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Effect of Blast Furnace Slag Fine Aggregate for Freezing-and-Thawing Durability of Mortar and Concrete under Salt Existence Environment†

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Abstract:

Cement concrete using blast furnace slag fine aggregate (BFSA) has been found to have excellent freezing-and-thawing durability, in case mixture conditions are appropriate. In this study, freezing-and-thawing durability under salt existence environment was investigated for mortar and concrete using BFSA, and testing of fatigue durability of concrete slab was conducted. Resistance of concrete to freezing and thawing in NaCl (aq) was improved by using BFSA. Reaction between BFSA and cement paste boundary and suppression of salt penetration might have a role for the improvement. BFSA concrete with compressive strength of 70 N/mm^2 showed enough load bearing ability after 88 000 tracks in wheel loading fatigue test with applied load of 200 kN under wet condition.

1. Introduction

Aging and deterioration of expressways and other social infrastructure constructed in Japan during the period of high economic growth are continuing. For example, about 40% of expressways have now been in service for more than 30 years. Severe deterioration characterized by disintegration of concrete to powder and gravel has also been observed, particularly in mountainous areas. According to an evaluation of the causes of deterioration, the effect of fatigue caused by heavy traffic is relative small; rather, the main factor is estimated to be compound deterioration involving freezing damage under the coexistence of salt due to existing salt in the concrete, anti-freezing agents, etc[1)].

Blast furnace slag aggregate (hereinafter, BFSA) is produced by lightly crushing the glassy particles obtained by rapidly cooling the complex oxides generated in the blast furnace (i. e., blast furnace slag) while in the molten state. Therefore, it is known that BFSA has the advantage of not containing chlorides or organic matter, but on the other hand, it also has disadvantages, including excessive bleeding if the mixture design is not appropriate, etc[2,3)]. Recent research has shown that superior effects such as a decrease in drying shrinkage, etc. can be expected if appropriate mixture conditions which suppress bleeding can be arranged[4,5)], and is continuing to yield new knowledge indicating that BFSA provides satisfactory performance against freezing and thawing[6,7)]. Nevertheless, the mechanism of freezing and thawing, and especially the mechanism responsible for the effect of BFSA against freezing-and-thawing deterioration under salt existence environments have not been clarified.

In order to implement reliable control of the amount of bleeding, etc. and ensure that BFSA demonstrates the above-mentioned properties, application as a secondary concrete product is considered most effective. On the other hand, since quality assurance of strength and other properties until product shipment is required in the case of concrete secondary products, conditions different from those of ordinary ready-mix concrete, such as limitations on the type of cement,

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application of steam curing, etc., may possibly influence the performance of BFSA concrete materials. In particular, early deterioration of steam-cured materials is considered to be possible[8].

In addition, cracking and punching shear fracture are known as representative types of damage in reinforced concrete (RC) slabs, and the wheel load running fatigue test is applied to evaluate resistance to those problems[9]. Moreover, as there are almost no examples of RC slabs using large amounts of BFSA, evaluation is also necessary in order to evaluate the applicability of this type of slab.

This report presents the results of tests to determine the durability of BFSA concrete against freezing-and-thawing deterioration under a salt existence environment, which were performed using multiple types of BFSA, the results of an investigation of the effect of BFSA in suppressing chloride ion penetration, and the results of an investigation of the correlation of blast furnace slag, cement and other materials, the effect of the curing method, etc. on freezing-and-thawing durability. In addition, a wheel load running fatigue test was performed under a wet environment assuming practical application of BFSA as a concrete secondary product, and the results of the investigation of fatigue deterioration durability in that test are also reported.

2. Experimental Method

2.1 Freezing–and–Thawing Tests under Condition of Coexistence of Salt of Mortar and Concrete Using BFSA

BFSA and crushed sandstone sand (density in saturated dry-surface condition: 2.59 g/cm^3, coefficient of water absorption: 1.5%) were used as fine aggregates. The properties of the various BFSAs are shown in **Table 1**. Aggregate A has a high coarse grain ratio and

Table 1 Properties of blast furnace slag fine aggregate

BFSA sample		A	B	C	D
Chemical composition	CaO (%)	41.0	41.8	43.4	42.5
	S (%)	0.5	0.7	0.8	0.9
	SO_3 (%)	< 0.1	< 0.1	< 0.1	< 0.1
	FeO (%)	0.3	0.3	0.3	0.5
Density in oven-dry (g/cm^3)		2.65	2.77	2.73	2.64
Density in saturated surface (g/cm^3)		2.69	2.78	2.75	2.68
Water absorption (%)		1.35	0.21	0.69	1.42
Bulk density (kg/L)		1.56	1.63	1.58	1.55
Material ratio $\leqq 75\,\mu$m		1.3	3.9	3.1	2.0
Finess modulus		3.53	2.13	2.60	2.43
Glass phase content (%)		95.8	99.5	99.5	99.2

Table 2 Mix proportion of cement mortar

W/C (%)	単位量(kg/m^3)			
	W	C	S	
			CS	BFSA
40	274	684	1 350	0
50	300	600	0	1 390

CS: Crushed sand stone sand

a low or somewhat low glass phase ratio, while Aggregates B-D have glass phase ratios of more than 99%. In the mortar tests, ordinary Portland cement was used as the binder. In the concrete tests, a comparison was also carried out using high early strength cement and Portland blast-furnace slag cement as binders. Crushed sandstone sand (density in saturated dry-surface condition: 2.75 g/cm^3, coefficient of water absorption: 0.6%) was used as the coarse aggregate in the concrete tests.

The mix proportion of the cement mortar in the freezing-and-thawing test is shown in **Table 2**. Water/cement (W/C) ratios of 50% and 40% were used, and only the fine aggregate was changed. The kneaded mortar was cast in forms with dimensions of 40 mm×40 mm×160 mm, after which the samples were removed from the forms and were water-cured to ages of 14 days, 28 days and 91 days.

For the freezing-and-thawing tests using small specimens, small cubic specimens with dimensions of 10 mm×10 mm×10 mm were cut from the water-cured mortar. Five of the mortar specimens (approx. 14 g) were placed in a glass beaker, and a 3% NaCl aqueous solution was added to obtain a liquid-solid weight ratio of 10 based on the RILEM CDF method[10] and results reported by Habara et al[11]. As the freezing-and-thawing cycle in this salt water environment, the temperature was increased and decreased for 3 h each over a temperature range of −18°C to 20°C for a period of 24 h/cycle. After completion of the thawing process of a designated cycle, the mortar specimens were removed, and the transition of material degradation was investigated by measuring the mass of the specimens after removing the disintegrated material. The microstructure of the recovered samples was also evaluated by observation with a polarizing microscope and scanning electron microscope (SEM) and by EPMA analysis.

The standard mix proportions for the cement concrete test are shown in **Table 3**. W/C ratios of 40% and 35% were used, and the fine aggregate and binder were changed. As the coarse aggregate, hard crushed sandstone sand (maximum dimension: 20 mm, density in saturated dry-surface condition: 2.74 g/cm^3, coefficient of water absorption: 0.64%) was used. The admixtures used were a high performance AE water reducing agent, an antifoaming agent and a viscosity improver.

Table 3 Mix proportion of typical cement concrete

W/B (%)	BFS/S (%)	Air (%)	s/a (%)	Unit content (kg/m^3) W	B OPC	B BB	S CSS	S BFS	G	HWRS (Bx%)	AE (Bx%)
40	0.0	2.0	5.0	175	438		883		913	0.5	0.004
	0.0					438	876		906	0.4	0
	33.3					438	590	290	906	0.4	0
	66.7					438	292	593	906	0.4	0
	100.0					438	0	889	906	0.4	0

The concrete was cast in molds with dimensions of 100 mm×100 mm×400 mm, removed from the molds, and steam-cured at 60˚C and water-cured for the specified period.

The freezing-and-thawing test of the concrete was performed in accordance with JIS A 1148 (2010). However, a 10% sodium chloride (NaCl) aqueous solution was used as the test liquid during freezing and thawing.

2.2 Chloride Ion Penetration of Mortar Using BFSA

The fine aggregates used in this test were BFSA and crushed sandstone sand (density in saturated dry-surface condition: 2.64 g/cm^3, coefficient of water absorption: 1.8%). Using ordinary Portland cement used as the binder and a W/C ratio of 50%, chloride ion penetration was compared with the two fine aggregates.

The chloride ion penetration test was performed in accordance with JSCE-G 572–2013 "Test method for apparent diffusion coefficient of chloride ion in concrete by submergence in salt water (draft)." After pouring the mortar into cylindrical molds with dimensions of ϕ100 mm×200 mm, the mortar was cured in the mold for 24 h, then removed from the mold and water-cured until an age of 7 days. The surface of the specimens was coated with an epoxy resin except for one cut circular surface, and the specimen was allowed to stand in the air until an age of 14 days in order to harden the epoxy resin completely. After hardening was confirmed, the specimens were immersed in a 10 mass% NaCl aqueous solution. The specimens were removed from the NaCl solution at 0.3 years (105 days), 1 year (365 days) and 3 years (1 092 days) after the start of immersion, and the distribution of chloride ions in the depth direction was measured.

2.3 Wheel Load Running Fatigue Test[12)] of Precast Slab Using BFSA

Figure 1 shows the conditions of the concrete specimen used in the wheel load running fatigue test. The conditions used for the sample structure were based on the 1964 edition of "Reference for Highway Bridge Design: Specifications for Reinforced Concrete Bridges,"[13)] which is assumed to be the standard for existing structures. As the mix proportion, the standard material (S1) was a concrete material having a design strength of 35 N/mm^2, which is equivalent to the standard material of existing structures, using crushed sand. The material using BFSA (S2) had a W/C ratio of 40% and design strength of 70 N/mm^2, assuming a material similar to that used in replacement of the existing slab.

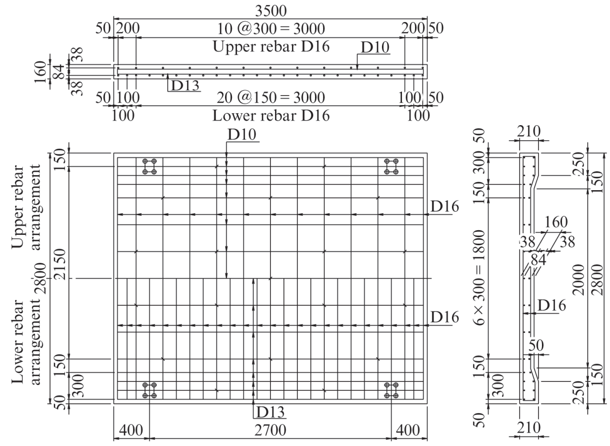

Fig. 1 Size and dimension of concrete slab for wheel load running fagigue test

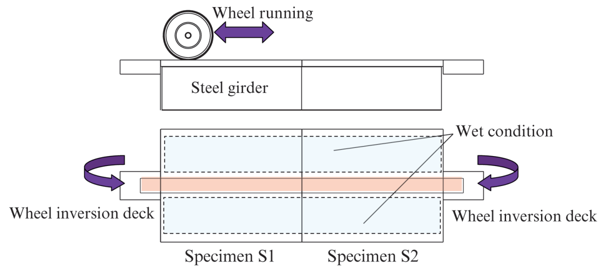

Fig. 2 Schematic diagram of wheel load runnning fatigue test

A schematic diagram of the wheel load running fatigue test is shown in **Fig. 2**. Because it is known that the existence of water influences the durability of concrete slabs, the sample was thoroughly sprinkled with water and allowed to stand for 24 h before the start of the test, and during the test, the top surface was adequately covered with wet rags, which were sprinkled with water in the morning and evening. The two specimen slabs were arranged side by side, and a rubber aircraft tire was run on the wheel deck under a constant applied load of 200 kN by reversing the wheel direction on the parts of the deck extending beyond the two edges of the samples. The amount of displacement at the central part was evaluated after 1, 10, 100, 200, 500 1 000, 2 000 10 000 passes, and at intervals of 10 000 passes thereafter. Cracks on the reverse side from the loaded surface were also observed.

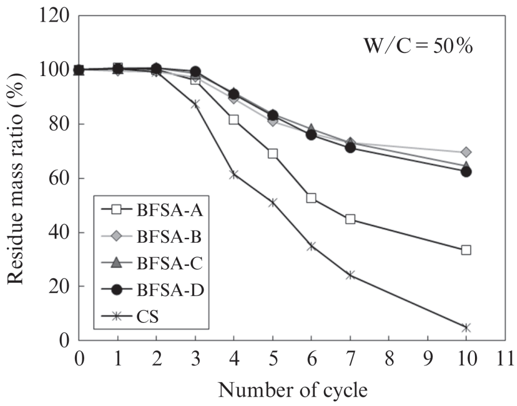

Fig. 3 Residue mass ratio of mortar using several types of fine aggregate after small size freezing-and-thawing test

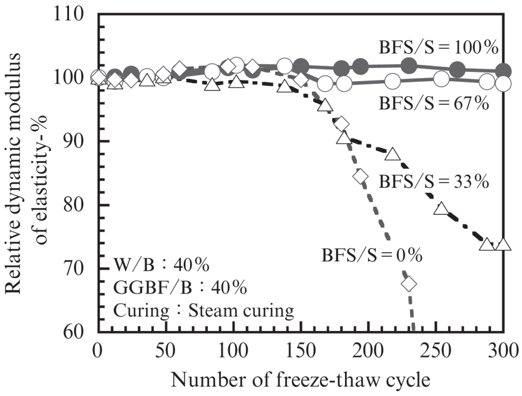

Fig. 4 Effect of replacement of BFS on resistance of concrete to freezing and thawing action in NaCl (aq)

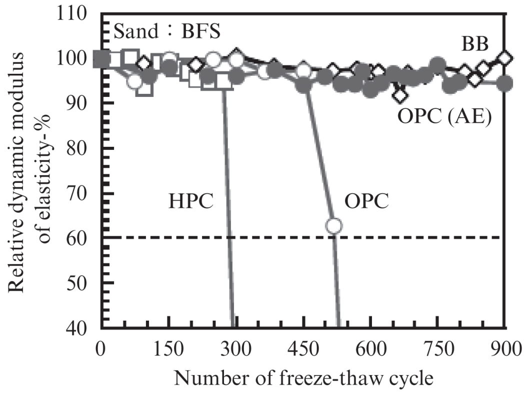

Fig. 5 Effect of cement types on resistance of concrete to freezing and thawing action in NaCl (aq)

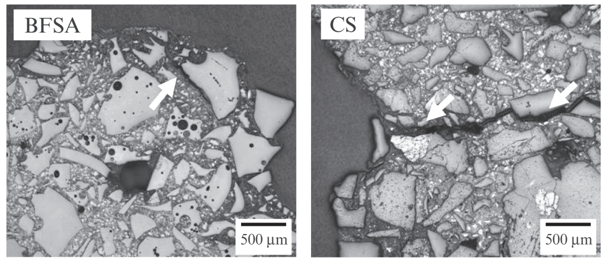

Fig. 6 Internal crack of mortar using BFSA or CS aggregate after freezing and thawing test in NaCl (aq)

3. Results and Discussion

3.1 Freezing and Thawing Durability of Mortar and Concrete under Salt Existence Condition

Figure 3 shows the transition of the residual mass ratio after the cyclical freezing-and-thawing test in salt water for the mortar with the W/C ratio of 50% after curing for 28 days. In the mortar using crushed sandstone sand, the material had crumbled after 10 cycles, and virtually no lumpy parts remained. In contrast to this, remaining lumpy material was confirmed in the BFSA mortar. Thus, superior freezing-and-thawing durability in a salt water environment was obtained by changing the fine aggregate to BFSA. Comparing the differences between the various BFSA materials, the mortar using Aggregate A with low glassy phase content was somewhat inferior.

Figure 4 shows the results of the test of freezing-and-thawing durability under the salt existence environment for the concrete in which the fine aggregate of crushed sandstone sand was replaced with BFSA. The concrete was produced without AE, and steam-curing was used for curing. As the BFSA replacement ratio increased, the freezing-and-thawing durability of the concrete also increased, and when BFSA was used for 33% of the fine aggregate, a 60% improvement was observed in the relative dynamic modulus of elasticity, which is a guideline for freezing resistance, even after 300 cycles of repeated freezing and thawing.

Figure 5 shows the effect of the type of cement on the freezing-and-thawing durability of the non-AE concrete using BFSA. A decrease in the relative dynamic modulus of elasticity was observed at around 300 freezing-and-thawing cycles in the material using the early high strength Portland cement (HPC) and at around 500 cycles in the material using the ordinary Portland cement (OPC). In contrast to this, the relative dynamic modulus of elasticity of the material using Portland blast-furnace slag cement type B (BB) was more than 90% up to 1 200 cycles of freezing-and-thawing action. Because there is a possibility that freezing-and-thawing durability increases in cement with delayed strength development, in the future, it will be necessary to verify the influence of the cement gelling reaction and other reactions, the influence of the residual condition of binding water, etc., and to optimize the mix proportion, etc. corresponding to the cement type.

Microscopic images of embedded-and-polished specimens of the remaining part after 5 cycles of freezing and thawing are shown in **Fig. 6**. A crack can be

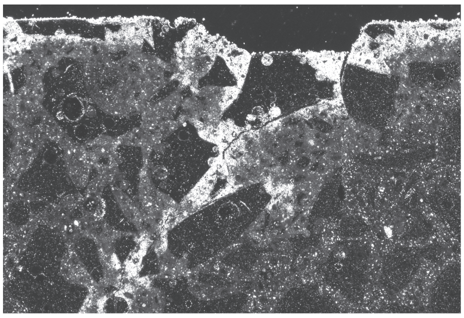

Fig. 7 Polarizing microscope photograph of mortar surface using BFSA after freezing and thawing test in NaCl (aq)

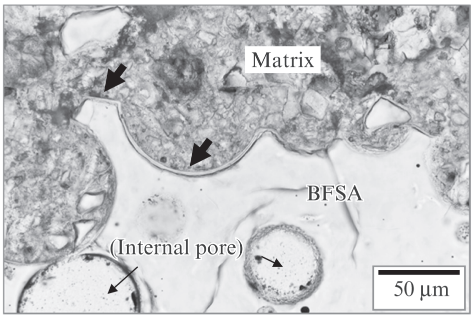

Fig. 8 Transmission microscope photograph of boundary area between BFSA and cement matrix

observed from the mortar surface toward the interior, and this crack has propagated along the interface between the cement paste and the aggregate. In the mortar using BFSA, the crack depth is limited to the outermost surface of the mortar, but when the crushed sandstone sand was used, the crack propagated deep into the interior. **Figure 7** shows the result of observation of the surface of the mortar with the polarizing microscope. Embrittlement of the microstructure has occurred at the surface, and similar deterioration can also be confirmed around the crack. Thus, it is estimated that salt water penetrated to the interior accompanying crack propagation, and this salt water accelerated the deterioration of the microstructure. This is estimated to be one cause of the difference in the durability under the existence of salt water in the mortar using BFSA and the mortar using the conventional crushed sandstone sand.

Figure 8 shows the result of transmission electron microscope observation of the boundary area between the aggregate and the cement matrix, and **Fig. 9** shows the results of SEM-EDX (Ca) observation of the mortar surface after the freezing-and-thawing test. The existence of a reactional phase with a thickness of approximately 2 μm can be confirmed at the boundary of the BFSA. From the SEM-EDX images, an area where elements are diluted could be seen at the aggregate interface in the case of the crushed sandstone sand, suggesting the existence of an embrittled area

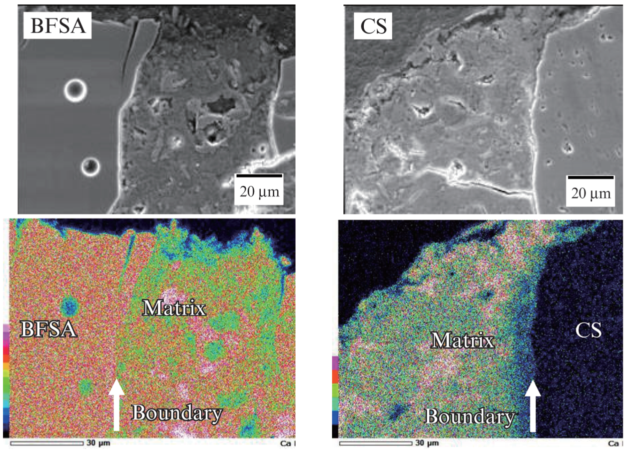

Fig. 9 SEM and Ca-mapping images of mortar surface after freezing and thawing test in NaCl (aq)

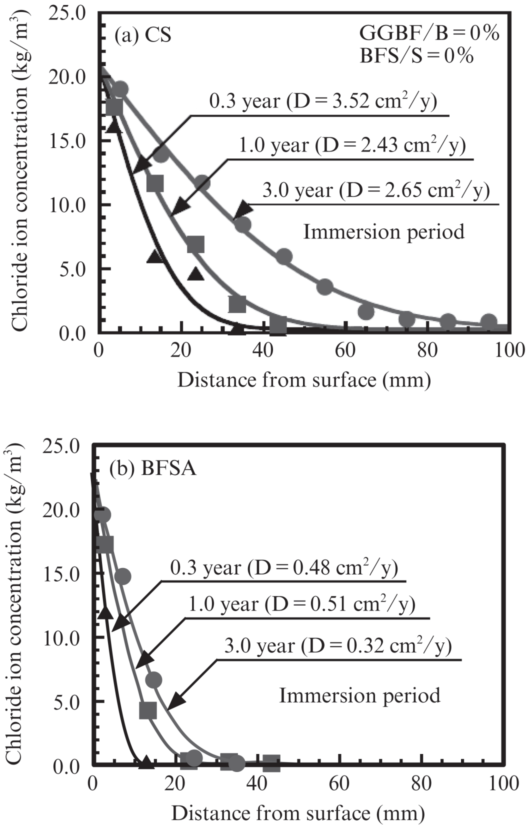

Fig. 10 Chloride ion concentration in mortar using BFSA or CS aggregate after varied immersion period in NaCl (aq.)

such as a transition zone, etc., whereas in the case of the BFSA, there was a low Ca region on the surface side which is in contact with the solvent, but no large differences in Ca, Si, etc. between the area around the aggregate and the matrix could be seen at the depth position of about several 10 μm. It is considered possible that freezing-and-thawing durability under a salt existence environment was improved by strengthening of the interface by some form of reaction with the BFSA, resulting in suppression of crack propagation and suppression of salt water penetration.

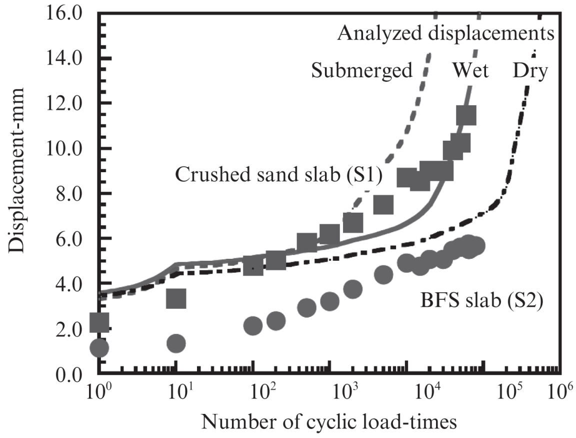

Fig. 11 Displacement of concrete slab specimens during wheel load running fatigue test

3.2 Chloride Ion Penetration of Mortar Using BFSA

Figure 10 shows the distribution of the chloride ion concentration of mortar using different types of fine aggregate when the samples were immersed in salt water. When ordinary Portland cement and crushed sandstone sand were used, chloride ions were detected to a position 100 mm from the specimen surface after immersion in salt water for 3 years, and the apparent diffusion coefficient of the chloride ions was 2.65 cm^2/y. On the other hand, when BFSA was used, detection of chloride ions was limited to about 30 mm from the surface. The apparent diffusion coefficient was greatly reduced, to 0.32 cm^2/y, and decreased as the immersion period increase. Since these results are consistent with the reaction of the BFSA, as noted in the previous section, there is a high possibility that this also contributed to improvement of salt blocking performance.

3.3 Results of Wheel Load Running Fatigue Test

Figure 11 shows the transition of the displacement of the specimen center during the wheel load running fatigue test and the results of a nonlinear FEM analysis by DuCOM[14]. The displacement of the specimens increased as the number of loading cycles increased, and fracture of the S1 slab occurred when displacement reached 12 mm. These test results are in good agreement with the results of the DuCOM simulation for a wet environment. On the other hand, displacement of the S2 slab was less than 1/2 that of the S1 slab, being less than 6 mm even after approximately 90 000 loading cycles.

Figure 12 shows the crack pattern on the back side of the slabs after completion of 50 000 loading cycles. In the initial period at the start of the test, cracks occurred in the longitudinal direction. This was followed by cracks radiating from the corners toward the center and then by cracks in the direction of the short axis. Subsequently, an increase in the crack density was observed as the number of loading cycles increased. Comparing the S1 slab and the S2 slab, the crack density was lower in the S2 slab. From this, it is thought that the effect of high strength is also effective under practical conditions.

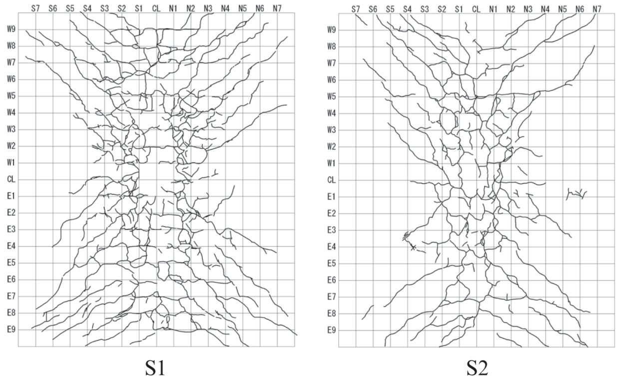

Fig. 12 Crack pattern of concrete slab after 50 000 times loading

From these results, it is thought that slab life can be improved by suppressing displacement by using high strength concrete. These results also confirmed that this effect can be achieved with no problems when BFSA is applied to this kind of high strength slab.

4. Conclusion

An evaluation of freezing-and-thawing durability under a salt existence environment and wheel load running fatigue tests were performed with mortar and concrete using BFSA (blast furnace slag fine aggregate) as a fine aggregate in place of the conventional crushed sand. The following results were obtained.

(1) Improvement of freezing-and-thawing durability under a salt existence environment by using BSFA was confirmed with both the mortar and the concrete.
(2) Deterioration during freezing and thawing proceeds by cracking along the aggregate-cement paste interface. When BFSA is used, it is suggested that the embrittled zone is strengthened by the reaction which occurs in this interfacial region, and as a result, crack propagation is suppressed.
(3) In concrete, freezing-and-thawing durability under a salt existence environment was improved as the BFSA replacement ratio increased. In addition, the freezing-and-thawing property also improved with cement that displays delayed strength development.
(4) When BFSA was used, chloride ion penetration in mortar during immersion in salt water was limited to the surface layer, and the apparent diffusion

coefficient was reduced to less than 1/5 of that with the conventional crushed sand fine aggregate.

(5) A trial high strength type precast slab was prepared using BFSA, and was used in a wheel load running fatigue test. The results confirmed that there are no problems of load fatigue when BFSA is used.

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