Chloride Penetration Profiles in Existing Harbor Structures

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ABSTRACT

Chloride penetration in existing harbor structures, more than 15 years old at the time, constructed with Ordinary Portland Cement (OPC) and Blast Furnace Slag Cement (BFC) was investigated. In this research, the surface chloride content (C_0) and the apparent chloride diffusion coefficient (D_{ap}) were obtained by Fick's Second Law's Equation, and both of them were categorized by the height of core-sampling locations and the existence of curtain walls. Then the difference of chloride penetration profiles between OPC and BFC concrete was discussed. Also, the incubation period, the duration between the construction and the occurrence of the steel bar corrosion, was calculated with the assumptions that the cover depth was 7cm and the member was located in the splash zone. As a result, the incubation period was calculated to be 20 years in the case of OPC and 50 years in the case of BFC. Also, the curtain walls were recognized to be effective to make the incubation periods much longer.

Keywords. Existing Harbor structures, Chloride Penetration, BFC, OPC, Curtain walls

INTRODUCTION

Generally, Fick's Second Law's Equation is commonly used to predict chloride penetration into concrete in the durability check against chloride attack. In this equation, there are two input parameters, namely, "surface chloride content (C_0)" and "apparent chloride diffusion coefficient (D_{ap})". However, these parameters are dependent on the structural and/or environmental factors such as the shape, the spatial location (the height from sea water level or the direction of members, etc.), and the wave condition as well as the material factors such as the type of cement and the mix proportion of concrete. Therefore, if these parameters can be defined considering the above factors, it is possible to predict chloride penetration more reasonably.

On the other hand, BFC concrete is often used for new harbor structures in Japan because the chloride diffusion coefficient and the CO_2 gas emission of BFC concrete are smaller than that of OPC concrete. However, there are very few researches to evaluate the durability of existing structures with BFC concrete against chloride attack.

In this paper, chloride penetration in existing harbor structures, more than 15 years old at that time, constructed with OPC and BFC was investigated. The values of C_0 and D_{ap} were discussed by considering the height from sea water level (H.W.L.) to core-sampling location and the existence of curtain walls in the structures. In addition, based on the prediction of chloride content at the depth of 7cm from concrete surface, the effectiveness of BFC concrete against chloride attack was examined.

OUTLINE OF INVESTIGATION

Outline of Structures with OPC Concrete. The outline of the structures with OPC concrete inspected in this research is shown in **Table 1**. These structures were jetties and located on the Pacific Ocean side of Japan. Core samples were taken from the superstructures of four jetties. The water-cement ratio of concrete used for each jetty was around 0.5. The number of core samples was around 100 altogether in four jetties. The feature of each jetty was as follows.

Jetty-A had no curtain walls as shown in **Fig. 1**. Jetty-B had curtain walls at the berthing side as shown in **Fig. 2**. Jetty-C had curtain walls as shown in **Fig. 3**. This jetty had 4 berths (A & B-berth, C-berth, and D-berth). A & B-berth had the curtain walls at both the seaside and the landside, while C-berth and D-berth had the curtain walls only at one side. Jetty-D had no curtain walls and there was revetment right behind the jetty as shown in **Fig. 4**.

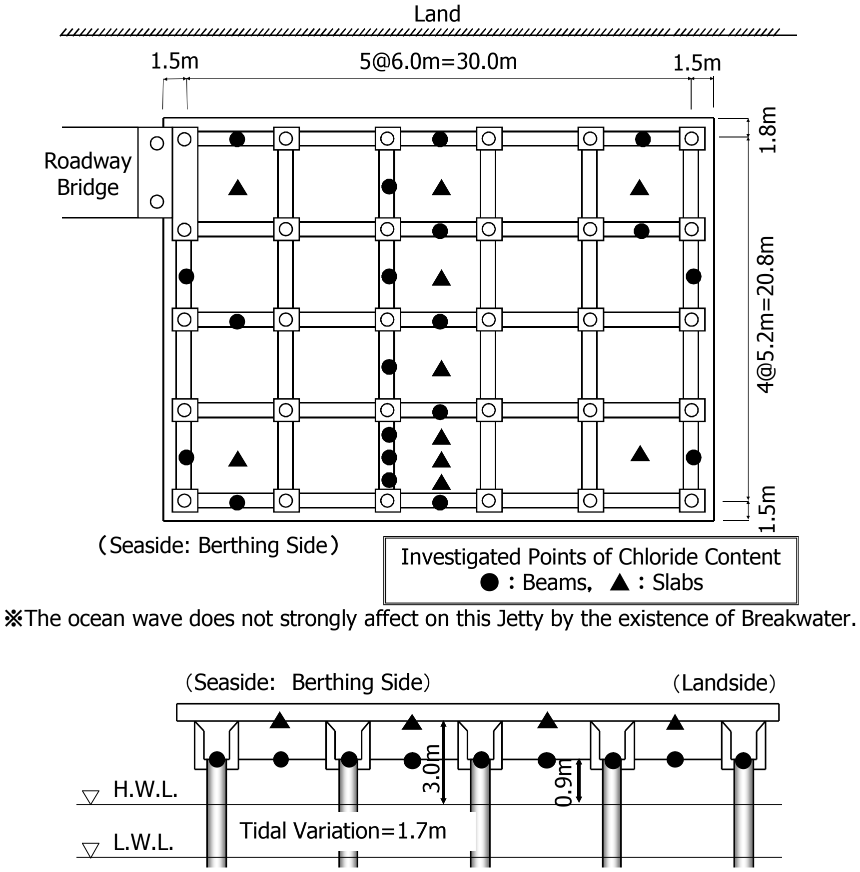
Table 1. Outline of Investigated Structures with OPC Concrete

Structure Name	Construction Year	Elapsed Years	Distance between H.W.L. and Core-sampling location (m)		With or without curtain walls in the structures
			Slabs	Beams	
A	1981	25	+3.00	+2.10	without
B	1987	15	+1.67	+0.95	with
C	1970	33	―	-0.60～+0.21	with
D	1975	29	+1.75	+0.00～+0.60	without

Outline of Structures with BFC Concrete. Core samples were taken from two existing harbor structures constructed with BFC concrete in Tokyo bay. BFC was Type-B in JIS A 5211 (the replacement ratio of blast furnace slag is about 40%). The water-cement ratio of concrete for each structure was around 0.5.

There were two types of structure with BFC concrete inspected. One structure was a breakwater that had been used for 20 years and the outline is shown in **Fig. 5**. Core samples were taken from three levels of height in the structure, which were 0.24m, 1.72m and 3.14m below from high water level (H.W.L.). In this site, the tidal variation was 2.0m. Thus, the sampling locations of 0.24m and 1.72m (named as H.W.L. -0.24m and H.W.L. -1.72m in this paper) were in the tidal zone, and those of 3.14m (named as H.W.L. -3.14m) were in the submerged zone.

Another one was a dock that had been used for 15 years and the outline is shown in **Fig. 6**. Core samples were taken from three levels of height of the structure on the sea side, which were 0.9m, 1.5m and 2.2m upper from H.W.L. (named as H.W.L. +0.9m, H.W.L. +1.5m and H.WL. +2.2m), and two core samples were taken at 1.0m upper from H.W.L. (named as H.W.L. +1.0m) on the inside the dock. These sampling locations were in the splash zone.



※The ocean wave does not strongly affect on this Jetty by the existence of Breakwater.

Fig. 1. Structural Drawings of Jetty-A (OPC concrete)

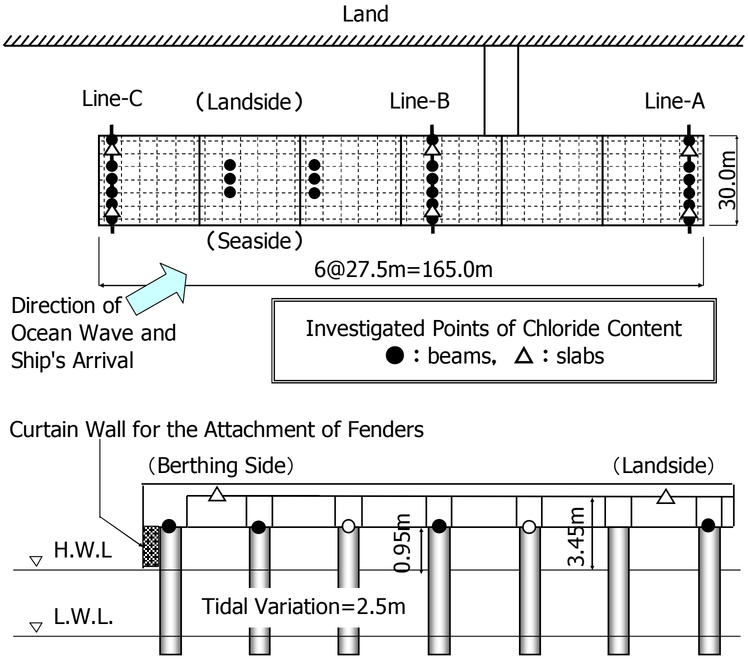


Fig. 2. Structural Drawings of Jetty-B (OPC concrete)

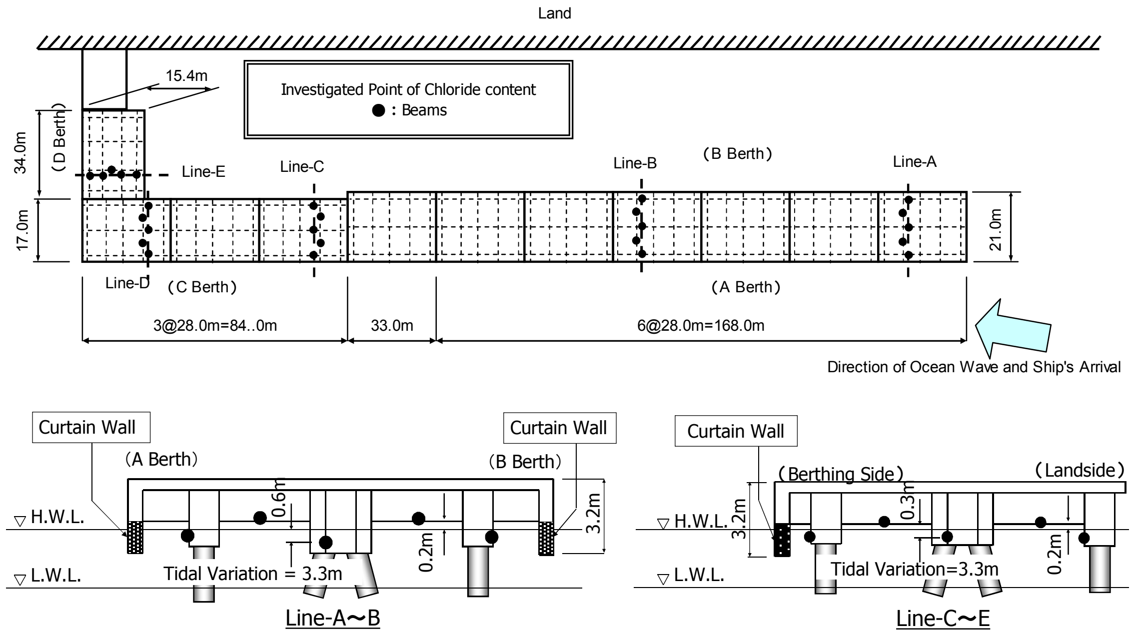


Fig. 3. Structural Drawings of Jetty-C (OPC concrete)

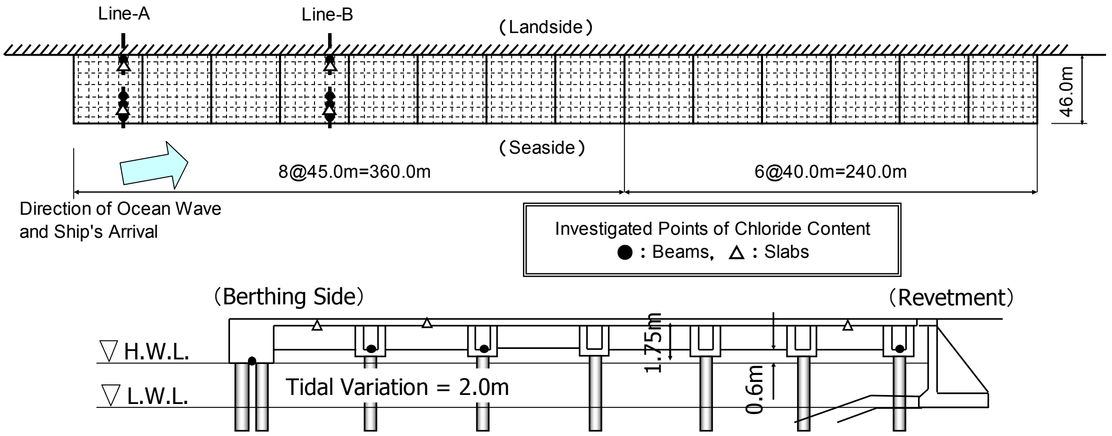


Fig. 4. Structural Diagrams of Jetty-D (OPC concrete)

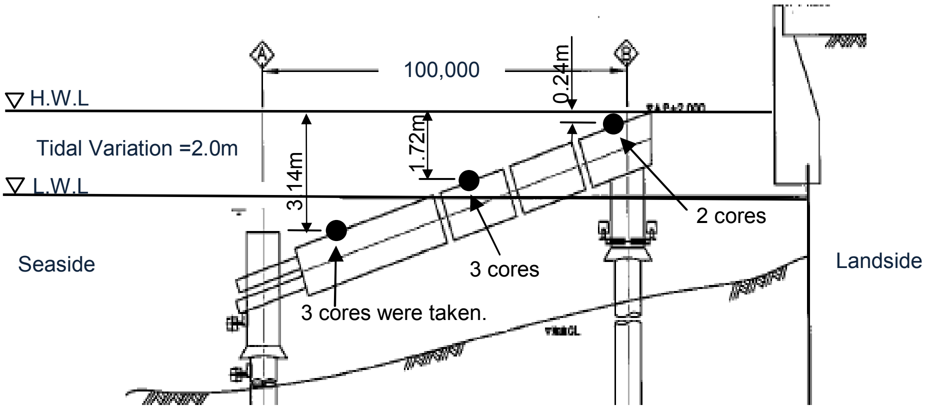


Fig. 5. Structural Drawing of Breakwater (BFC concrete)

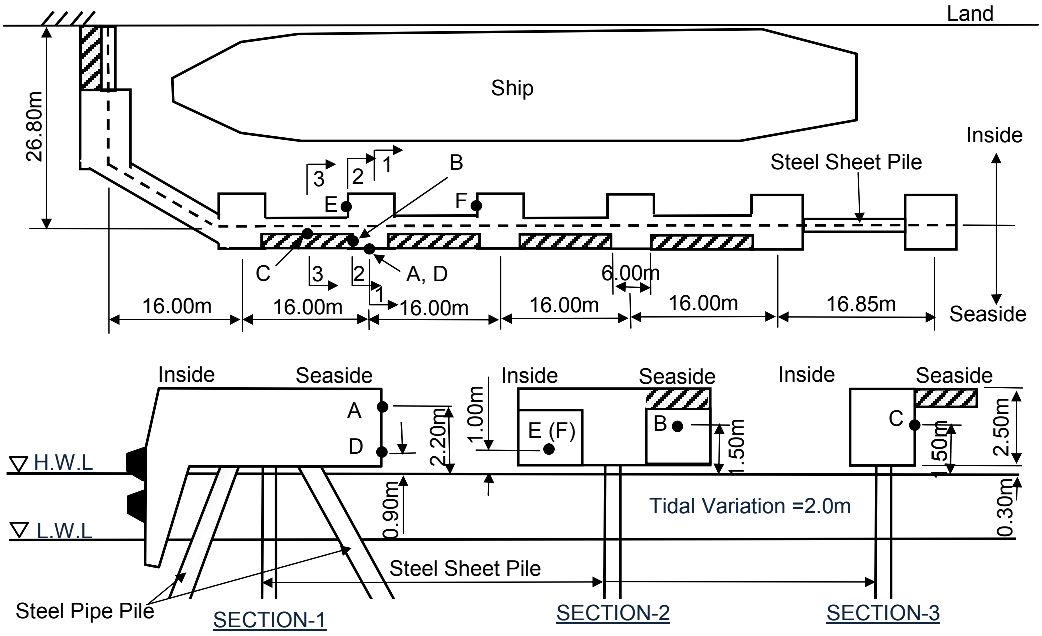


Fig. 6. Structural Drawings of Dock (BFC concrete)

Estimation Method of C_0 and D_{ap}. The procedure were as follows; as the first step, core samples from the structures with OPC concrete shown in **Fig. 1** to **Fig. 4** were sliced at every 20mm from the exposure surface to inside, and those with BFC concrete were sliced at every 10mm. Then as the second step, total chloride content in each sliced sample was measured according to JIS A 1154 [Methods of test for chloride ion content in hardened concrete]. As the third step, the results were plotted on diagram. In the diagram of chloride penetration profile, the y-coordinate shows the total chloride content and the x-coordinate shows the depth from the surface of each sample. The surface chloride content (C_0) and the apparent chloride diffusion coefficient (D_{ap}) could be obtained by fitting **Eq. (1)** to the plotted profile. Although the previous research [Takeda et al. (1998) and Maruya et al. (1989)] indicates that the values of C_0 and D_{ap} of less than 10 years old concrete change with time. In this paper, however, those values could be regarded as constant because all the structures shown in **Fig. 1** to **Fig. 6** had been used for more than 15 years at the time of investigation.

$$C(x,t) = C_0\left(1 - \mathrm{erf}\left(\frac{0.1x}{2\sqrt{D_{ap}\cdot t}}\right)\right) \qquad (1)$$

where, C(x,t): Chloride content in the concrete at the x mm distance from the surface after t years of exposure (kg/m^3) , C_0: Chloride content on the surface (kg/m^3) , D_{ap}: Apparent chloride diffusion coefficient (cm^2/year) , erf: Error function.

CHLORIDE PENETRATION PROFILES OF OPC & BFC CONCRETE

Fig. 7(a) shows representative chloride penetration profiles in cores sampled from the structures with OPC concrete shown in **Fig. 1** to **Fig. 4**, and **Fig. 7(b)** shows those with BFC concrete shown in **Fig. 5** and **Fig. 6**. Black-dots in these graphs represent the data from the submerged and tidal zone, and white-dots show those from the splash zone. From these figures, the followings can be recognized.

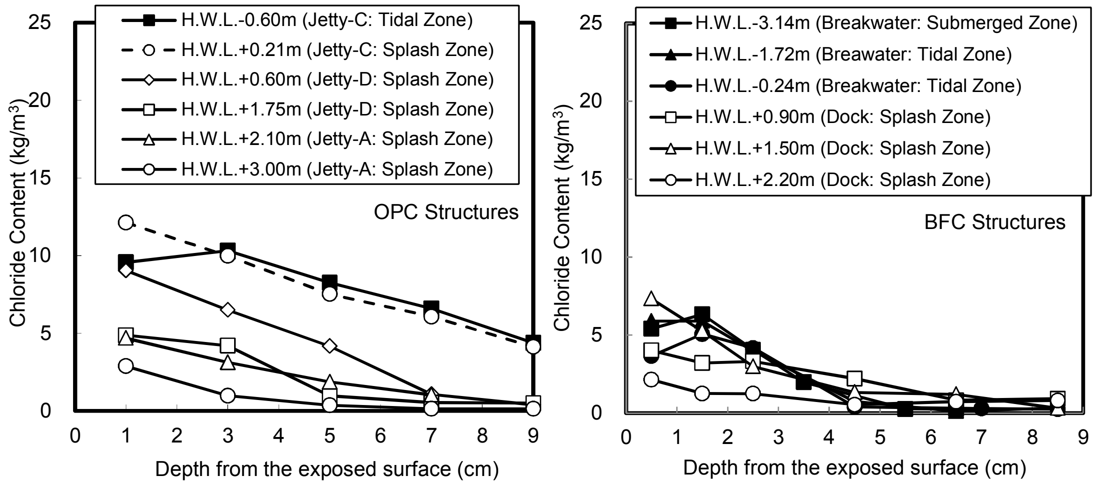
1) According to the data for the splash zone (white-dotted data) of both OPC and BFC structures, chloride content is smaller with higher part of the sampling locations. This tendency can be particularly found between 5cm depth or more from the surface in case of OPC structures, and between 2.5cm depth and more in case of BFC concrete.

2) In case of OPC structures, chloride penetration profile of the sample from the tidal zone (H.W.L. -0.60m) is very similar to that from the splash zone (H.W.L. +0.21m) at 3cm depth or more. However, chloride content at 1cm depth of the sample from the tidal zone (H.W.L. -0.60m) is smaller than that from the splash zone (H.W.L. +0.21m).

3) In case of BFC structures, chloride penetration profiles of the samples from the submerged and tidal zone (black-dotted data) are almost the same at 2.5cm depth or more. Also, chloride content of the samples from the submerged and tidal zone (black-dotted data) reduces rapidly between 2.5cm and 5.5cm from the surface, while that from the splash zone (white-dotted data) decreases gently between 1.5cm or more.

Thus, it can be recognized that the height from H.W.L. affects the amount of chloride penetration into concrete in the splash zone but the height does not affect in the submerged and tidal zone.

The profiles close to the surface (the data of 0.5 and 1.5 cm) sometimes show different tendencies. The differences can be caused by the effects of carbonation and sulphate ion. So, the data of 0.5 and 1.5cm depth are removed for the calculation of the surface chloride content (C_0) and the apparent chloride diffusion coefficient (D_{ap}).



(a) OPC Structures **(b) BFC structures**

Fig. 7. Chloride Penetration Profiles

CORRELATION BETWEEN C_0 AND HEIGHT FROM H.W.L.

Fig. 8(a) and **(b)** show the correlation between C_0 and height of core-sampling location from H.W.L. (H) using all data of OPC and BFC structures respectively. In these graphs, the data for the structures with curtain walls are represented by grey-dots and those without curtain walls are represented by white-dots. In **Fig .8(b)**, the data obtained from BFC concrete specimens (shown as △ and the water-cement ratio was 0.56), which had been exposed for two years in open space under the superstructure of a jetty located in Yokosuka bay, part of Tokyo bay, are added to the data obtained from existing structures shown in **Fig. 5** and **Fig.**

6. Also, in **Fig .8(b)**, two data of the samples from the inside of dock shown in **Fig. 6** are highlighted by grey-dots on the assumption that these were under similar exposure condition to the structures with curtain walls.

As seen in these figures, although the correlation between C_0 and H is not so strong, the tendency can be found that the values of C_0 decrease with higher part of sampling locations in the splash zone. Using the data obtained from the structures without curtain walls, the relation between the height from HWL and the C_0 for OPC and BFC can be approximately presented by the following liner equations as shown in **Equation (2)** and **(3)** on these graphs respectively. **Equation (4)** shown in **Fig .8(a)** for reference is reported in “Technical Standard and Commentaries for Port and Harbor (2008)” (named as “Port and Harbor Standard” in this paper).

OPC Structures $C_0 = 15.3 - 3.9H \ (-0.6 \leqq H \leqq 3.0)$ (2)

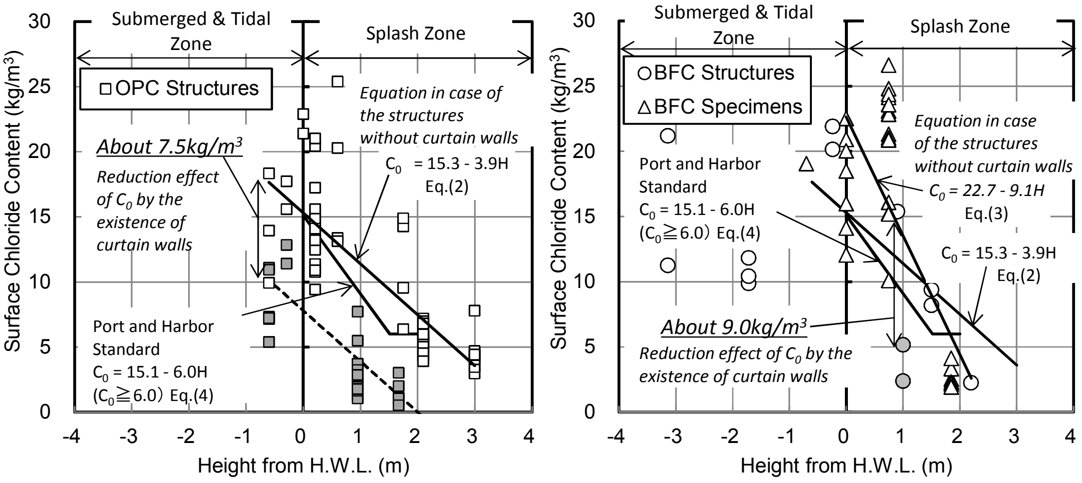
BFC Structures $C_0 = 22.7 - 9.1H \ (0 \leqq H \leqq 2.2)$ (3)

Port and Harbor Standard $C_0 = 15.1 - 6.0H \ (C_0 \geqq 6.0, \ 0 \leqq H \leqq 2.0)$ (4)

where, C_0: Chloride content on the surface (kg/m^3), H: Height from H.W.L. (m).

Compared between **Equation (2)** and **(3)**, C_0 values of BFC structures are larger than those of OPC structures when H is between 0 and 1.5m, while those of BFC structures are smaller than those of OPC structures when H is more than 1.5m.

Then the effect of the curtain walls are recognized as follows. As shown in **Fig. 8(a)**, the values of C_0 for OPC structures with curtain walls (grey-dots) are about 7.5kg/m^3 smaller than those calculated by **Equation (2)**. Also, as shown in **Fig. 8(b)**, the values of C_0 obtained from two samples at the inside of dock (grey-dots) are about 9.0kg/m^3 smaller than those calculated by **Equation (3)**. Thus, the possibility can be indicated that the curtain walls might be effective to reduce the values of C_0 with curtain walls.



(a) OPC structures **(b) BFC structures**

Fig. 8. Correlation between C_0 and Height from H.W.L. (H)

CORRELATION BETWEEN D_{ap} AND HEIGHT FROM H.W.L.

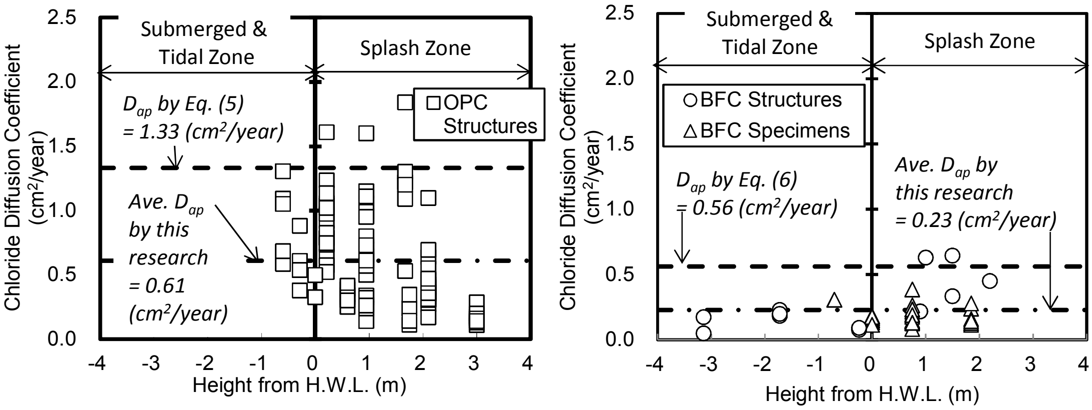
Fig. 9 shows the correlation between D_{ap} and height of core-sampling location from H.W.L. (H) using all data of OPC structures, BFC structures and BFC specimens. The values of D_{ap} calculated by substituting the water-cement ratio of 0.5 to **Equation (5)** and **(6)**, those are reported in "Port and Harbor Standard", are shown on these graphs for reference.

In case of OPC $D_{ap} = -3.9(W/C)^2 + 7.2(W/C) - 2.5$ (5)

In case of BFC $D_{ap} = -3.0(W/C)^2 + 5.4(W/C) - 2.2$ (6)

where, D_{ap}: Apparent chloride diffusion coefficient (cm^2/year), W/C: Water-cement ratio.

According to **Fig. 9(a)** (in case of OPC structures), the correlation between D_{ap} and H cannot be clear because the values of D_{ap} widely vary. However, according to **Fig. 9(b)** (in case of BFC structures and specimens), the values of D_{ap} are almost the same without depending on H. Generally, as shown in **Equation (5)** and **(6)**, it is regarded that the value of D_{ap} is dependent on the quality of concrete such as the type of cement and the water-cement ratio of concrete, etc. Furthermore, Nishida et al. (2011) indicate that the values of D_{ap} widely vary by the influences of temperature of concrete and the water advection which occurs under wet-dry cyclic condition, etc. Based on the above knowledge, the average values of D_{ap} of OPC and BFC structures were calculated using all data obtained by this research. The average was 0.61cm^2/year in case of OPC and 0.23cm^2/year in case of BFC. The value of D_{ap} of BFC concrete was approximately one third of that of OPC concrete.



(a) OPC structures **(b) BFC structures**

Fig. 9. Correlation between D_{ap} and Height from H.W.L. (H)

CHLORIDE PENETRATION PREDICTIONS

With the above results, the prediction of chloride penetration was conducted in order to verify the effectiveness of BFC concrete against chloride attack. Here the cover thickness over reinforcement of 7cm is often used for Harbor structures in Japan. Therefore, in the predictions, the chloride content at 7cm depth were analysed on the assumption that reinforced concrete was positioned in the splash zone (Height from H.W.L.=1.0m). The other assumptions were as follows; (1) the initial chloride content in concrete was 0kg/m^3; (2) there were assumed to be no cracks in the structures; (3) threshold chloride content for the steel corrosion initiation was 2.0kg/m^3 according to "Port and Harbor Standard".

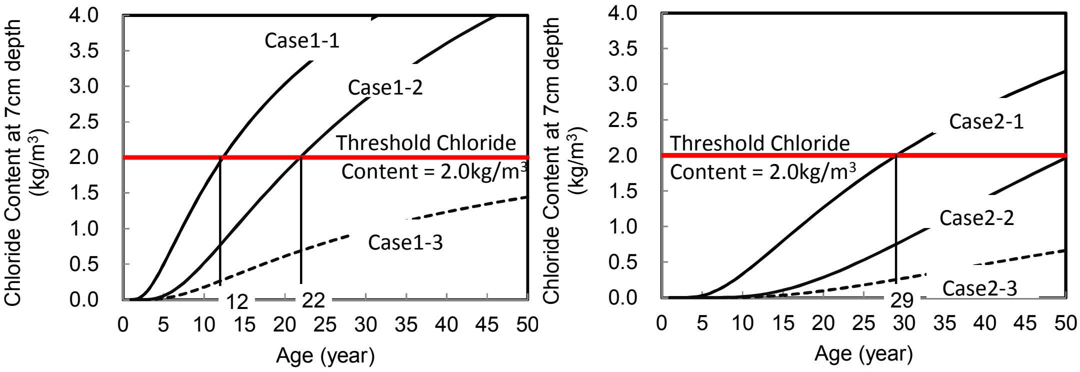
The analysis cases are shown in **Table 2**. In the cases of 1-1 and 2-1, the values of C_0 and D_{ap} are based on "Port and Harbor Standard". In the other cases, the values of C_0 and D_{ap} are based on this research. **Fig. 10(a)** and **(b)** show the time dependent changes of chloride content at 7cm depth in case of OPC and BFC structures respectively.

The prediction results based on "Port and Harbor Standard" show that it is expected to take 12 years to initiate steel corrosion for OPC structure without curtain walls (Case1-1) and 29 years for BFC structures (Case2-1). Also, in the predictions based on the results obtained from this research, it is expected to take 22 years for OPC (Case2-2) and around 50 years for BFC (Case2-2). From these prediction results, chloride penetration in BFC concrete is much slower than that in OPC concrete, therefore the use of BFC concrete is very effective to prolong the service life time for the harbor structures.

Further, in case of the structures with curtain walls, it is expected to take more than 50 years for both OPC and BFC structures (Case1-3 and Case2-3). It can be found that the installation of curtain walls on the harbor structures is also effective to prolong the service life time.

Table 2. Analysis Cases

Case Name	Case1-1	Case1-2	Case1-3	Case2-1	Case2-2	Case2-3
Type of Cement	OPC			BFC		
Water-cement ratio of conc.	0.5			0.5		
With or without of curtain walls in the structures	Without		With	Without		With
C_0 (kg/m^3)	9.1 **[Eq.(4)]**	11.4 **[Eq.(2)]**	3.9 **[Eq.(2)-7.5]**	9.1 **[Eq.(4)]**	13.6 **[Eq.(3)]**	4.6 **[Eq.(3)-9.0]**
D_{ap} ($cm^2/year$)	1.33 **[Eq.(5)]**	0.61	0.61	0.56 **[Eq.(6)]**	0.23	0.23
Remarks	Based on Port and Harbor Standard	Based on the data in this research		Based on Port and Harbor Standard	Based on the data of this research	



(a) OPC structures **(b) BFC structures**

Fig. 10. Time Dependent Changes of Chloride Content at 7cm Depth from the Surface

CONCLUSIONS

The conclusions of this research are shown as below;

1) The tendency is confirmed that the values of C_0 can be smaller with the higher part of core-sampling locations from sea water level in the splash zone, although the correlation between the values of C_0 and the height from H.W.L (H) is not strong. In addition, the values of C_0 of BFC structures is larger than those of OPC structures when H is between 0 and 1.5m, and those of BFC is smaller than those of OPC when H is more than 1.5m.

2) There is possibility that the installation of curtain walls can reduce the value of C_0.

3) It is confirmed that the value of D_{ap} is not dependent on the height. The average value of D_{ap} of BFC concrete is approximately one third of that of OPC concrete.

4) According to the predictions of chloride content at the depth of 7cm in concrete with the assumption that reinforced concrete member is positioned in the splash zone (Height from H.W.L.=1.0m), the incubation period is expected to be about 20 years in case of OPC structures and around 50 years in case of BFC structures without curtain walls. In addition, it is expected that the incubation period is much longer when there are the curtain walls in the structures.

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