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Chloride penetration in anchorage concrete of suspension bridge during construction stage

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Abstract. Steel corrosion in embedded steel causes a significant durability problems and this usually propagates to structural degradation. Large-scaled concrete structures, PSC (Pre-stressed Concrete) or RC (Reinforced Concrete) structures, are usually constructed with mass concrete and require quite a long construction period. When they are located near to sea shore, chloride ion penetrates into concrete through direct or indirect exposure to marine environment, and this leads durability problems. Even if the structures are sheltered from chloride ingress outside after construction, the chloride contents which have been penetrated into concrete during the long construction period are differently evaluated from the initially mixed chloride content. In the study, chloride profiles in cores extracted from anchorage concrete block in two large-scaled suspension bridge (K and P structure) are evaluated considering the exposure periods and conditions. Total 21 cores in tendon room and chamber room were obtained, and the acid-soluble chlorides and compressive strength were evaluated for the structures containing construction period around 3 years. The test results like diffusion coefficient and surface chloride content from the construction joint and cracked area were also discussed with the considerations for maintenance.

Keywords: anchorage block; construction stage; concrete core; strength; apparent diffusion coefficient; surface chloride content

1. Introduction

Concrete structures constructed near to sea water are exposed to chloride attack so that a quantitative durability design has been carried out for satisfying their performances (Thomas and Bamforth 1999, JSCE 2013, Duracrete 2000). Among the large-scaled RC (Reinforced Concrete) or PSC (Pre-stressed Concrete) structures which have been constructed in such environments, typical structures are power plants for a large quantity of cooling water and huge bridges structures across sea. Durability designs are usually performed for hardened concrete and simply take account of initial chloride content in mixing stage. However, if the construction period is extended to few years, the chloride contents with the initial chlorides are assessed differently due to the additional chloride ions from outside during the construction period.

For large structures constructed along the sea shore, considerable chloride contents exist in ground water and penetration of chloride ion occurs through air supplying with salt, even if not directly exposed to sea water or splash (Yoon *et al.* 2019, Oslakovic *et al.* 2010, Yang *et al.* 2019, Tadayon *et al.* 2016). When exposed directly to sea water for a long period of time, diffusion phenomenon becomes the main mechanism which governs movement of chloride ion. However, in the case of atmospheric condition with chloride spraying, the relative humidity of the outside and the concrete saturation inside are considered to be very important since complicated mechanism of diffusion and convection occurs simultaneously (Park *et al.* 2012, Ishida and Maekawa 2003, Tutti 1993). In addition, the structures at the atmospheric and tidal zone require special attention to corrosion control since corrosion is easily initiated through continuous supply of oxygen and chloride (Tutti 1993, Tutti 1982, Broomfield 1997, Du *et al.* 2015).

Physical and chemical models have been proposed on evaluation of chloride behaviors and complicated governing equation such as Nernst-Einstein Equation is adopted for considering permeation and diffusion (Park *et al.* 2012, Ishida and Maekawa 2003, Maekawa *et al.* 2015, Petcherdchoo 2018). Chloride profiles based on Fick's 2nd Law can provide actual chloride content along to cover depth and the results from the equation are utilized for durability design and chloride assessment (Bamforth 1999, Kwon *et al.* 2009, Thomas and Bamforth 1999). Many researches on evaluation of chloride behavior have been carried out from real assessment in RC structures. In the studies, an assumption of steady state condition is very important since the parameters such as surface chloride content and apparent diffusion coefficient can have reasonable values in Fick's 2nd Law in that condition (Lee *et al.* 2015, Kwon 2015, Luping and Gulikers 2007). The parameters are reported to have time-dependent

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characteristics (Bamforth 1999, Thomas and Bamforth 1999, Luping and Gulikers 2007, Muthulingam *et al.* 2016). In the atmospheric conditions, chloride profiles in concrete usually show stable level after exposure of 10 years since the parameters based on Fick's 2nd Law are obtained from the regression referred to the chloride profiles along to cover depth in a given exposure period (Lee *et al.* 2015, Kwon 2015, Thomas and Bentz 2002).

Large-scales structures like suspension bridges and cable-suspended bridges conventionally have anchorage structures at starting and ending piers for resisting the tensile force in cables. Self-weight in mass concrete is very effective to resisting the tensile force so that large anchor concrete blocks are constructed at each end location. In the anchorage blocks, tendon room and chamber room are constructed for holding the tendons subjected to high tensile stress. While they are constructed, the inside of each room is exposed to air-carrying chloride ions for few years, which can cause a different chloride profiles.

In the study, chloride profiles in concrete cores extracted from anchorage block in two large-scaled structures (*K* and *P* suspension bridge structures) were evaluated considering the exposure periods. Total 21 cores in tendon room and chamber room were obtained, and the acid-soluble chloride content and compressive strength were evaluated. The chloride content at cracked and construction joint were also measured and discussed.

2. Analysis of penetrated chloride content at initial construction period

2.1 Apparent diffusion coefficient and surface chloride content

In the analysis of induced chloride content from outside, the parameters such as apparent diffusion coefficient and surface chloride content are obtained considering chloride profiles and exposed period assuming steady-state condition. Linear and non-linear regression analysis are conventionally adopted based on the profiles and the related parameters are derived (Luping and Gulikers 2007, Zhou 2014). Several standard methods like KS F 2714 and AASHTO T 260 are usually adopted, and water soluble or acid-soluble chloride ions are calculated through $AgNO_3$ titration method (KS F 2714 2017, AASHTO T 260 1997, Glasser *et al.* 2008). In the range of $0 \le z \le \sqrt{3}$, $1 - \mathrm{erf}\,(z)$ shows a similar value from $(1 - \frac{z}{\sqrt{3}})^2$ so that linear regression method which is for the relationship between cover depth (m) and square root of chloride content ($\sqrt{\mathrm{kg/m^3}}$) is conventionally used for its simplicity. RCPT (Rapid Chloride Penetration Test) has been widely used for its efficiency of chloride diffusion measurement, but the chloride contents from profiles exposed to chloride ingress can explain realistic phenomena reasonably. The evaluation process of apparent diffusion coefficient and surface chloride content is shown in Fig. 1.

2.2 Effect of exposure period and mixture proportions on chloride penetration

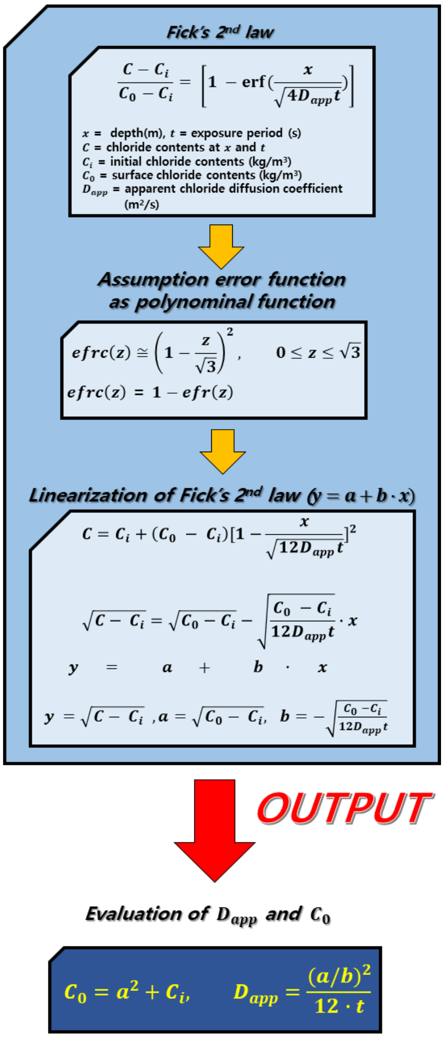
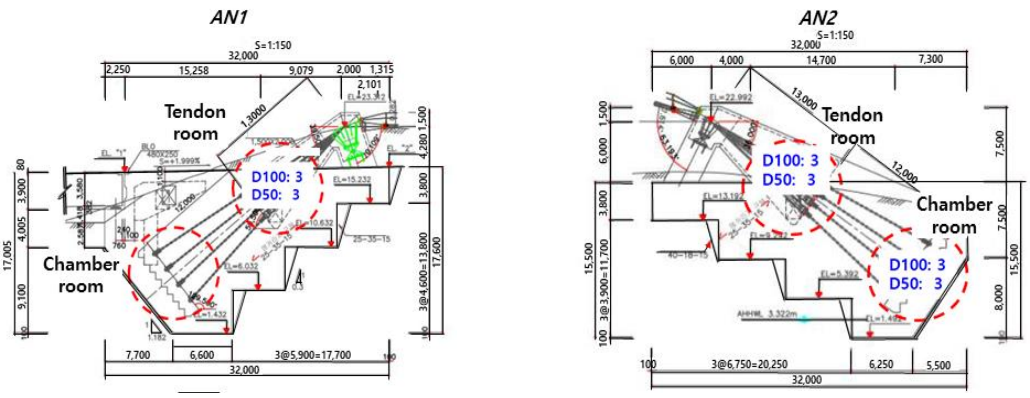
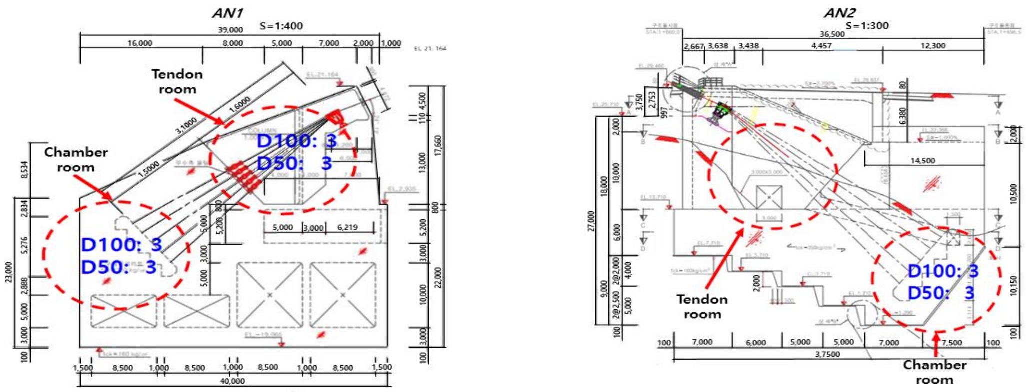


Fig. 1 Evaluation of apparent chloride diffusion coefficient and surface chloride content

In the previous researches on field assessment (Lee *et al.* 2015, Kwon 2015), reasonable information for surface chloride content and apparent diffusion coefficient were obtained in the long-term exposure condition under high chloride concentration like sea water-submerged condition. If the evaluated surface chloride content is low, too high diffusion coefficient is derived through regression analysis since initial chloride content affects. Furthermore, longer than 10 years are assumed for the full built-up of surface chloride content and the maximum values vary with exposure conditions, geometry of structure, and mix proportions. The previous studies showed that surface chloride content in concrete with mineral admixtures like GGBFS (Ground Granulated Blast Furnace Slag) was slightly higher than that in OPC (Ordinary Portland Cement) concrete due to its enlarged bound chloride ions. In the conditions with relatively short exposure period, the reasonable parameters were obtained below 6.0 m of sea level, which indicated the chlorides in splashed zone were still effective to providing sufficient chlorides, but very high diffusion coefficient was obtained over 6.0 m of sea level since the penetrated chloride contents had small quantity (Luping and Gulikers 2007).

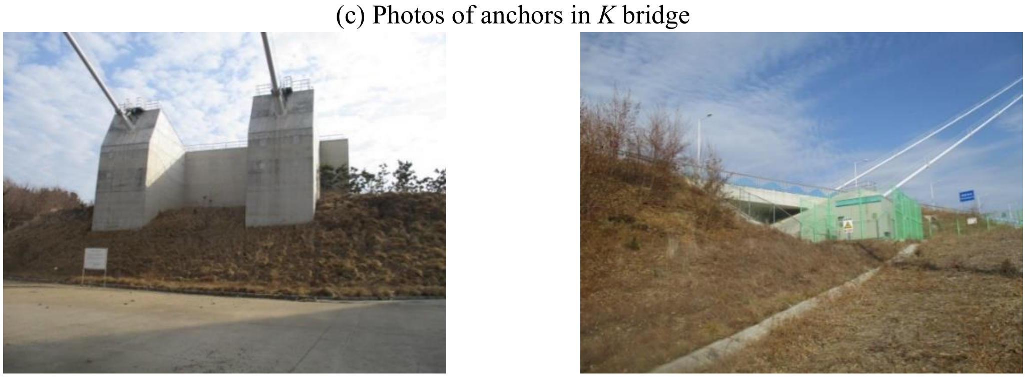


(a) *K* structure



(b) *K* structure

(c) Photos of anchors in *K* bridge



(d) Photos of anchors in *P* bridge

Fig. 2 Typical and perspective view of concrete anchorage

3. Evaluation of durability and engineering properties in cored samples

3.1 Anchorage structure geometry and exposure conditions

3.1.1 Overview of target structures and concrete mix conditions

The target structures are suspension bridges (*K* and *P* bridge) and concrete cores were extracted from tendon room (1st basement) and chamber room (2nd basement) at

(a) Chamber room - *K* bridge

(b) Cable room - *K* bridge

(c) Chamber room - *P* bridge

(d) Cable room - *P* bridge

Fig. 3 Photos of chamber room and anchorage for *K* and *P* bridge

Table 1 Concrete mix proportions for *K* and *P* concrete anchorage

Case	*W/C*	*S/a*	Unit weight: kg/m^3					
			W	LC	SC	S	G	AD
K anchorage	36.9	43.6	161	436	0	749	972	4.36
P anchorage	42.4	45.4	166	0	391	786	948	3.90

* W: Water, LC: Low heat cement, SC: Slag cement, S: Sand, G: Gravel, AD: Admixture

starting and ending anchorages. In the huge bridge structures, main objective of anchorage block is to resist the tensile force with self-weight so that mass concrete has been widely used, which may cause cracks due to hydration heat and cold joint (Huynh and Kim 2017). K bridge is the suspension bridge with one pylon and 1 span of 400 m length. Starting (AN1) and end anchorage (AN2) of K bridge were constructed on the foundation rocks after removing soil layers. *P* bridge is the suspension bridge with two pylons and one span of 850 m. The features and photo of the target structures were shown in Fig. 2 and Fig. 3. Also, the related concrete mix conditions are listed in Table 1, where the design strength was 35 MPa. In particular, low heat cement and slag cement were considered in *K*-bridge and *P*-bridge, respectively. The detailed cement type and properties were listed in Table 2.

3.1.2 Environmental exposure conditions

The tendon room and chamber room in K-bridge anchorage were all located over ground water level and they had been constructed for 3.08 years. On the other hand, only the chamber room in P-bridge anchorage was located below underground water level and constructed for 2.65 years. The water protection for outside rooms was sufficiently performed, however the rooms have been exposed to indirect (air-carrying) chlorides for almost 3 years, which may lead different chloride content in anchorage blocks. The averages temperature and R.H. (Relative Humidity) are plotted in Fig. 4.

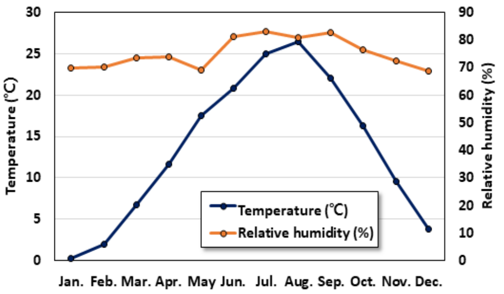
3.2 Evaluation of strength and chloride profiles in concrete cores

3.2.1 Evaluation of strength in concrete core

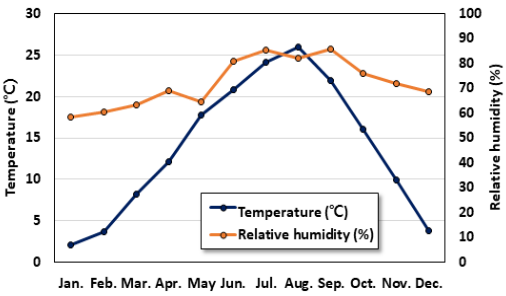
Table 2 Cement properties and replacement ratio of GGBFS

Type	Chemical components (%)								Physical properties	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	LOI	Specific gravity	Blaine (cm^2/g)
Low heat cement	30.06	12.00	2.60	45.20	3.50	0.22	0.80	1.10	2.91	4,050

Type	Chemical components (%)			Physical properties				
	SO_3	MgO	LOI	Slag replacement ratio	Blaine (cm^2/g)	Autoclave expansion (%)	Initial setting (min)	Final setting (hour)
Slag cement	2.17	3.74	1.88	0.5	3,960	0.04	330	6.83



(a) *K* anchorage



(b) *P* anchorage

Fig. 4 Annual temperature and R.H. for the structures

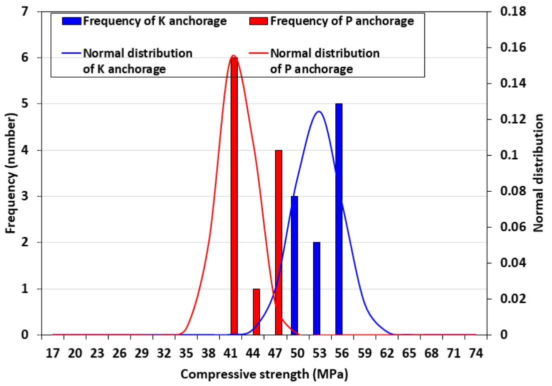


Fig. 5 Compressive strength in extracted core

The compressive strengths in core showed much higher than the design concrete strength (35 MPa) in all the locations since the mix proportions contained low W/C (Water to Cement) ratios around 0.4 and longer than 4 years have passed after construction without special deteriorating agents. 10 cores from *K* bridge and 11 cores from *P* bridge were obtained. The compressive strength distributions are plotted in Fig. 5, where 52.7MPa and 6.4 % and 41.7 MPa and 6.2 % were evaluated for mean and COV (Coefficient of Variation) in *K* and *P* bridge, respectively.

3.2.2 Evaluation of apparent diffusion and surface chloride in concrete cores

Total chloride contents referred to KS F 2422 were evaluated along to 150 mm of cover depth and listed in Table 3 and Table 4 for *K* and *P* anchorage block, respectively. In the results not only sound cores but also unsound cores like cracked and joint area are considered. The core number with mark (*) shows test results from cracked or joint area.

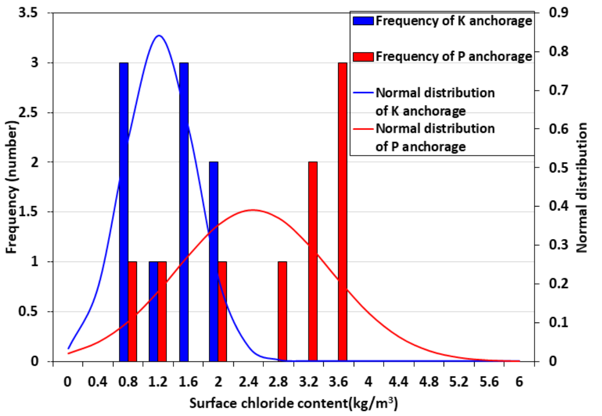
Table 3 Chloride content profile in *K* anchorage

Core number	Location	Average depth (mm)	Total chloride content (kg/m^3)
AN1-S-1	Tendon room	10	1.392
	Declined saddle zone	30	1.044
	Sound condition	50	0.939
AN1-S-2	Tendon room	10	0.611
	Declined saddle zone	30	0.592
	Sound condition	50	0.537
AN1-S-3*	Tendon room	10	1.136
	Declined saddle zone	30	0.767
	Joint condition	50	0.641
AN2-S-1	Tendon room	10	0.548
	Declined saddle zone	30	0.337
	Sound condition	50	0.164
AN2-S-2	Tendon room	10	0.513
	Declined saddle zone	30	0.347
	Sound condition	50	0.281
AN2-S-3*	Tendon room	10	1.394
	Declined saddle zone	30	0.673
	Joint condition	50	0.485
AN2-C-1	Chamber room	10	1.448
	Bottom zone	30	0.958
	Sound condition	50	0.632
AN2-C-2	Chamber room	10	1.679
	Stair zone	30	1.046
	Sound condition	50	0.711
AN2-C-3*	Chamber room	10	1.05
	Bottom zone	30	0.99
	Cracked condition	50	0.919

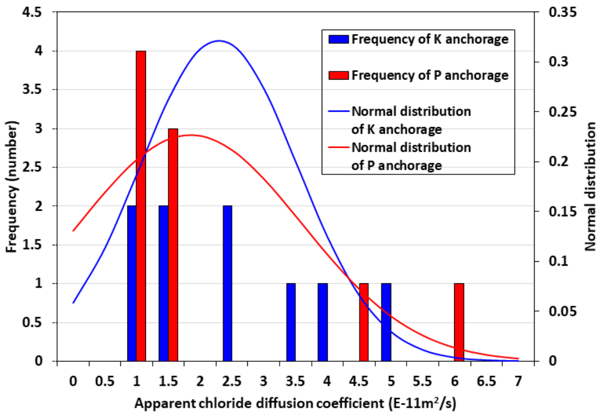
Table 4 Chloride content profile in *P* anchorage

Core number	Location	Average depth (mm)	Total chloride content (kg/m^3)
AN1-S-1	Tendon room	10	0.664
	Declined saddle zone	30	0.567
	Sound condition	50	0.453
AN1-S-2	Tendon room	10	0.755
	Declined saddle zone	30	0.624
	Sound condition	50	0.475
AN1-S-3*	Tendon room	10	1.533
	Declined saddle zone	30	0.649
	joint condition	50	0.503
AN1-C-1	Chamber room	10	2.770
	Declined saddle zone	30	0.998
	Sound condition	50	0.574
AN1-C-2	Chamber room	10	3.036
	Declined zone	30	0.911
	Sound condition	50	0.673
AN1-C-3	Chamber room	10	2.737
	Declined zone	30	0.709
	Sound condition	50	0.573
AN2-C-1	Chamber room	10	2.626
	Declined zone	30	1.821
	Sound condition	50	0.892
AN2-C-2	Chamber room	10	2.507
	Declined zone	30	1.710
	Sound condition	50	0.977
AN2-C-3*	Chamber room	10	2.385
	Stair zone	30	1.152
	Cracked condition	50	0.913

*: Test results from unsound concrete (cracked or joint area)



(a) Surface chloride content distribution-*K* and *P* anchorage

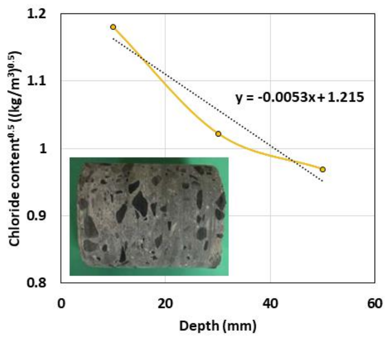


(b) Apparent chloride diffusion coefficient distribution-*K* and *P* anchorage

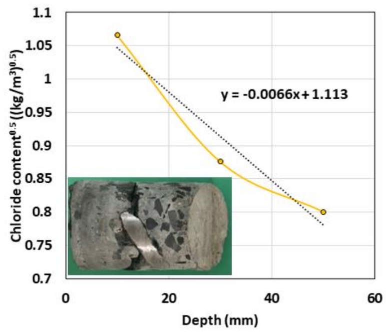
Fig. 6 Histogram of the derived results

The apparent diffusion coefficients and surface chloride contents from Table 3 and Table 4 are summarized in Fig. 6. The representative plots of chloride profiles and the related core photos are shown in Fig. 7 and Fig. 8.

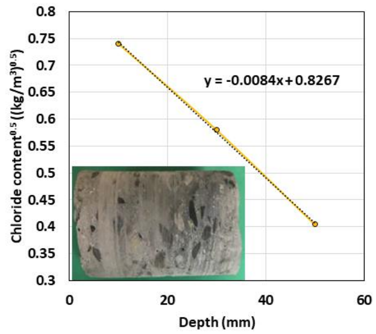
K-anchorage had 1.21 kg/m^3 of average surface chloride content with 41.5% of COV while 2.29 E-11 m^2/s and 57.5% were obtained for apparent diffusion coefficient. The range of surface chloride content is 0.564~1.941 kg/m^3 which is much lower than the sea water (18.0 kg/m^3~23.0 kg/m^3) and atmospheric zone (3.0 kg/m^3~8.0 kg/m^3) (Kwon 2015) since the measured range is only for the results during construction stage around 3 years. Relatively high range was measured in cracked core in chamber room (AN2-C-3*). P-anchorage showed 2.46 kg/m^3 of average surface chloride content with 43.9% of COV. In the apparent diffusion coefficient, very low average diffusion coefficient of 1.84 E-11 m^2/s and high COV of 101.2% were measured, but diffusion coefficient of 2 cases are relatively high. The entire ranges of surface chloride content were 0.728~3.474 kg/m^3 which was low level, however relatively high level was evaluated in chamber room with 3.089~3.474 kg/m^3 range since the chamber room located in 2nd basement line was constructed firstly and subjected to chloride-atmospheric condition longer. The diffusion coefficient from regression analysis in atmospheric condition shows higher value despite of using GGBFS concrete (Lee *et al.* 2015, Kwon 2015). In the case



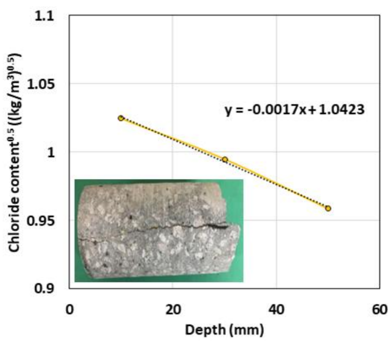
(a) AN1-S-1



(b) AN1-S-3*



(c) AN2-S-1

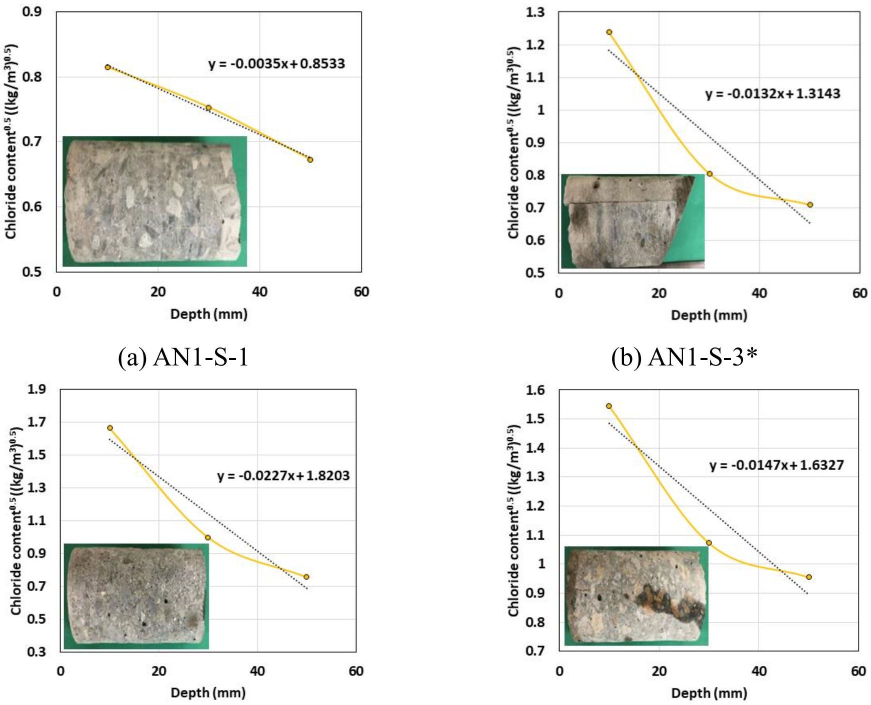


(d) AN2-C-3*

Fig. 7 Representative chloride profiles in the extracted cores for K bridge

with high surface chloride content, 0.61~0.65 E-11 m^2/s of diffusion coefficient was derived. Particularly construction joint area (AN1-S-3*) has higher surface chlorides.

As shown in Fig. 4, low surface chloride content and high diffusion coefficient were evaluated in concrete with low heat cement while high surface chlorides and low diffusion coefficient were done in that with slag cement,



(a) AN1-S-1 (b) AN1-S-3*

(c) AN1-C-1 (d) AN2-C-3*

Fig. 8 Representative chloride profiles in the extracted cores for P bridge

which still showed the effectiveness of GGBFS for resistance to chloride intrusion at atmospheric area as well as submerged area (Park *et al.* 2018, Kouloumbi *et al.* 1994). For all the two structures, the critical problems due to chloride attack was not reported since tendon room and chamber room are covered with wall after final construction. Regardless of insignificant chloride amount in the two rooms, weak areas containing cracks and construction joint showed relatively higher chloride ingress so that simple repairing technique for the areas can be effective for maintenance during construction stage.

4. Conclusions

In this study, chloride behavior in concrete cores extracted from 2 bridge anchorage blocks which had construction period around 3 years and located near to sea shore. The conclusions on this work are as follows.

- The two bridge structures had relative long construction period around 3 years so that the induced chloride content from outside caused different chloride behavior even in the closed chamber and tendon rooms. The cores extracted from anchorage showed different chloride profiles regardless of the used concrete mix proportions. The design compressive was satisfied through core test.
- With construction period around 3 years, the firstly constructed chamber room contained relatively higher surface chloride. The effect of induced chloride ions in the rooms was insignificant since the rooms (tendon and chamber) had enough cover depth of 150 mm and additional intrusion of chlorides was not allowed after final construction.
- Low heat cement and slag cement were used for K and P bridge anchorage, respectively, which considered resistance to cracking and resistance to chloride attack. The field assessment from the relatively short period around 3 years have high variations of measurement. K bridge had low surface chloride contents and relatively high diffusion coefficient while P bridge has the opposite trends.
- The main role of anchorage block is enhancement of self-weight for resisting tensile stress in cables. The induced chloride ions in the tendon room and chamber room are very limited during construction stage, but repairs for cracks and construction joint are effective to maintenance of anchorage structure under construction.

Acknowledgments

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