fatigue life equal to or less than 2 million (cycles), σ_{sp} is the stress of rebar by dead load, f_{ud} is the design tensile strength of the rebar (N/mm^2), a is an exponent equal to k_{0f} (0.81-0.003ϕ) where $k_{0f} = 1.0$ and ϕ is the diameter of the rebar (mm), k is the coefficient of fatigue life (0.12), and γ_s is the coefficient of the rebar material $= 1.05$.

Stresses applied to the concrete and steel in the PC and RC beams are illustrated in **Fig. 9**. They are calculated at the middle of the span statically for the minimum and maximum loads. The stresses of concrete and steel differ significantly for the RC and PC beams because of the structural differences. As seen in this figure, the amplitude of concrete stress in the PC beam is larger than that in the RC beam. However, the amplitude of steel stress of the PC beam is smaller than that of the RC beam. This is because the centroid of the resultant force of concrete compressive stress caused by the bending moment in the PC beams is changed much more than that of the RC beams by loading. From these differences in structural properties between the PC and RC beams, it can be concluded that RC deck slabs of bridges likely fail because of rebar fatigue. However, in existing structures, RC bridge deck slabs fail because of fatigue deterioration of concrete accelerated by water. If such concrete is applied for PC bridge deck slabs, they are more likely to fail by fatigue deterioration of concrete accelerated by water. Because the possibility of failure by the fatigue

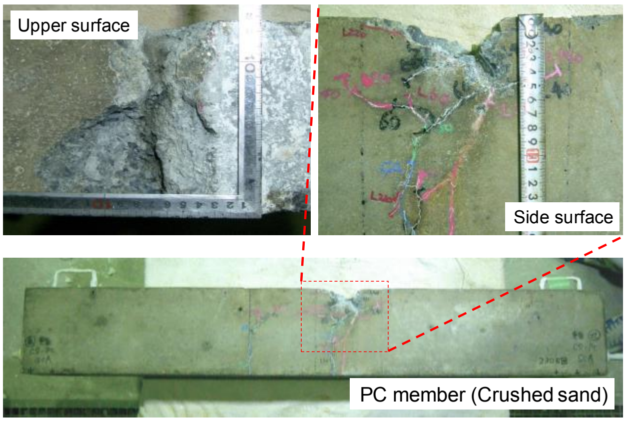


Fig. 12. PC AE concrete member with crushed sand.

Fig. 13. PC non-AE concrete member with BFS.

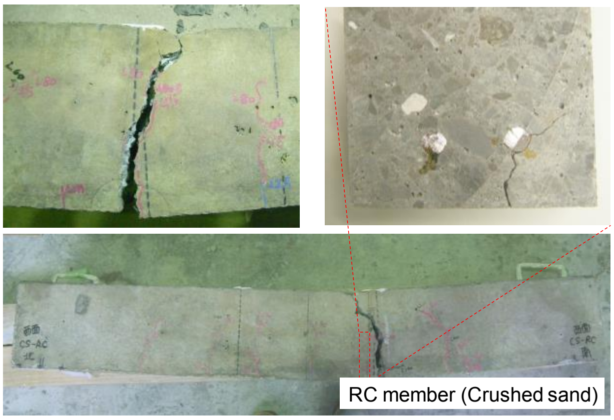


Fig. 14. RC AE concrete member with crushed sand.

Fig. 15. RC non-AE concrete member with BFS.

of prestressing steel in PC bridge deck slabs is low, the prevention of failure by fatigue deterioration of concrete accelerated by water would prolong the lifespan of such deck slabs.

Figure 10 shows the resistance to freezing and thawing attacks of the concrete used for the test beams. AE concrete using crushed sand as fine aggregate and non-AE concrete using BFS show similar resistances to freezing and thawing attacks. Both concretes withstand more than 400 freeze–thaw cycles.

Figure 11 shows the fatigue life of concretes used for test beams after subjection to cycles of freezing and thawing. Fatigue tests were performed on cylindrical specimens with diameters of 75 mm and heights of 150 mm. The fatigue life of non-AE concrete using BFS is somewhat longer than that of AE concrete using crushed sand, but the difference is not great.

3.3. Test Results

Figures 12–15 show the conditions of the PC beam cast with AE concrete using crushed sand, the PC beam cast with non-AE concrete using BFS, the RC beam cast with AE concrete using crushed sand, and the RC beam cast with non-AE concrete using BFS, respectively, after the composite degradation tests are finished.

The PC beam cast with AE concrete using crashed sand, as shown in **Fig. 12**, fails via fatigue deterioration of concrete accelerated by water after 360 cycles of freezing and thawing and 2.4 million loading cycles. The RC beam cast with AE concrete using crashed sand, as shown in **Fig. 14**, fails via rebar fatigue after 240 freeze–thaw cycles and 1.6 million loading cycles. However, as shown in **Figs. 13** and **15**, the PC and RC beams cast with non-AE concrete using BFS do not fail, remaining sound even after 600 freeze–thaw cycles and 4.0 million loading cycles of loading. These are more than twice the numbers of cycles sustained by the beams cast with concrete using crashed sand. The resistance to freezing and thawing and resistance to fatigue are not significantly different between the AE concrete with crushed sand and non-AE concrete with BFS, as shown in **Figs. 10** and **11**, when small size specimens are used. However, significant differences are apparent in the test using beam specimens. These results demonstrate that concrete using BFS as a fine aggregate has a higher resistance to composite degradation, or the combination of freezing and thawing action with fatigue.

4. Resistance to Freezing and Thawing Action of Concrete

4.1. Outline of Experiment

Ordinary Portland cement (hereafter, OPC) (density: 3.15 g/cm^3, Blaine fineness: 3,350 cm^2/g), HPC (density: 3.13 g/cm^3, Blaine fineness: 4,600 cm^2/g), and GGBF (density: 2.89 g/cm^3, Blaine fineness: 4,150 cm^2/g) are used as binders. As fine aggregates, crushed sandstone sand (density in saturated-surface dry condition: 2.64 g/cm^3, water absorption: 2.00%, fineness: 2.93) and BFS (density in saturated-surface dry condition: 2.77 g/cm^3, water absorption: 0.69% fineness: 2.32) are used. As a coarse aggregate, crushed sandstone (maximum size: 20 mm, density in saturated-surface dry condition: 2.75 g/cm^3, water absorption: 0.56%) is used. Polycarboxylate-type high-range water-reducing

Table 4. Mix proportions of concrete with OPC.

W/B (%)	GGBF/B (%)	Design air (%)	s/a (%)	Unit content(kg/m^3) W	B OPC	B GGBF	S CSS	S BFS	G	HRWRA (B×%)	DF (B×%)	TA (B×%)	Measured air (%)	Comp. strength (N/mm^2)
40	0	2.0	50.0	175	438	0	879	0	916	0.5	0.00	0.00	2.2	59.6
40	20	2.0	50.0	175	350	88	876	0	912	0.5	0.00	0.00	2.4	64.0
40	40	2.0	50.0	175	263	175	873	0	909	0.4	0.00	0.00	2.5	48.5
40	40	2.0	50.0	175	263	175	591	296	909	0.4	0.00	0.00	2.6	63.3
40	40	2.0	50.0	175	263	175	300	601	909	0.4	0.00	0.00	3.3	69.1
40	40	2.0	50.0	175	263	175	0	916	909	0.4	0.00	0.00	4.2	55.0
40	60	2.0	50.0	175	175	263	869	0	906	0.3	0.00	0.00	2.2	46.7
35	0	2.0	42.2	175	500	0	0	755	1,027	0.5	0.01	0.08	4.8	48.2
35	15	2.0	42.0	175	425	75	0	750	1,027	0.5	0.01	0.08	3.5	55.3
35	30	2.0	41.8	175	350	150	0	744	1,027	0.5	0.01	0.08	2.9	61.1
35	45	2.0	41.6	175	275	225	0	738	1,027	0.5	0.01	0.08	2.2	64.8
35	60	2.0	41.4	175	200	300	0	732	1,027	0.5	0.01	0.08	1.3	53.2
35	0	2.0	42.2	175	500	0	0	755	1,027	0.5	0.01	0.00	1.4	65.3
35	10	2.0	42.1	175	450	50	0	751	1,027	0.5	0.01	0.00	1.6	69.2
35	20	2.0	41.9	175	400	100	0	748	1,027	0.5	0.01	0.00	1.3	71.0
35	30	2.0	42.2	175	350	150	0	744	1,027	0.5	0.01	0.00	1.0	71.6
35	40	2.0	41.7	175	300	200	0	740	1,027	0.5	0.01	0.00	1.0	72.0

OPC: Ordinary Portland cement, GGBF: Ground granulated blast furnace slag, BFS: Granulated blast furnace slag sand, HRWRA: High-range water-reducing agent, DF: De-forming agent, TA: Thickener, Compressive strength at 28 days

Table 5. Mix proportions of concrete with HPC.

W/B (%)	Air (%)	s/a (%)	Unit content (kg/m^3) W	B HPC	B GGBF	S CSS	S BFS	G	AE (B×%)	HRWRA (B×%)	DF (B×%)	TA (B×%)	Measured air (%)	Comp. strength (N/mm^2)
35	4.5	39.8	155	443	0	682	0	1,086	0.01	0.8	0.00	0.00	4.0	58.3
35	2.0	42.0	155	443	0	0	795	1,086	0.00	0.8	0.01	0.04	3.5	72.1

HPC: High-early-strength Portland cement, GGBF: Ground granulated blast furnace slag, CSS: Crushed sandstone sand, BFS: Granulated blast furnace slag sand, AE: Air entrained agent, HRWRA: High-range water-reducing agent, DF: De-forming agent, TA: Thickener, Compressive strength at 28 days

agent, AE agent, de-forming agent, and alkyl aryl sulfonate and alkylammonium salt thickeners are used as additives [14, 15].

The designed slump of the concrete is 21 cm, while the water content of concrete is 175 kg/m^3. The water-to-binder ratio of the concrete is fixed constant of 35% for every mixture. The mix proportions of the concretes are shown in **Tables 4** and **5**. **Tables 4** and **5** depict the OPC concretes and HPC, respectively. The dosage of AE agent for concrete with BFS is zero.

Two types of specimens were used. One concrete specimen was cured in water at 20°C. The other was steam-cured before de-molding. After casting was completed, the water-cured specimen was cured for 20 ± 2 h at 20 ± 2°C. The steam-cured specimen was cured in the steaming room. The temperature of the steaming room was increased by 15°C every hour for 2 h. The room temperature for steam curing was then held at 60°C for 3 h. 100 × 100 × 400 mm prismatic concrete specimens were used. 10% salt water was used for the freezing and thawing tests. The specimens were alternately exposed to temperatures of −18°C and 5°C every 5 h in 10% salt water by mass.

4.2. Test Results

Figure 16 shows the effect of GGBF on the resistance to freezing and thawing action. The water-to-binder ratio is 40%. The circles, triangles, lozenges, and squares in the figure represent the results of concretes with GGBF-to-binder ratios of 0%, 20%, 40%, and 60% by mass, respectively. These are steam-cured with no included entrained air. The sand is crushed sandstone sand. Higher ratios of GGBF-to-binder correspond to higher resistances to freezing and thawing in the concrete. The concrete with 60% GGBF does not fracture until 300 freeze–thaw cycles have passed.

Figure 17 shows the effect of BFS on the resistance to freezing and thawing action of concrete. The lozenges in this figure are the same data points as those in **Fig. 16**. The

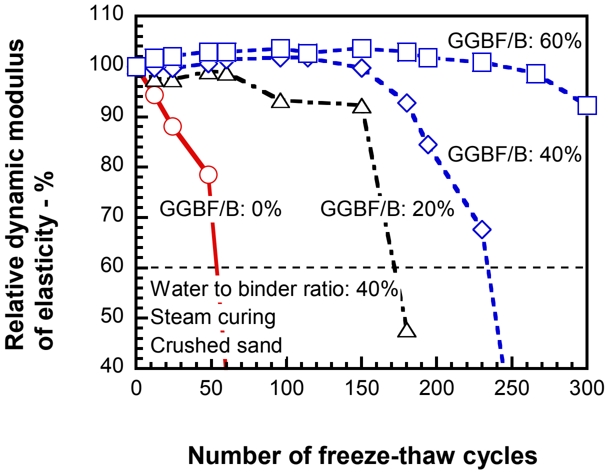


Fig. 16. Effect of GGBF on freeze-thaw resistance.

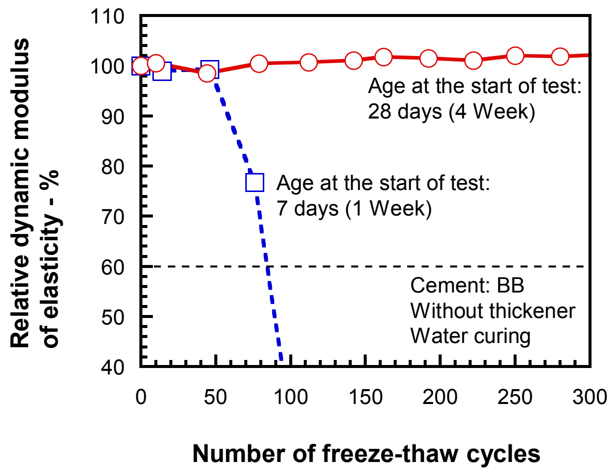


Fig. 18. Freeze-thaw test result of concrete with BB.

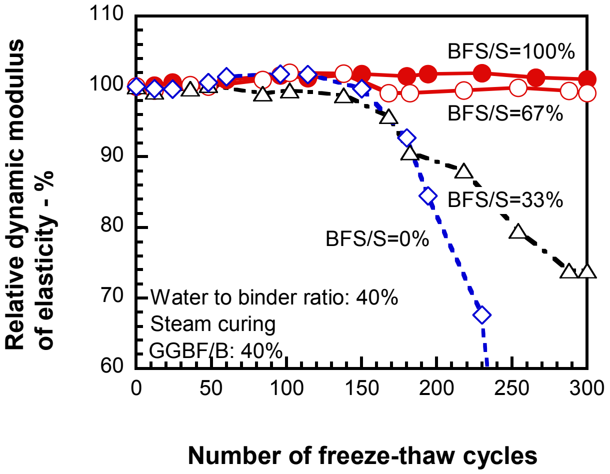


Fig. 17. Effect of BFS on freeze-thaw resistance.

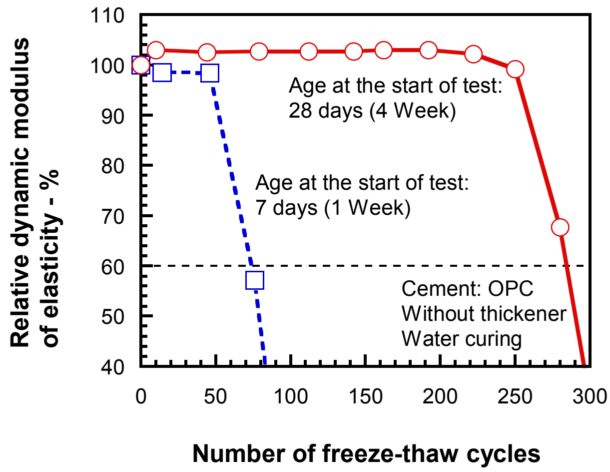


Fig. 19. Freeze-thaw test result of concrete with OPC.

results shown by lozenges are those from concrete with 0% BFS. BFS can also improve the resistance to freezing and thawing action because the relative dynamic modulus of elasticity of the concrete is higher when the amount of BFS is increased. When BFS-to-total sand ratio exceeds 66.7%, the relative dynamic modulus of elasticity remains at 100% until 300 freeze–thaw cycles have elapsed. Granulated blast furnace slag improves the resistance to freezing and thawing of concrete even if when used as binder and fine aggregate. When an adequate amount of granulated blast furnace slag is used, AE agent is not necessary.

Figures 18 and **19** show the effect of the type of cement on the resistance to freezing and thawing action. **Fig. 18** shows the result of concrete with blast-furnace slag cement type B (hereafter, BB) whose GGBF-to-binder ratio is 40%. **Fig. 19** shows the result of concrete with OPC. The concrete was cured in water until the start of the test. No AE agent is used. When the water curing period reaches 7 days, the concrete is broken after 100 freeze–thaw cycles regardless of cement type. When the water curing period is 28 days, the relative dynamic modulus of elasticity of the concrete with BB remains at 100% until after 300 freeze–thaw cycles have elapsed. However, when OPC is used, this does not occur. The results of combining BB and BFS are better than that of the combination of OPC and BFS. It is proposed that the total amount of granulated blast furnace slag affects the resistance to freezing and thawing action.

Figures 20 and **21** show the effect of the thickener on the resistance to freezing and thawing action. The durability factor DF is calculated by Eq. (2). In general, the concrete is judged to have a high resistance to freezing and thawing action when DF exceeds 60:

$$DF = \frac{P \times N}{300} \quad \dots\dots\dots\dots\dots \quad (2)$$

where P is the relative dynamic modulus of elasticity at N cycles (%) and N is the cycle number at which the relative dynamic modulus of elasticity of concrete is decreased to 60% of its original value. However, N must be equal to or less than 300.

All concrete specimens are cured in water until the start of the test. The sand is not crushed sand but BFS. **Fig. 20** shows the results when the freezing and thawing test starts after 28 days of water curing. The durability factor is less than 60 when GGBF is not used. However, when the thickener is used, the durability factor of every concrete reaches 100. That is, the relative dynamic modulus

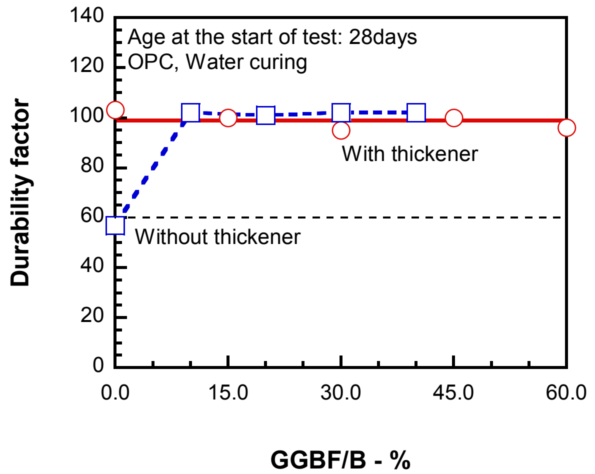


Fig. 20. Effect of the thickener on freeze-thaw resistance (Age at the start of test: 28days).

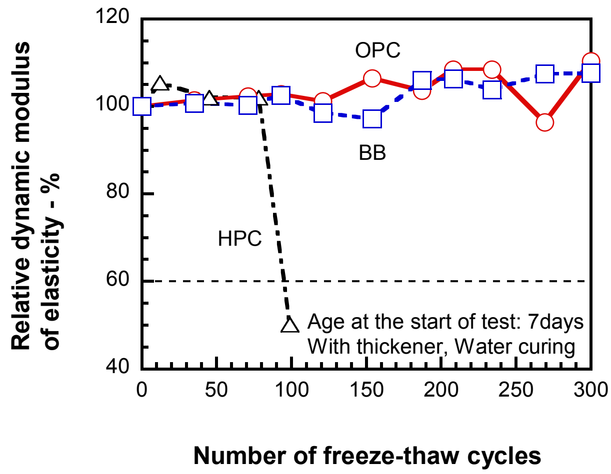


Fig. 22. Effect of type of cement on freeze-thaw resistance of concrete with BFS.

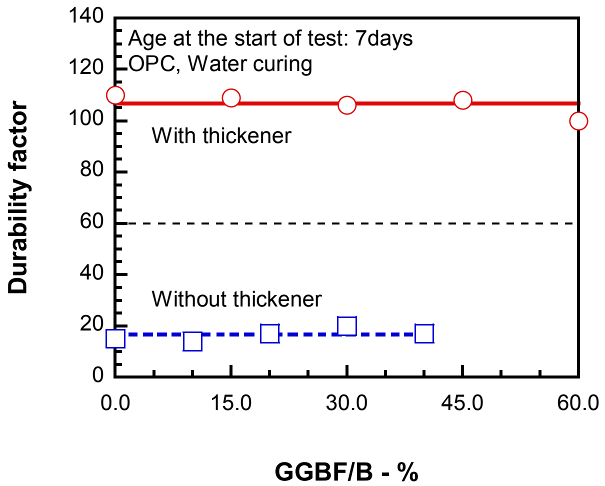


Fig. 21. Effect of the thickener on freeze-thaw resistance (Age at the start of test: 7days).

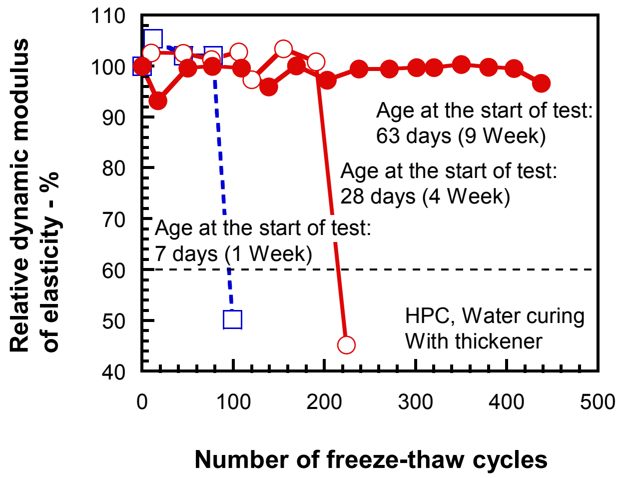


Fig. 23. Freeze-thaw test result of concrete with HPC.

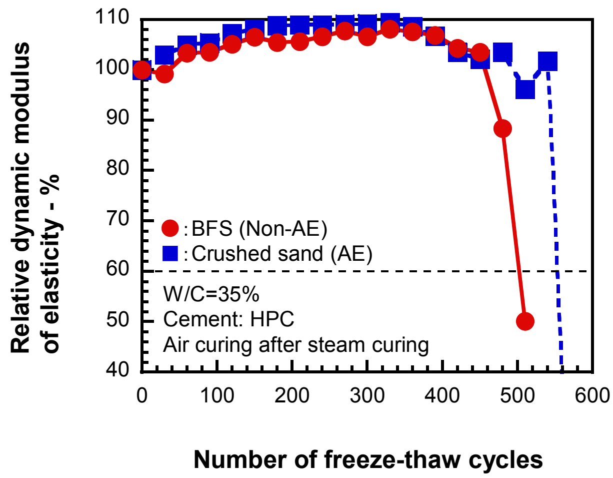


Fig. 24. Effect of steam curing on freeze-thaw resistance of concrete with HPC.

of elasticity of every concrete remains near 100% for 300 freeze-thaw cycles. **Fig. 21** shows the results when the freezing and thawing test starts after 7 days of water curing. Without thickener, the durability factor is very low at 20. However, when the thickener is used, the durability factor of every concrete is 100. The thickener can improve the resistance to freezing and thawing action of concrete with BFS. It is supposed that the thickener may prevent the formation of small internal defects around aggregate particles by bleeding.

Figure 22 shows the comparison of the effect of the cement type on the resistance to freezing and thawing action. The freezing and thawing test begins after 28 days of water curing. When both BB and OPC are used, the relative dynamic modulus of elasticity of the concrete remains near 100% until after 300 freeze-thaw cycles have elapsed, because the thickener is used in every concrete. However, when HPC is used, it breaks after 100 freeze-thaw cycles. HPC or hydrates thereof seem to react poorly with BFS.

Figure 23 shows the effect of age on the resistance to freezing and thawing action of concrete with HPC and BFS. When the age is less than 28 days, the concrete is broken after 200 freeze-thaw cycles. However, the relative dynamic modulus of elasticity remains near 100% for over 400 freeze-thaw cycles when the test starts at the age

Table 6. Mix proportions of concrete.

<table>
<tr><th rowspan="3">Type of cement</th><th rowspan="3">W/C (%)</th><th rowspan="3">Air (%)</th><th rowspan="3">s/a (%)</th><th colspan="5">Unit content(kg/m³)</th><th rowspan="3">HRWRA (B×%)</th><th rowspan="3">AE (B×%)</th><th rowspan="3">DF (B×%)</th><th rowspan="3">TA (B×%)</th><th rowspan="3">Measured air (%)</th><th rowspan="3">Comp. strength (N/mm²)</th></tr>
<tr><th rowspan="2">W</th><th rowspan="2">C</th><th colspan="2">S</th><th rowspan="2">G</th></tr>
<tr><th>CSS</th><th>BFS</th></tr>
<tr><td>BB</td><td rowspan="7">35</td><td rowspan="4">4.5</td><td>39.4</td><td rowspan="7">155</td><td rowspan="7">443</td><td>681</td><td rowspan="3">0</td><td rowspan="7">1,090</td><td rowspan="7">0.5</td><td rowspan="4">0.01</td><td rowspan="3">0.00</td><td rowspan="3">0.00</td><td>3.0</td><td>60.3</td></tr>
<tr><td>HPC</td><td>39.8</td><td>692</td><td>3.5</td><td>58.7</td></tr>
<tr><td rowspan="3">OPC</td><td rowspan="2">39.9</td><td>694</td><td>5.5</td><td>63.7</td></tr>
<tr><td rowspan="4">0</td><td>728</td><td rowspan="4">0.01</td><td rowspan="4">0.08</td><td>3.5</td><td>72.2</td></tr>
<tr><td rowspan="3">2.0</td><td>42.1</td><td>798</td><td rowspan="3">0.00</td><td>2.4</td><td>90.1</td></tr>
<tr><td>HPC</td><td>42.0</td><td>795</td><td>1.8</td><td>83.3</td></tr>
<tr><td>BB</td><td>41.6</td><td>784</td><td>2.5</td><td>84.7</td></tr>
</table>

BB: Blast-furnace slag cement type B, OPC: Ordinary Portland cement, HPC: High-early-strength Portland cement, CSS: Crushed sand-stone sand, BFS: Granulated blast furnace slag sand, HRWRA: High-range water reducing agent, AE: Air entraining agent, DF: De-forming agent, TA: Thickener, Compressive strength at 91 days

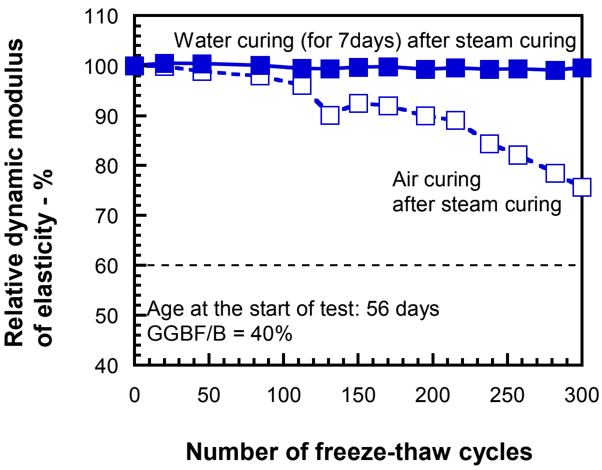


Fig. 25. Effect of steam curing on freeze-thaw resistance of concrete with BB.

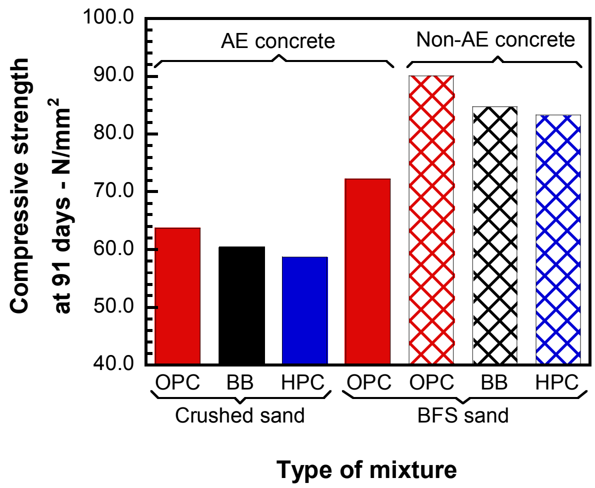


Fig. 26. Compressive strength of concrete used for fatigue life.

of 63 days. The cement that gains the highest strength at the earliest age is HPC. However, regarding resistance to freezing and thawing action, HPC requires more time to reach high resistance.

Figure 24 shows the comparison between two types of concrete: AE concrete with crushed sand and non-AE concrete with BFS. The cement of both concretes is HPC. Both concretes are cured by steam and stored in air until the start of testing. The age at the start of the test is 7 days. The non-AE concrete with HPC and BFS is not broken until after 500 freeze-thaw cycles. It seems that steam curing accelerates the reaction of BFS.

Figure 25 shows the relative dynamic modulus of elasticity of the concrete with BB and BFS. One is cured by steam and stored in air until the start of testing. Another is steam-cured and stored in water until the start of test. The concrete stored in air after steam curing deteriorates with the cycling of freezing and thawing. However, the concrete cured by steam and stored in water retains 100% of its relative dynamic modulus of elasticity until 300 freeze-thaw cycles have elapsed. Both the reaction of GGBF and that of BFS is accelerated by the heat of steam-curing. If sufficient moisture is not supplied to the concrete, unhydrates of GGBF or cement are generated. These initial defects cause concrete deterioration. When both BFS and GGBF are used, the reaction is much faster than with HPC. Therefore, sufficient moisture is necessary at early stage of curing, especially after steam curing.

5. Fatigue of Concrete

5.1. Outline of Experiment

As cement, OPC (density: 3.15 g/cm^3, Blaine fineness: 3,350 cm^2/g), HPC (density: 3.13 g/cm^3, Blaine fineness: 4,600 cm^2/g), and BB (density: 3.04 g/cm^3, Blaine fineness: 3,950 cm^2/g) are used. As a fine aggregate, crushed sandstone sand (density in saturated-surface dry condition: 2.64 g/cm^3, water absorption: 2.00%, fineness: 2.93) and BFS (density in saturated-surface dry condition: 2.77 g/cm^3, water absorption: 0.69%, fineness: 2.32) are used. As a coarse aggregate, crushed sandstone (maximum size: 20 mm, density in saturated-surface dry condition: 2.75 g/cm^3, water absorption: 0.56%) is used. Polycarboxylate high-range water-reducing agent, AE agent, de-forming agent, and alkyl aryl sulfonate and alkylam-

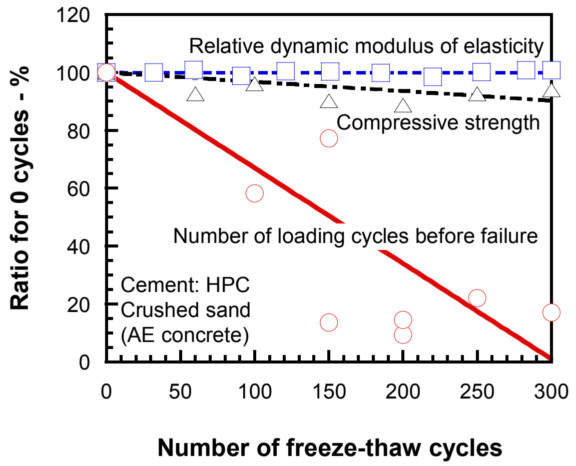


Fig. 27. The relative dynamic modulus of elasticity, compressive strength and the fatigue life of concretes after freezing and thawing action test.

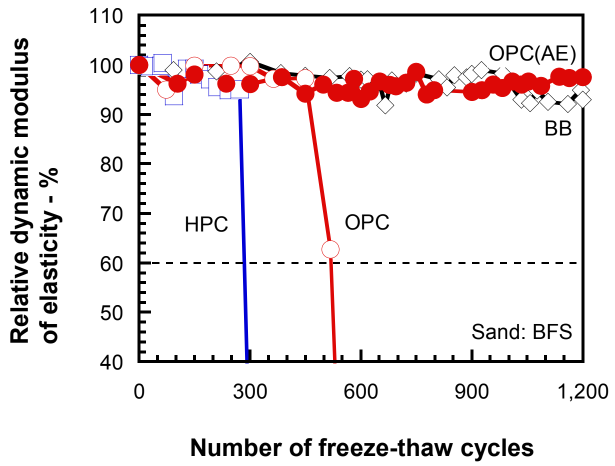


Fig. 28. The effect of type of cement on fatigue life of concrete.

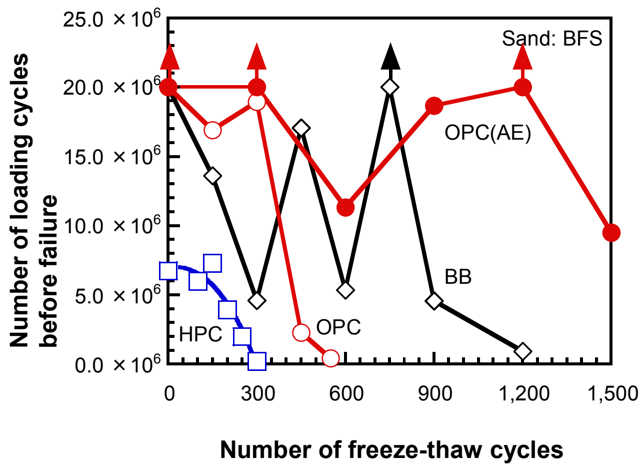


Fig. 29. The effect of type of cement on fatigue life of concrete.

monium salt thickeners are used as additives.

Cylindrical specimens with diameters of 75 mm and heights of 150 mm are used. Fatigue tests are performed after subjecting the specimens to arbitrary cycles of freezing and thawing action. The frequency of cyclic loading is 20 Hz. The minimum and maximum stresses applied to the specimens are 2.5% and 25% of the concrete strength at 91 days, respectively. The age at the start of test exceeds 91 days.

Figure 26 shows the 91-day compressive strength of the concretes shown in **Table 6**. Although the water-to-binder ratios, water contents, and gravel contents are equal in all concretes, the strength of the concrete with BFS is much higher than that with crushed sand. As the ratio of applied stress to 91-day concrete strength is also equal, the applied stress applied to the concrete with BFS is much higher than that applied to the concrete with crushed sand.

5.2. Test Results

Figure 27 shows the relative dynamic modulus of elasticity, compressive strength, and fatigue lifetime of concretes after freezing and thawing action using 10% salt water instead of fresh water. Squares in this figure are the relative dynamic modulus of elasticity. Triangles are the compressive strength, determined as a ratio to the initial strength before freezing and thawing action. When the relative dynamic modulus of elasticity remains near 100%, the compressive strength maintains its initial value. However, the fatigue life of the concretes is decreased with freeze-thaw cycling, even when the relative dynamic modulus of elasticity remains near 100%.

Figure 28 shows the relative dynamic modulus of elasticity of concrete measured from a ϕ75 mm × 150 mm cylindrical specimen. The fine aggregate in all concretes is BFS. The relative dynamic modulus of elasticity of the concretes with HPC and OPC suddenly drop after 300 and 550 cycles, respectively.

Figure 29 shows the effect of cement type on the fatigue lifetime of concretes. The fine aggregate of each concrete is BFS. OPC (AE) indicates OPC concrete with AE agent. The fatigue life of concrete after freezing and thawing is influenced strongly by the type of cement used. The fatigue lifetimes of concretes with OPC are much longer than that with HPC. The results for the concrete with BB cement do not show a stable tendency. However, BB concrete seems to sustain cyclic loading after the most cycles of freezing and thawing among the non-AE concretes. Regarding the fatigue life of concrete, the combination of BB and BFS provides better results.

Figure 30 shows the failure probability [17] of AE concrete with HPC and crushed sand. **Fig. 31** shows that of non-AE concrete with OPC and BFS. Fatigue testing with six specimens of AE concrete with HPC and crushed sand after 300 cycles of freezing and thawing action and five specimens of non-AE concrete with OPC and BFS after 550 cycles of freezing and thawing action, respectively. 50% failure probability occurs after 867,000 and 430,000 fatigue cycles, respectively. The fatigue lifetime of the concrete is scattered over several orders of magnitude. However, it is clear that BFS can improve the fatigue life under freezing and thawing action in 10% salt water.

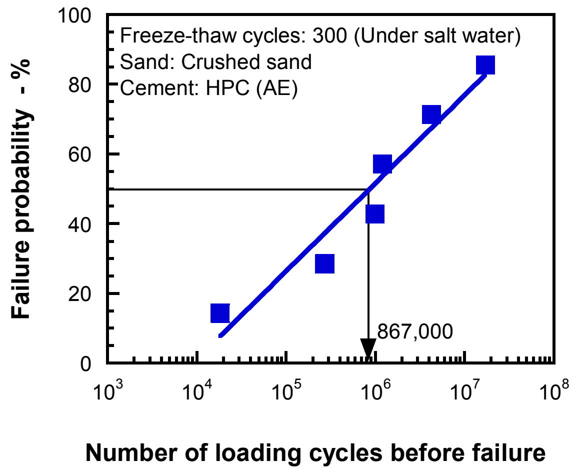


Fig. 30. The failure probability of AE concrete with HPC and crushed sand.

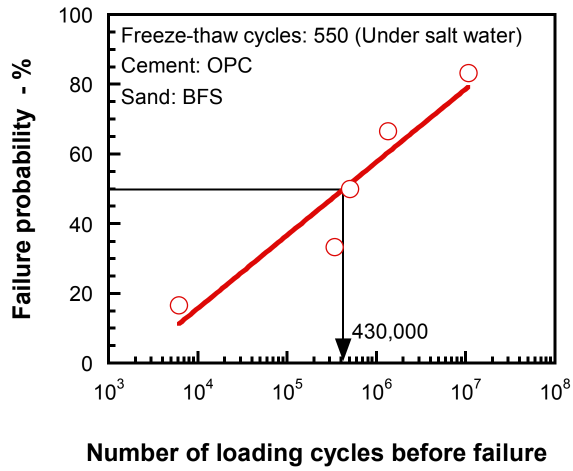


Fig. 31. The failure probability of non-AE concrete with OPC and BFS.

6. Conclusions

Many concrete slabs require replacement within 30 years after construction. Some must be replaced with new slabs. The concrete of most deteriorated slabs has become soil and gravel. It no longer provides the performance of concrete. The main causes of deterioration in concrete are freezing and thawing action, deicing salt, heavy traffic, and poor waterproofing. Not only new concrete slabs, but also renewed concrete slabs used in cold regions, should be manufactured with highly durable concrete.

In Japan, the ratio of precast concrete to site-cast concrete is 1 to 9. The amount of precast concrete used is very small. However, precast concrete members are necessary when deteriorated members are replaced with renewal concrete slabs to reduce the restriction of traffic as much as possible. It was shown in this study that highly durable precast PC members can be manufactured when BFS is used. The main test results are as follows:

1. Non-AE concrete with BFS is not fractured by over 300 cycles of freezing and thawing action, even in 10% salt water.
2. OPC concrete with BFS is not fractured by 20,000,000 cycles of fatigue loading in water.
3. The effect of BFS strongly depends on the type of cement used in the concrete.
4. The test results of beams and slabs with BFS are superior to those with normal crushed sand.

Acknowledgements

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