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Durability of Seawater Mixed Concrete with Different Replacement Ratio of BFS (Blast Furnace Slag) and FA (Fly Ash)

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Abstract: Using seawater in concrete can be considered as one of the sustainable approaches in construction industry not only to save the freshwater resource but also to promote the use of abandoned seawater resource, especially in the construction at the uninhabited area close to the sea where the procurement of fresh water is difficult. In this study, durability against chloride attack of seawater mixed concrete with different replacement ratio of BFS (blast furnace slag) and FA (fly ash) is discussed and the life time until the occurrence of corrosion crack is evaluated. The results show that: (1) Chloride penetration rate of seawater mixed specimens with BFS and FA is lower than that of freshwater mixed OPC (ordinary Portland cement) specimens; (2) Oxygen permeability of seawater mixed specimens with BFS and FA is almost the same or lower than that of freshwater mixed OPC specimens; (3) Total life time (corrosion incubation period and propagation period) of seawater mixed specimens with BFS and FA is almost the same or only slightly shorter than that of freshwater mixed OPC specimens. From the results, it was confirmed that the usage of seawater in concrete mixing is feasible in concrete with the appropriate BFS and FA replacement ratio.

Key words: Seawater, chloride attack, corrosion, durability of concrete, blast furnace slag, fly ash.

1. Introduction

The usage of seawater in concrete mixing can be considered as one of the sustainable approaches in construction industry not only to save the world freshwater resource but also to promote the effective use of seawater resource, for example, the construction at the remote island and uninhabited area close to the sea where the procurement of fresh water is difficult [1]. However, the usage of seawater in reinforced concrete is strictly limited in international codes and standards due to the rebar corrosion inside concrete by chloride attack [2]. In general, these limitations such as maximum allowable content of chloride in the concrete specified in the codes and standards are far conservative than the values which can reduce the actual durability performance of concrete against chloride attack [3]. Therefore, the authors conducted this study to evaluate the durability performance of sea water mixed concrete with different cement replacement ratio of BFS (blast furnace slag) and FA (fly ash) against chloride attack. Objectives of the study includes: (1) investigation of material properties such as chloride ion penetration rate, oxygen permeability; (2) investigation of rebar corrosion; (3) prediction of life time for seawater mixed concrete with different cement replacement ratio of BFS and FA.

2. Experiment Details

2.1 Specimen Outlines

Two types of specimen are produced to investigate chloride attack, namely cylinder concrete specimen (φ 100 mm × 200 mm, Table 1) without rebar and prism shape (width-40 mm × height-40 mm × length-160 mm, Table 2) mortar specimen.

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Table 1 Mix proportion of concrete specimens.

No.	W/C	Mixing water	s/a (%)	Unit of weight								Slump (cm)	Air (%)
				(kg/m^3)						C_x (%)			
				W	C	BFS	FA	S	G	AW	AE		
0.5-OPC-T	0.5	Tap water	42	171	342	0	0	764	1,052	1.4	0.017	5.00	3.0
0.5-B40-T					205	137	0	748	1,047	1.4	0.021	10.5	3.0
0.5-B55-T					154	188	0	748	1,044	1.2	0.021	7.50	2.9
0.5-B70-T					103	239	0	748	1,041	1.2	0.021	8.00	2.8
0.5-FA10-T					308	0	34	761	1,047	1.4	0.017	11.0	1.8
0.5-FA30-T					239	0	103	754	1,036	1.4	0.017	10.0	1.6
0.5-OPC-S		Artificial seawater			342	0	0	764	1,052	1.4	0.017	7.00	3.0
0.5-B40-S					205	137	0	748	1,047	1.4	0.021	13.0	3.1
0.5-B55-S					154	188	0	748	1,044	1.2	0.021	10.5	3.1
0.5-B70-S					103	239	0	748	1,041	1.2	0.021	11.5	3.0
0.5-FA10-S					308	0	34	761	1,047	1.4	0.017	9.50	4.0
0.5-FA30-S					239	0	103	754	1,036	1.0	0.021	8.00	2.1
0.7-OPC-T	0.7	Tap Water	46	174	249	0	0	870	1,018	1.0	0.010	7.50	3.1
0.7-B40-T					149	99	0	868	1,013	1.0	0.010	7.50	2.4
0.7-B55-T					112	137	0	865	1,013	1.0	0.011	10.0	2.6
0.7-B70-T					75	174	0	865	1,010	0.7	0.011	6.00	2.5
0.7-FA10-T					308	0	34	761	1,047	1.4	0.017	11.0	1.8
0.7-FA30-T					239	0	103	754	1,036	1.0	0.020	10.0	1.6
0.7-OPC-S		Artificial seawater			249	0	0	870	1,018	1.0	0.010	3.50	3.8
0.7-B40-S					149	99	0	868	1,013	1.0	0.010	4.50	3.1
0.7-B55-S					112	137	0	865	1,013	1.0	0.011	10.0	3.5
0.7-B70-S					75	174	0	865	1,010	0.7	0.011	6.50	4.5
0.7-FA10-S					308	0	34	761	1,047	1.4	0.017	9.50	4.0
0.7-FA30-S					239	0	103	754	1,036	1.0	0.020	8.00	2.1

Note: W: water (fresh water or seawater); C: ordinary Portland cement (density: 3.14 g/cm^3; Blaine fineness: 3,210 cm^2/g); s/a: sand/aggregate ratio; BFS: blast furnace slag (density: 2.89 g/cm^3; Blaine fineness: 4,310 cm^2/g; activity index (28 days): 94%); FA: fly ash Class F (density: 2.23 g/cm^3; Blaine fineness: 3,630 cm^2/g; activity index (28 days): 84%); S: natural river sand (density (SSD saturated surface dry): 2.60 g/cm^3; water absorption ratio: 2.20%; fineness modulus: 2.59); G: gravel; AW: water reducing admixture ; AE: air entraining admixture ; C_x: chemical admixture.

Tables 1 and 2 show the mix proportion of concrete and mortar specimens, respectively. OPC (ordinary Portland cement) and OPC and OPC with cement replacement ratio of BFS at 40%, 55% and 70% and OPC with cement replacement ratio of FA (Class F) at 10% and 30% are used. Artificial seawater, with chemical composition as shown in Table 3, and tap water are used as mixing water. The water to binder ratios are 0.5 and 0.7 for both types of specimen. The round steel bars of SR235 (φ 13 mm × 100 mm) are embedded in mortar specimens with 10 mm cover thickness. Concrete specimens are cured under moist condition and mortar specimens are cured under submerged condition in water for seven days. The moist curing periods are five days for OPC concrete specimen and seven days for BFS/FA concrete specimens. Curing water is used as the same type of water as mixing water of each specimen. Then, except under surface of specimens at casting used for exposure surface, concrete and mortar specimens were coated with epoxy resin before exposure.

2.2 Measurements

In this study, the lifetime of seawater mixed concrete is calculated with the outline of lifetime prediction as shown in Fig. 1. Against chloride attack,

Table 2 Mix proportion of mortar specimens.

No.	W/C	Mixing water	Unit of weight (kg/m^3)				
			W	C	BFS	FA	S
0.5-OPC-T	0.5	Tap water	311	622	0	0	1,245
0.5-B40-T			305	366	244	0	1,220
0.5-B55-T			303	272	333	0	1,210
0.5-B70-T			301	181	421	0	1,200
0.5-FA10-T			312	562	0	62	1,249
0.5-FA30-T			307	430	0	184	1,229
0.5-OPC-S		Artificial seawater	311	622	0	0	1,245
0.5-B40-S			305	366	244	0	1,220
0.5-B55-S			303	272	333	0	1,210
0.5-B70-S			301	181	421	0	1,200
0.5-FA10-S			312	562	0	62	1,249
0.5-FA30-S			307	430	0	184	1,229
0.7-OPC-T	0.7	Tap water	393	561	0	0	1,122
0.7-B40-T			390	334	223	0	1,114
0.7-B55-T			389	250	306	0	1,111
0.7-B70-T			388	166	388	0	1,108
0.7-FA10-T			389	500	0	56	1,111
0.7-FA30-T			383	383	0	164	1,095
0.7-OPC-S		Artificial seawater	393	561	0	0	1,122
0.7-B40-S			390	334	223	0	1,114
0.7-B55-S			389	250	306	0	1,111
0.7-B70-S			388	166	388	0	1,108
0.7-FA10-S			389	500	0	56	1,111
0.7-FA30-S			383	383	0	164	1,095

Note: seawater: artificial seawater mixed with chemicals shown in Table 3.

Table 3 Chemical composition of artificial seawater.

Chemicals	NaCl	$MgCl_2{}^{-6}H_2O$	Na_2SO_4	$CaCl_2$	KCl	$NaHCO_3$
Concentration (gram/liter)	24.54	11.1	4.09	1.16	0.69	0.2

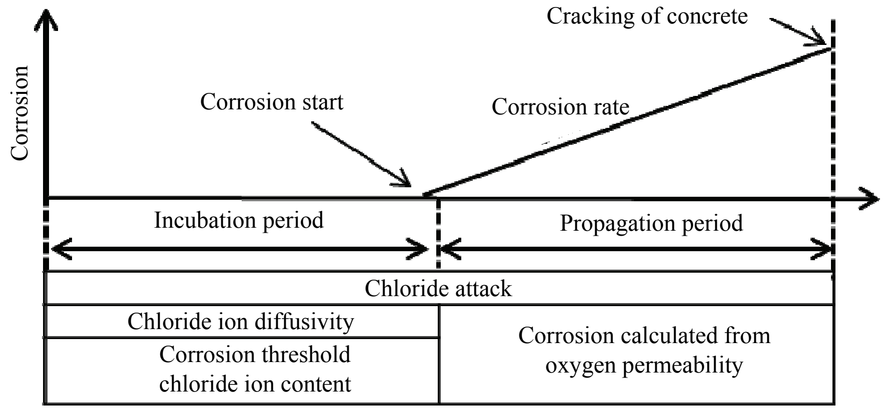


Fig. 1 Outline of concrete life time prediction.

chloride ion penetration rate and threshold chloride content for corrosion are required to calculate the corrosion incubation period and corrosion rate of steel bars and the conditions for cracking are required to calculate the corrosion propagation period.

2.2.1 Chloride Ion Penetration Rate

In order to determine the chloride ion penetration rate, concrete specimens are submerged into artificial seawater for four months and the distributions of total chloride content at different depths from the exposure surface are measured. Based on the measurement results, the chloride ion penetration rate coefficient is calculated using Eq. (1), Fick's laws of diffusion:

$$C_{(x,\ t)} = C_0\left(1 - erf\left(\frac{x}{2\sqrt{D_c \cdot t}}\right)\right) \tag{1}$$

where, $C_{(x,\ t)}$ is the chloride concentration at any position x at the time t in kg/m^3, C_0 is the chloride concentration on the concrete surface in kg/m^3, x is the distance from the concrete surface in mm, t is the time in year, *erf* is the error function, and D_c is the diffusion coefficient in cm^2/year.

2.2.2 Threshold Chloride Content for Corrosion

The mortar specimens are used to determine the threshold chloride content for steel bar corrosion in concrete. Chloride ion content in mortar around steel bar is measured when the corrosion current density reached to 0.2 μA/cm^2 [4].

2.2.3 Corrosion Current Density of Steel Bar

The mortar specimens are used to investigate the corrosion behavior of steel bar in concrete. After curing, the mortar specimens are exposed into accelerated sprayed chamber with 50 °C of NaCl solution (3.0% by weight). During the experiment period, the polarization resistance is measured by AC (alternating current) impedance method using high frequency (10 kHz) and low frequency (10 MHz) of alternative current and corrosion current density is calculated with Stern-Geary constant [5] based on following Eq. (2):

$$I_{\text{corr}} = \frac{K}{R_{ct} \cdot S} \tag{2}$$

where, I_{corr} is corrosion current density in μA/cm^2, R_{ct} is polarization resistance in Ω, S is surface area of steel bar which equals to 40.82 cm^2, K is Stern-Geary constant which equals to 0.0209 V.

2.2.4 Oxygen Permeability and Corrosion Rate of Steel Bar

The mortar specimens are used to measure oxygen permeability. Limit corrosion current density obtained from electro chemical measurement using cathodic polarization curves were utilized as shown in following Eq. (3). Corrosion rate was directly calculated from i_{lim}:

$$\frac{\partial Q}{\partial t} = -\frac{i_{\text{lim}}}{n \cdot F} \tag{3}$$

where, $\partial Q/\partial t$ is oxygen permeability in mol·cm^2/s, i_{lim} is limit corrosion current density in μA/cm^2, n is atomic value (= 4), F is Faraday constant (= 96,500 C/mol). In addition to cathodic polarization curves, anodic polarization curves are measured.

3. Results and Discussion

3.1 Chloride Ion Penetration Rate

3.1.1 Results for Concrete with BFS

Fig. 2 shows the comparison between chloride ion penetration rate of concrete mixed with seawater and tap water with different cement replacement ratio of BFS. As shown in Fig. 2, chloride ion penetration rate of concrete mixed with seawater is smaller than that of concrete mixed with tap water. This might be due to the initial chloride content increased by seawater, and it could result in the decrease of chloride concentration

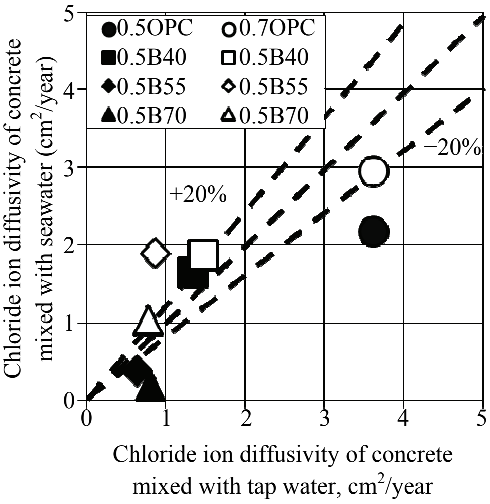


Fig. 2 Chloride penetration rate of BFS concrete (seawater vs. tap water).

difference between concrete and surrounding seawater or seawater mixed improve the pore structure of concrete [6].

Fig. 3 shows the influence of BFS replacement ratio on chloride ion penetration rate of concrete. From Fig. 3, it is confirmed that chloride ion penetration rate of concrete using BFS is smaller than that of OPC and chloride ion penetration rate of concrete decreases as BFS replacement ratio increases.

3.1.2 Results for Concrete with FA

Fig. 4 shows the comparison between chloride ion penetration rate of concrete mixed with seawater and tap water with different FA replacement ratio. As shown in Fig. 4, chloride ion penetration rate of concrete mixed with seawater is lower than that of concrete mixed with tap water which is the same phenomenon observed in the case of BFS. Fig. 5 shows the influence of FA replacement ratio on chloride ion penetration rate of concrete. For Fig. 5, it is confirmed that chloride ion penetration rate of concrete using FA is smaller than OPC and chloride ion penetration rate of concrete decreases as FA replacement ratio increases.

3.2 Corrosion Current Density and Threshold Chloride Content for Corrosion

3.2.1 Results for Concrete with BFS

To investigate threshold chloride content for corrosion, corrosion current density changed with time is measured. The authors adopted the current density of 0.2 μA/cm^2 as the threshold current density which is defined by CEB (European Committee for Concrete) [4] for structural concrete. Fig. 6 shows the change of corrosion current density with time in the case W/C is 0.5 with BFS. The dotted line indicates the value of 0.2 μA/cm^2, which is the threshold current density of corrosion [4].

The corrosion starting time steadily became longer with increase in BFS replacement ratio, because increase in BFS replacement reduced chloride ion penetration rate. Besides, in the case of OPC and BFS

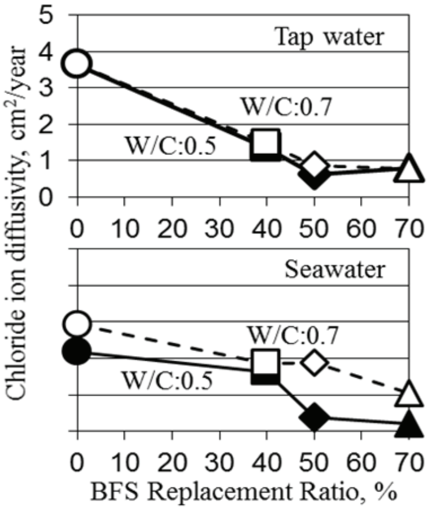


Fig. 3 Chloride penetration rate of concrete for different BFS replacement ratio.

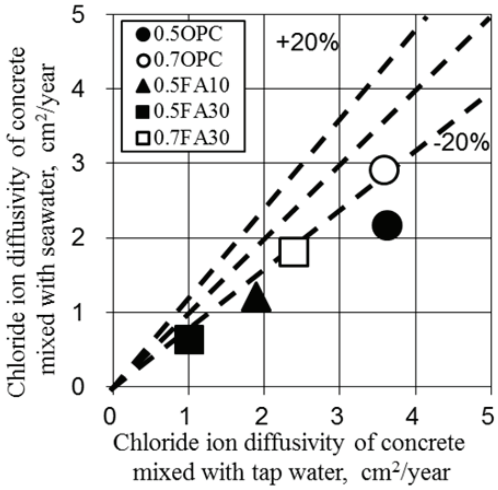


Fig. 4 Chloride penetration rate of FA concrete (seawater vs. tap water).

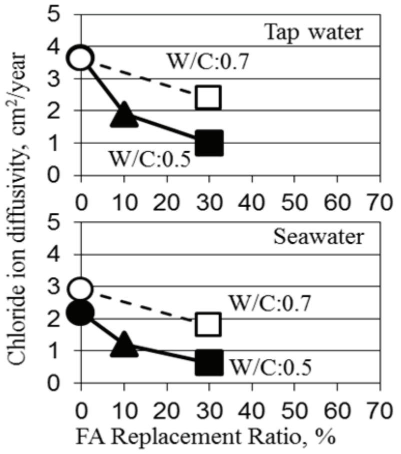
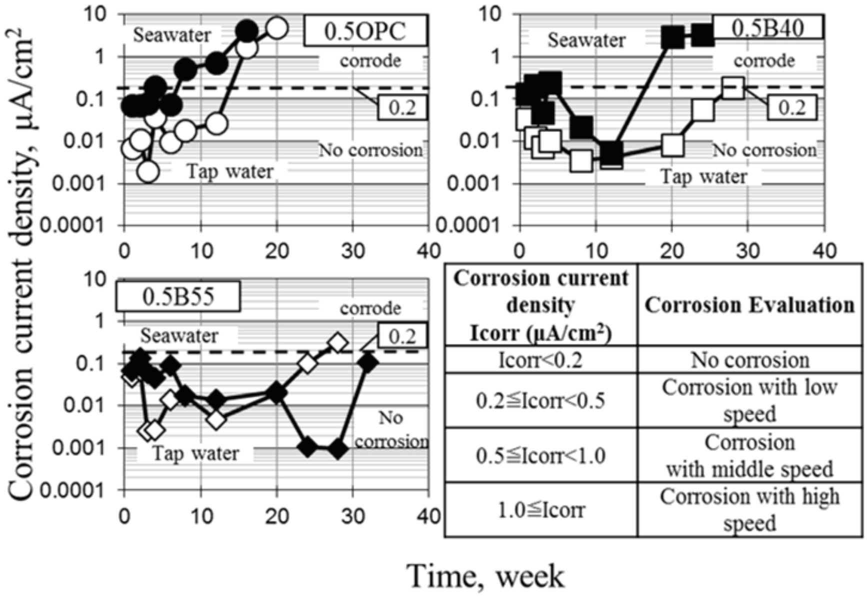


Fig. 5 Chloride penetration rate of concrete for different FA replacement ratio.



Corrosion current density Icorr (μA/cm²)	Corrosion Evaluation
Icorr<0.2	No corrosion
0.2≦Icorr<0.5	Corrosion with low speed
0.5≦Icorr<1.0	Corrosion with middle speed
1.0≦Icorr	Corrosion with high speed

Fig. 6 Time dependent change of corrosion current density of specimen with BFS (W/C = 0.5).

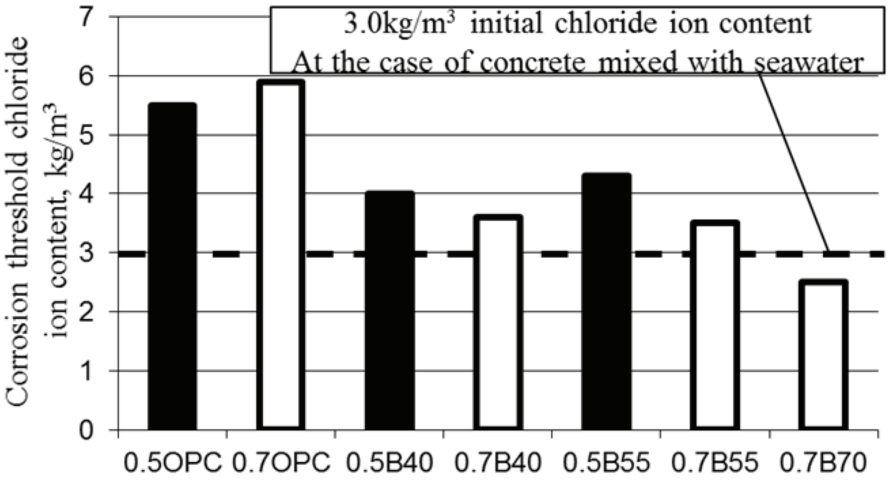
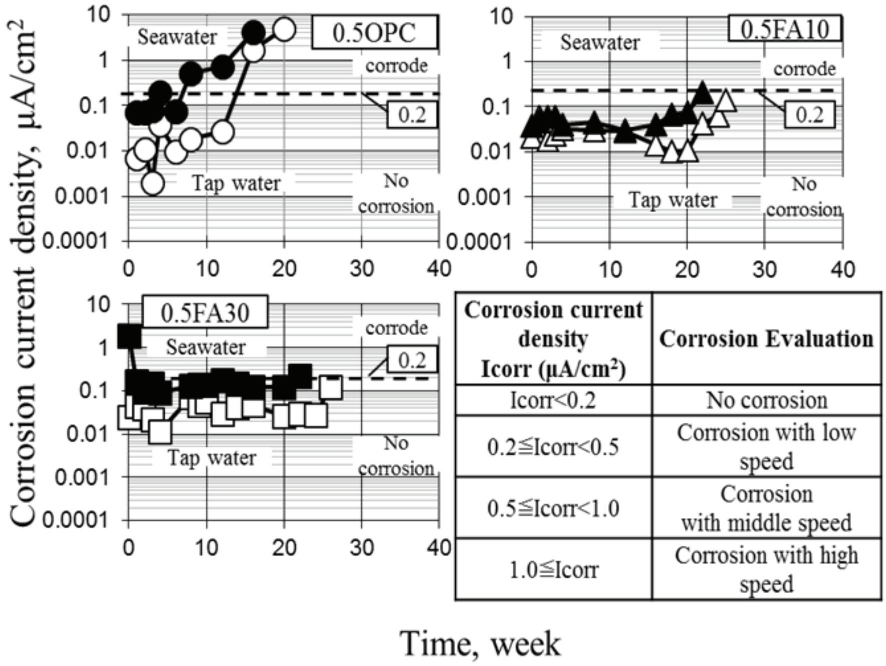


Fig. 7 Threshold chloride content for corrosion in BFS specimens.

40% replaced case, duration of the mortar mixed with seawater to reach the critical value of corrosion current density (0.2 μA/cm^2) was shorter than that with tap water. It is considered that initial chloride content increased by seawater shortened the duration to reach the corrosion threshold chloride content. On the other hand, BFS 55% replaced mortar mixed with seawater has almost the same resistance against corrosion as that of mortar mixed with tap water. It is considered that it has a longer duration to reach critical value of corrosion current density and its chloride ion penetration rate is lower than that of mortar mixed with tap water for this case. Fig. 7 shows the threshold chloride content for corrosion in mortar specimen with different BFS replacement ratio. From Fig. 7, it can be seen that BFS replaced specimens had smaller corrosion threshold chloride ion content than that of OPC specimens. It can be considered that the ratio of Cl^-/OH is increased with increasing of BFS replacement ratio because high BFS replaced cement had low pH. Additionally, the value of BFS 70 % replacement (in case of W/C = 0.7) is less than initial chloride contents (dotted horizontal line shown in Fig. 7) induced by concrete mixed with seawater. It means BFS 70% replaced concrete mixed with seawater induces corrosion at the initial stage. As a result, in case of OPC, corrosion threshold chloride content was about 5~6 kg/m^3 and in case of BFS specimens, the value was about 3~4 kg/m^3.

3.2.2 Results for Concrete with FA

Fig. 8 shows the change of corrosion current density with time in the case W/C is 0.5 with FA. The corrosion starting time steadily became longer with increase in FA replacement ratio, because increase in FA replacement reduced chloride ion penetration rate. Moreover, duration of the mortar mixed with seawater to reach critical value of corrosion current density (0.2 μA/cm^2) was shorter than that with tap water as the same in case of BFS. Fig. 9 shows the threshold chloride content for corrosion in mortar specimen with different FA replacement ratio. From Fig. 9, it can be seen that FA replaced specimens have smaller



Corrosion current density Icorr (μA/cm^2)	Corrosion Evaluation
Icorr<0.2	No corrosion
0.2≦Icorr<0.5	Corrosion with low speed
0.5≦Icorr<1.0	Corrosion with middle speed
1.0≦Icorr	Corrosion with high speed

Fig. 8 Time dependent change of corrosion current density of specimen with FA (W/C = 0.5).

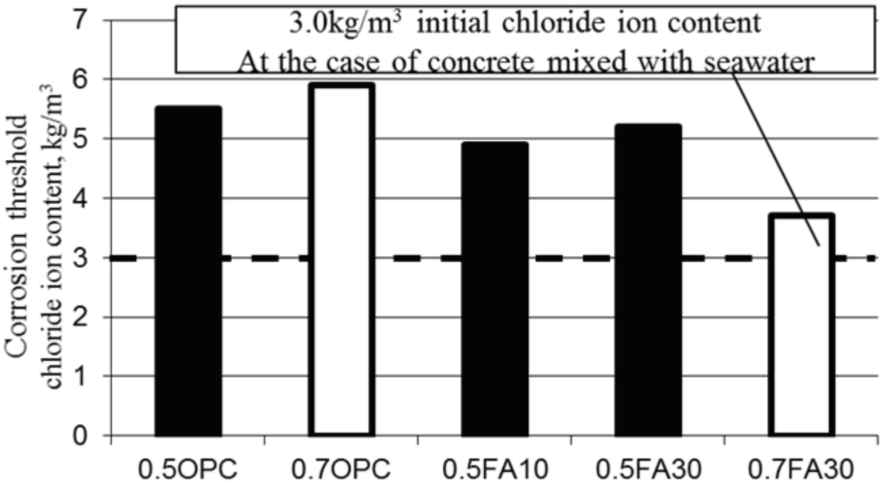


Fig. 9 Threshold chloride content for corrosion in FA specimens.

corrosion threshold chloride content than OPC specimen as the same in case of BFS. As a result, in case of FA specimens, the corrosion threshold chloride ion content is about 3~5 kg/m^3.

3.3 Oxygen Permeability

3.3.1 Results for Concrete with BFS

Fig. 10 shows the comparison between oxygen permeability of concrete mixed with seawater and tap water with BFS. As shown in Fig. 10, oxygen permeability of concrete mixed with seawater is almost the same as that of concrete mixed with tap water. Fig. 11 shows the influence of BFS replacement ratio on oxygen permeability. From Fig. 11, it is confirmed that oxygen permeability of mortar specimen using BFS is smaller than that of OPC specimens and oxygen permeability of concrete decreased as BFS replacement ratio increased.

3.3.2 Results for Concrete with FA

Fig. 12 shows the comparison between oxygen permeability of mortar mixed with seawater and tap water with FA. As shown in Fig. 12, oxygen permeability of mortar mixed with seawater is almost the same as that of concrete mixed with tap water. Fig. 13 shows the influence of FA replacement ratio on oxygen permeability. From Fig. 13, it is confirmed that oxygen permeability of mortar specimens using FA is smaller than that of OPC specimens and it decreased as FA replacement ratio increased. Therefore, it seems that concrete with higher replacement ratio of BFS or FA has better corrosion resistance against chloride attack than OPC concrete [6, 7].

3.4 Life Time Prediction against Chloride Attack

In order to predict the life time against chloride attack, corrosion incubation period (life time duration until the start of steel corrosion) and corrosion propagation period (life time duration from the start of steel corrosion to the occurrence of corrosion crack) are calculated with above material properties and

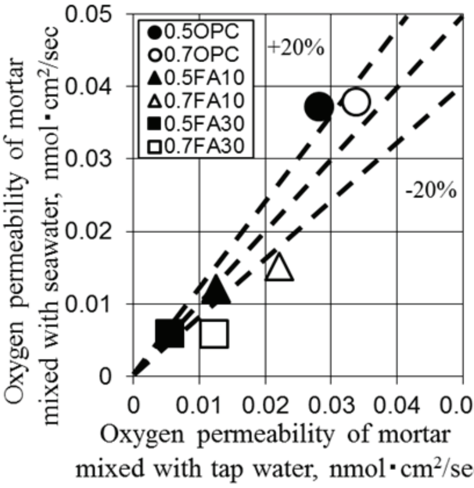


Fig. 10 Oxygen permeability of mortar specimens with BFS (seawater vs. water).

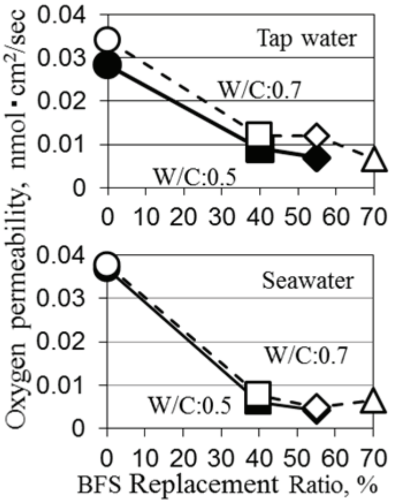


Fig. 11 Oxygen permeability of mortar specimens with different BFS replacement ratio.

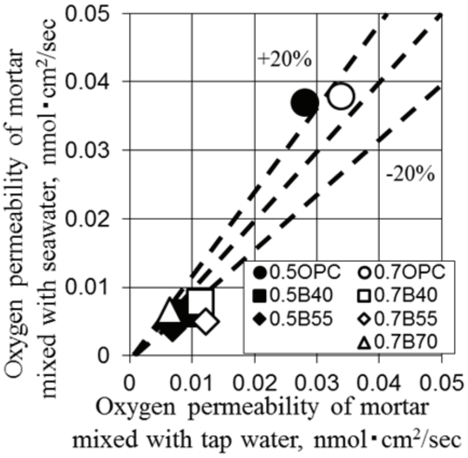


Fig. 12 Oxygen permeability of mortar specimens with FA (seawater vs. water).

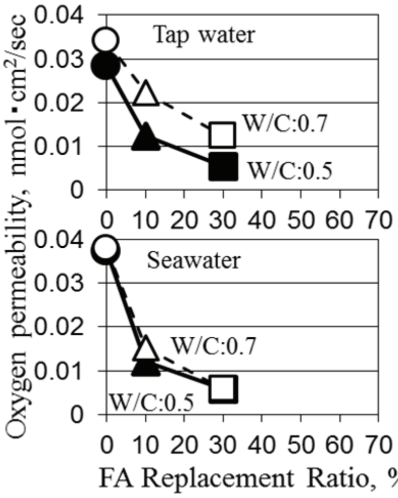


Fig. 13 Oxygen permeability of mortar specimens with different FA replacement ratio.

assumptions. In this study, lifetime against chloride attack is defined as summation of corrosion incubation period and propagation period. For estimation of incubation period, cover depth, initial chloride ion content, surface chloride ion content, chloride penetration rate and corrosion threshold chloride content are required. By using Fick's diffusion equation, the period is calculated when the calculated chloride content is equal to the corrosion threshold chloride content. For estimation of propagation period, the corrosion rate and the critical amount of corrosion product, which generates cracks in cover concrete, should be assumed. Then the periods are calculated when the amount of the corrosion product reaches to the critical value. In this study, the amount of the corrosion product is calculated with the following Eq. (4) [8]:

$$W_{cr} = -1.841\varphi(\varphi - 8.6661) + 145.1\alpha^{-1.194} + 3809A^{-0.8351} + 10.60X - 72.30 \tag{4}$$

where, W_{cr} is amount of corrosion product around steel bar at the end of propagation period (mg/cm^2), φ is creep coefficient (= 0.4), α is coefficient of thermal expansion (= 3.2)， A is corrosion angle (360°), X is shape function (covering depth/diameter of steel bar). The value became 53.8 mg/cm^2 in the case of 70 mm covering depth and 13 mm diameter of steel bar. In order to calculate lifetime against chloride attack, the environment is defined as submerged zone, and covering depth is defined as 70 mm.

3.4.1 Results for Concrete with BFS

Incubation period against chloride attack. Fig. 14 shows the comparison between incubation period of concrete mixed with seawater and tap water with BFS against chloride attack. As shown in Fig. 14, incubation period of concrete mixed with seawater is shorter than that of concrete mixed with tap water. It is considered that seawater as mixing water increased initial chloride content, and shortened the duration to reach corrosion threshold chloride ion content. Hence, the concrete mixed with seawater with BFS is not feasible when the life time is considered only for incubation period. Fig. 15 shows the influence of BFS replacement ratio on incubation period against chloride attack. As shown in Fig. 15, 55% BFS replaced concrete with W/C-0.5 shows the longest incubation period regardless of type of mixing water.

Propagation period against chloride attack. Fig. 16 shows the comparison between propagation period of concrete mixed with seawater and tap water with BFS against chloride attack. As shown in Fig. 16, propagation period of concrete mixed with seawater is longer than that with tap water. It is considered that low corrosion rate of concrete and low oxygen permeability mixed with seawater using BFS contributed to this period.

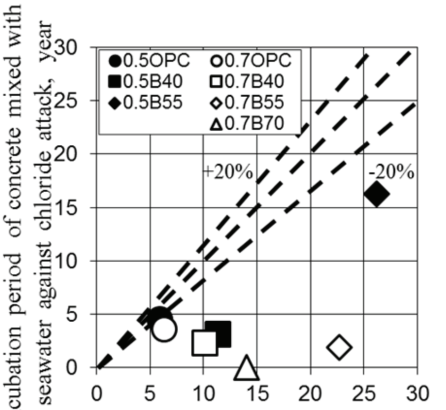


Fig. 14 Corrosion incubation period of specimens with BFS (seawater vs. water).

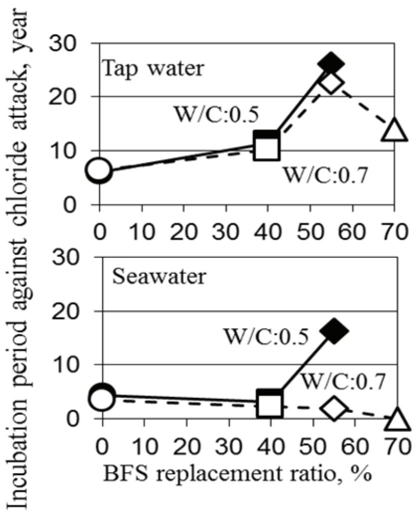


Fig. 15 Corrosion incubation period of specimens with different BFS replacement ratio.

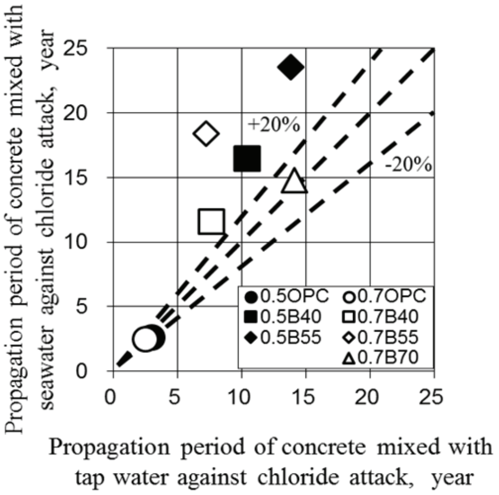


Fig. 16 Corrosion propagation period of specimens with BFS (seawater vs. water).

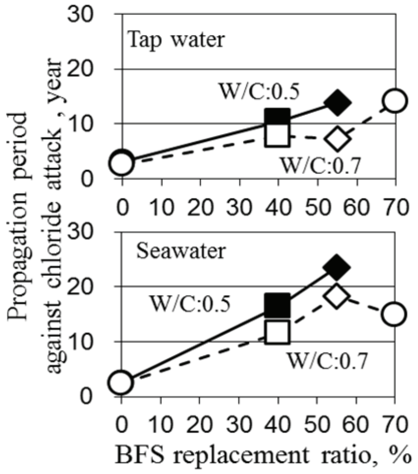


Fig. 17 Corrosion propagation period of specimens with different BFS replacement ratio.

Fig. 17 shows the influence of BFS replacement ratio on propagation period against chloride attack. As shown in Fig. 17, 55% BFS replaced concrete shows the longest initiation period regardless of type of mixing water.

Total lifetime against chloride attack. From the results of corrosion incubation period and propagation period against chloride attack, the total lifetime against chloride attack, is calculated by the summation of two periods. The results are shown in Figs. 18, 19 and Table 4.

From the results, concrete mixed with seawater

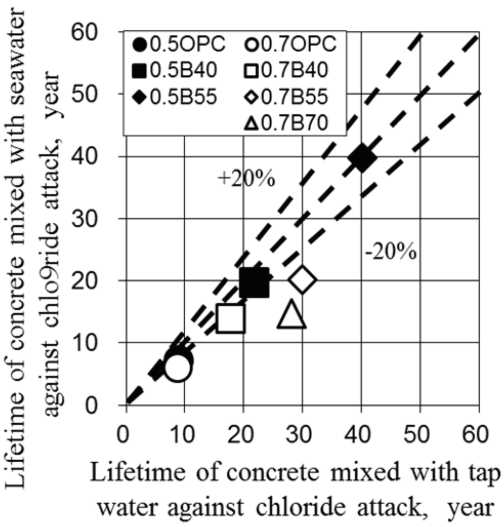


Fig. 18 Life time of specimens with BFS (seawater vs. water).

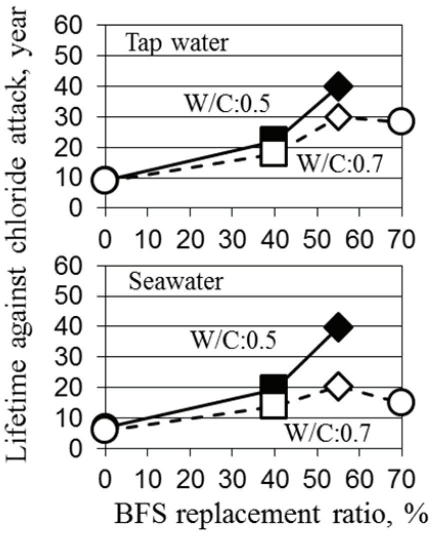


Fig. 19 Life time of specimens with different BFS replacement ratio.

Table 4 Life time of concrete with BFS against chloride attack.

Mixing water	Initiation period			Propagation period			Lifetime (total)		
	Duration (year)		Best mix	Duration (year)		Best mix	Duration (year)		Best mix
Tap water	Ave.	13.8	0.5B55	Ave.	8.4	0.5B55	Ave.	22.3	0.5B55
	Max.	26.2		Max.	14.1		Max.	40.1	
	Min.	6.0		Min.	2.5		Min.	8.9	
Sea water	Ave.	4.5	0.5B55	Ave.	12.8	0.5B55	Ave.	17.3	0.5B55
	Max.	16.3		Max.	23.5		Max.	39.9	
	Min.	0		Min.	2.4		Min.	5.9	

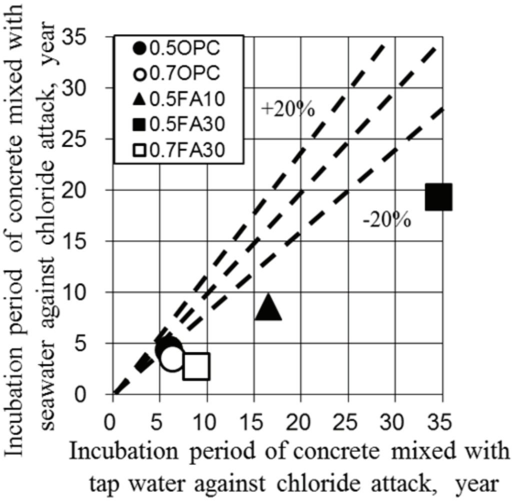


Fig. 20 Corrosion incubation period of specimens with FA (seawater vs. water).

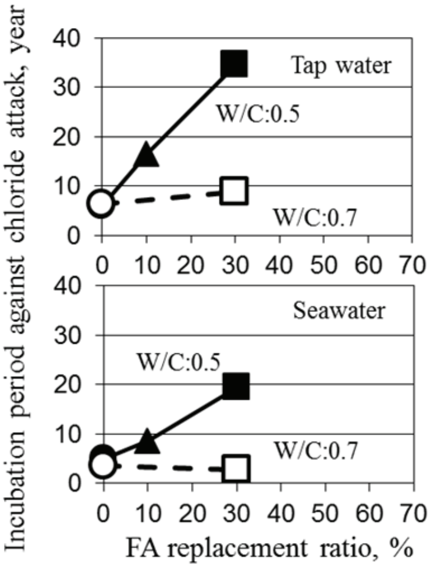


Fig. 21 Corrosion incubation period of specimens with different FA replacement ratio.

using BFS may not be feasible when only incubation period is considered. However, when total life time, summation of incubation and propagation periods, is considered, concrete mixed with seawater has almost the same or slightly shorter lifetime than that of concrete mixed with tap water. Especially, in the case of BFS 55% with W/C = 0.5, the lifetime difference between seawater and tap water mixed concrete has minimum value. And the estimated lifetime of concrete mixed with seawater is about 40 years.

3.4.2 Results for Concrete with FA

Incubation period against chloride attack. Fig. 20 shows the comparison between incubation period of concrete mixed with seawater and tap water with FA against chloride attack. As shown in Fig. 20, incubation period of concrete mixed with seawater is shorter than that with tap water. Hence, the concrete mixed with seawater with FA is not feasible when only the life time for corrosion incubation period is considered, which is the same as the case of BFS.

Fig. 21 shows the influence of FA replacement ratio on incubation period against chloride attack. As shown in Fig. 21, 30% FA replaced concrete with W/C = 0.5 showed the longest incubation period regardless of type of mixing water.

Propagation period against chloride attack. Fig. 22 shows the comparison between propagation period of concrete mixed with seawater and tap water with FA against chloride attack. As shown in Fig. 22, propagation period of concrete mixed with seawater is longer than that of concrete mixed with tap water. It is considered that low corrosion rate of steel and low oxygen permeability mixed with seawater using FA extended this period.

Fig. 23 shows the influence of FA replacement ratio on propagation period against chloride attack. As shown

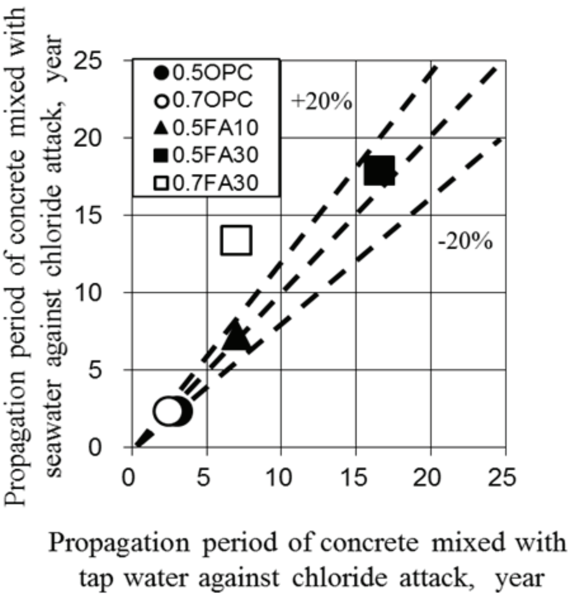


Fig. 22 Corrosion propagation period of specimens with FA (seawater vs. water).

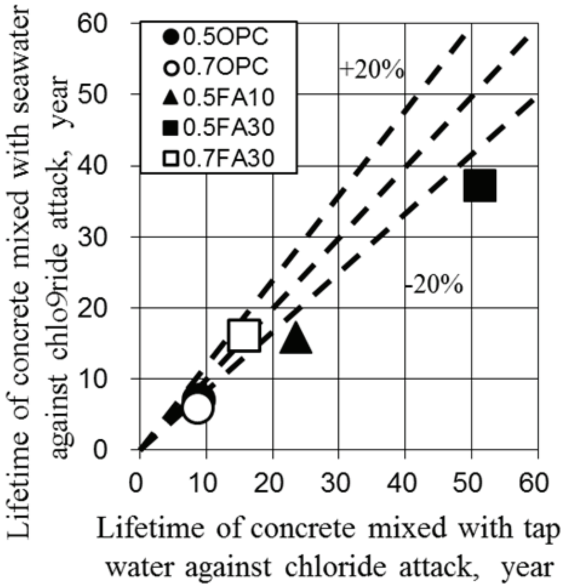


Fig. 24 Life time of specimens with FA (seawater vs. water).

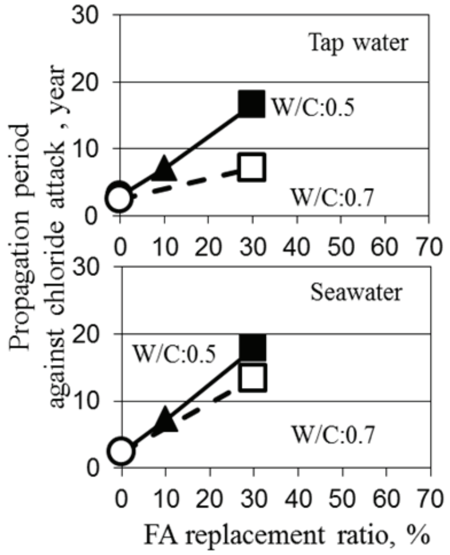


Fig. 23 Corrosion propagation period of specimens with different FA replacement ratio.

in Fig. 23, 30% FA replaced concrete shows the longest propagation period regardless of type of mixing water.

Total lifetime against chloride attack. From the results of incubation period and propagation period against chloride attack, the total lifetime including incubation and propagation periods is calculated by summation of two periods. The results are shown in Figs. 24, 25 and Table 5. The results of FA has the same trend with BFS case that concrete mixed with seawater using FA may not be feasible when only incubation period is considered. However, when total life time is considered, concrete mixed with seawater has almost the same or only slightly shorter lifetime than that of concrete mixed with tap water,

Table 5 Life Time of Concrete with FA against Chloride Attack.

Mixing water	Initiation period			Propagation period			Lifetime (total)		
	Duration (year)		Best mix	Duration (year)		Best mix	Duration (year)		Best mix
Tap water	Ave.	14.5	0.5FA30	Ave.	7.2	0.5FA30	Ave.	21.7	0.5FA30
	Max.	34.6		Max.	16.6		Max.	51.2	
	Min.	6.0		Min.	2.5		Min.	8.9	
Sea water	Ave.	7.8	0.5FA30	Ave.	8.6	0.5FA30	Ave.	16.4	0.5FA30
	Max.	19.3		Max.	17.9		Max.	37.2	
	Min.	3.5		Min.	2.4		Min.	5.9	

especially, in the case of FA 30% concrete (0.5FA30), the estimated life time of concrete mixed with seawater is about 40 years.

4. Conclusions

Considering lifetime of reinforced concrete against chloride attack, maximum estimated lifetime of seawater mixed concrete with BFS and FA are almost the same and both cases obtained estimated life time of 40 years, almost four times longer than seawater mixed concrete with OPC (0% replacement ratio). The estimated life time of 40 years is acceptable for reinforced concrete structure in industrial facilities such as petro-chemical plant or liquefied neutral gas plant for which the design life is usually considered as 40 years [9]. Usage of BFS or FA for concrete can reduce chloride ion diffusivity and oxygen permeability and as a result, it can reduce the corrosion of steel bar in the concrete. In performance based design and the life time is determined by both incubation and propagation periods, it is feasible to use seawater and if with BFS or FA, it is much better than with OPC. However, further study is needed to control the corrosion incubation period which is shorter than that of OPC concrete mixed with fresh water due to the higher initial chloride content in seawater mixed concrete.

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