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Effects of loading conditions and cold joint on service life against chloride ingress

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Abstract. RC (Reinforced Concrete) members are always subjected to loading conditions and have construction joints when constructed on a big scale. Service life for RC structure exposed to chloride attack is usually estimated through chloride diffusion test in sound concrete, however the test is performed without consideration of effect of loading and joint. In the present work, chloride diffusion coefficient is measured in concrete cured for 1 year. In order to evaluate the effect of applied load, cold joint, and mineral admixtures, OPC (Ordinary Portland Cement) and 40%-replaced GGBFS (Ground Granulated Blast Furnace Slag) concrete are prepared. The diffusion test is performed under loading conditions for concrete containing cold joint. Investigating the previous test results for 91 days-cured condition and the present work, changing diffusion coefficients with applied stress are normalized considering material type and cold joint. For evaluation of service life in RC continuous beam with 2 spans, non-linear analytical model is adopted, and service life in each location is evaluated considering the effects of applied stress, cold joint, and GGBFS. From the work, varying service life is simulated under various loading conditions, and the reduced results due to cold joint and tensile zone are quantitatively evaluated. The effect of various conditions on diffusion can provide more quantitative evaluation of chloride behavior and the related service life.

Keywords: service life; chloride ingress; stress; cold joint; GGBFS

1. Introduction

Steel corrosion due to chloride ingress in RC (Reinforced Concrete) structure has been both engineering and social problem. Even if RC structures with one mix proportions are exposed to the constant corrosive condition, the service life varies with locations due to heterogeneous characteristics of concrete. Concrete members with a large dimension usually have construction joint for reasonable placing and crack control, however cold joint happens due to poor quality control of concrete treatment and delay of concrete placing (JSCE 2000, ACI 224.3R-95 2001). Cold joint causes durability problems like spalling of concrete cover and steel corrosion due to carbonation and chloride attack (Kwon and Na 2011, Abe 1999, Yang *et al.* 2017).

The conditions of concrete are not stress-free since RC structures are always subjected to loadings whether the stress is big or small. The effects of loading conditions on mass transport have been studied for a long time (Choi *et al.* 2015, Kim *et al.* 2009, Yoo and Kwon 2016, Ye *et al.* 2015). The region under compressive stress show a reduced permeability and diffusivity in the initial loading condition since effective pore channel for mass transport decreases with pore condensation, however it increases with loading over 50-60% of peak load due to micro-cracking development (Hoseini *et al.* 2009, Banthia *et al.* 2005). On the contrary, tensile region under loading shows increasing mass transport from the initial loading condition (Yoo and Kwon 2016, Oh and Kwon 2017). If concrete member has cold joint section, it permits more intrusion of harmful ions regardless of tensile or compressive conditions. The area with cold joint is not perfect due to insufficient of material integrity and interlocking of aggregates.

Concrete is durable and cost-benefit construction material, however it has pores. The pores in concrete allows a good thermal insulation performance and pore pressure balance, but they also act as paths of intrusion of mass transport (Ishida and Maekawa 2003, Ishida *et al.* 2007). The intruded chlorides are dissociated into bound and free chloride ions, and the free chloride ions accelerate corrosion initiation through breaking passive layer on steel (Arya and Newmann 1990, Song and Kwon 2009, Broomfield 1997). The durability problems with corrosion due to chloride ingress start with serviceability problems like cracking and rust staining, but they propagate to structural safety problem like reduction of reinforcement area and spalling of concrete cover (Broomfield 1997, RILEM 1994).

Even if exterior condition has constant, diffusion and flux in concrete are changed with loading conditions and cold joint, which leads varying service life. In the present work, the changes in chloride diffusion in concrete

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Table 1 Mix proportions for the test

<table>
<tr><th rowspan="3">Case</th><th rowspan="3">G_{max} (mm)</th><th rowspan="3">Slump (mm)</th><th rowspan="3">S/a (%)</th><th rowspan="3">W/B</th><th rowspan="3">Air (%)</th><th colspan="5">Unit weight: kg/m^3</th></tr>
<tr><th rowspan="2">W</th><th colspan="2">Binder</th><th rowspan="2">S</th><th rowspan="2">G</th></tr>
<tr><th>C</th><th>GGBFS</th></tr>
<tr><td>OPC</td><td rowspan="2">25</td><td rowspan="2">180</td><td rowspan="2">41.4</td><td rowspan="2">0.6</td><td rowspan="2">4.5</td><td rowspan="2">180</td><td>300</td><td>-</td><td rowspan="2">735</td><td>1040</td></tr>
<tr><td>GGBFS</td><td>180</td><td>120</td><td>1020</td></tr>
</table>

W/B: Water to binder ratio, S/a: fine aggregate ratio, W: Water, C: Cement, S: Sand, G: Gravel

containing OPC (Ordinary Portland Cement) and GGBFS (Ground Granulated Blast Furnace Slag) are evaluated considering various effects like cold joint, mineral admixture, and loading conditions. Based on the previous and the performed test results in the work, simple diffusion parameters are obtained for loading conditions, cold joint, and GGBFS. Assuming continuous RC beam with 16.0 m of span, service life in one continuous beam is evaluated considering the effects. The crack effect on diffusion is an important parameter to variation of service life but it is not considered since the changes in diffusion are handled before the condition of cracking stage in the present work. The varying service life with the various effects on diffusion provides valuable information on maintenance plan for RC structures with cold joint under loadings.

2. Changing diffusion in cold joint concrete under loading conditions

2.1 Diffusion coefficient under various conditions

In the previous studies, chloride diffusion coefficients in the concrete cured for 91 days were evaluated considering cold joint and loading levels (Yoo and Kwon 2016, Oh and Kwon 2017). In the work, concrete cured for 365 days are prepared and the diffusion coefficients are evaluated with the same procedures and materials as the previous studies (Yoo and Kwon 2016, Oh and Kwon 2017, Mun 2016). The mix proportions for OPC and GGBFS concrete are listed in Table 1.

The cylindrical samples with diameter 100 mm and height 200 mm for tensile loading and rectangular parallelepiped specimens with 100 mm×100 mm×50 mm for compressive loading are prepared, respectively. In order to induce cold joint, concrete is placed to a half and cure for 24 hours, then the rest half is filled with the same mix proportions and cured for 24 hours in the room condition. After cast removal, they are cured for 1 year. For the same test procedures as the previous tests (Choi *et al.* 2015, Yoo and Kwon 2016, Oh and Kwon 2017), the cold joint section is prepared without surface treatment. After measuring the maximum tensile and compressive loads, 30% and 60% of loading levels are induced to the concrete samples confined with steel frame. After designated loading level, the steel frame is fixed and accelerated diffusion coefficient is measured based on Tang's method (Tang and Nilsson 1992). The test procedure is summarized in Table 2 with the related photos.

Table 2 Test procedures for loading and diffusion coefficient measurement

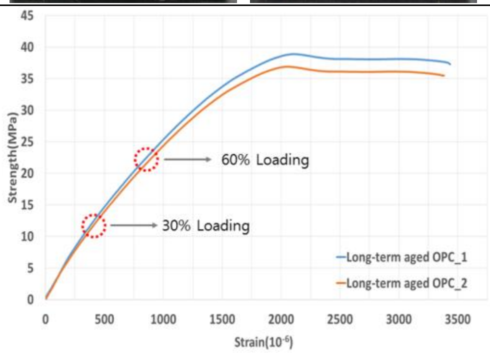
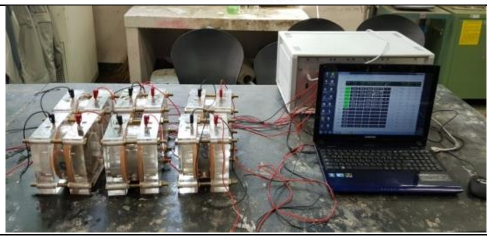
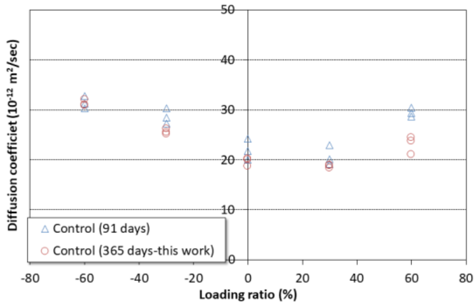
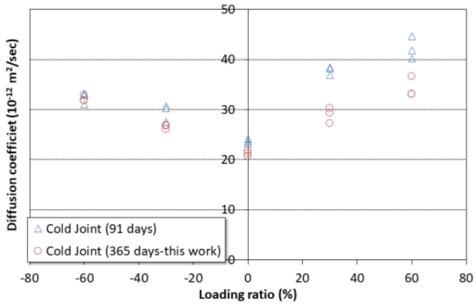
<table>
<tr><th>Order</th><th>Step</th><th>Related photos</th></tr>
<tr><td>1</td><td>Side coating the samples with epoxy</td><td rowspan="2"></td></tr>
<tr><td>2</td><td>Measurement of peak loading for tensile and compressive strength</td></tr>
<tr><td>3</td><td>Installation of steel frame and gauges on the concrete and frame</td><td rowspan="3">
</td></tr>
<tr><td>4</td><td>Loading level control and confinement (30% and 60% level)</td></tr>
<tr><td>5</td><td>Measurement of strain for steel frame</td></tr>
<tr><td>6</td><td>RCPT test for 6 hours
- Anode: 0.3 M NaOH
- Cathode: 0.5 M NaCl
- Applied voltage: 30 V
- Test duration: 8 hours</td><td></td></tr>
</table>

Table 3 Quantification of parameters for diffusion coefficient with loadings

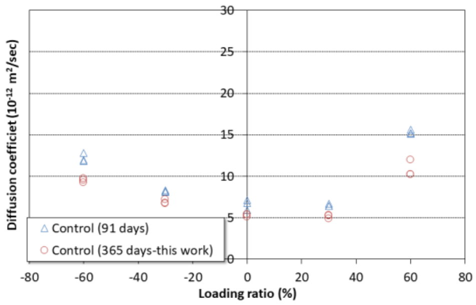
Loading conditions	Mixture		Parameter y: changing ratio, x: loading ratio to failure	R^2
Tensile	OPC	N	$y = -0.0088x + 1$	0.89
		CJ	$y = -0.0076x + 1$	0.91
	GGBFS	N	$y = -0.0127x + 1$	0.93
		CJ	$y = -0.0132x + 1$	0.92
Compressive	OPC	N	$y = 0.0002x^2 - 0.0078x + 1$	0.77
		CJ	$y = 0.0125x + 1$	0.85
	GGBFS	N	$y = 0.0007x^2 - 0.0213x + 1$	0.96
		CJ	$y = 0.021x + 1$	0.91



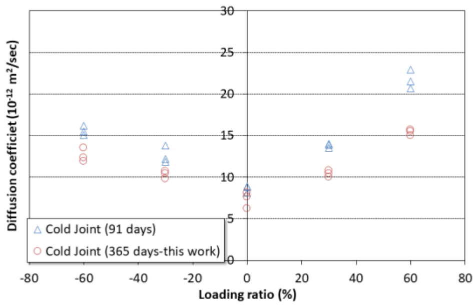
(a) OPC without cold joint



(b) OPC with cold joint



(c) GGBFS without cold joint



(d) GGBFS with cold joint

Fig. 1 Effects of loading and cold joint on diffusion coefficient

2.2 Parameter derivation considering loading, cold joint, and GGBFS

The parameters for tensile and compressive loading conditions are summarized in Table 3, where the effects of loading vary with the used material (OPC and GGBFS) and presence of cold joints. The changing tendencies of diffusion with loading conditions are shown in Fig. 1.

As shown in Fig. 1, linear increases in chloride diffusion are evaluated on tensile region regardless of ages (91 and 365 days) and material types (OPC and GGBFS). In the compressive region, non-linear relation which shows a reduced diffusion around 30% of loading then increasing diffusion afterwards is evaluated in normal condition, however linear increasing diffusion from initial loading is observed in cold joint condition. The test results from the present work (365 days) are consistent with the previous results at the age of 91 days (Choi *et al.* 2015, Yoo and Kwon 2016). The determinant coefficients (R^2) are all greater than 0.84. The decreasing ratios with extended curing period are 89.3% for OPC without cold joint, 87.2% for OPC with cold joint, 78.3% for GGBFS without cold joint, and 78.8% for GGBFS with cold joint, respectively. The reduced diffusion coefficient and the enhanced chloride resistance through GGBFS replacement have been reported in many literatures (Yoo and Kwon 2016, Song and Kwon 2009, Thomas and Bamforth 1999, Erdem and Kirca 2008). The flowchart for service life evaluation considering various effects is shown in Fig. 2.

3. Service life simulation for continuous RC beam under chloride attack

3.1 Diffusion coefficient under various conditions

For service life simulation, continuous-2 span RC girder is considered. Rectangular section with 500 mm×700 mm is used with 30 MPa for concrete strength and 400 MPa for steel. The structural design parameters are listed in Table 4 with section geometry.

3.2 Analytical approach and calculation results

In order to calculate the strains and stresses at each layer of concrete and steel reinforcing bars for a given external moment, a non-linear analytical approach developed by Yang and Kang (Yang and Kang 2011) was modified, as shown in Fig. 2. In the nonlinear analysis of the beam governed by flexure, the following assumptions are considered, 1) Bernoulli's principle implying that the normal strain in the concrete and the reinforcing bars at various points across a section is proportional to the distance from the neutral axis, 2) strain compatibility condition indicating that the strain in reinforcing bars is equal to the strain in concrete at the same level, 3) flexural cracks occur whenever the applied tensile stress exceeds the modulus of rupture of concrete, and 4) the tensile capacity of concrete after cracking is ignored. Moreover, compressive stresses of unconfined concretes at various points are calculated using the material constitutive

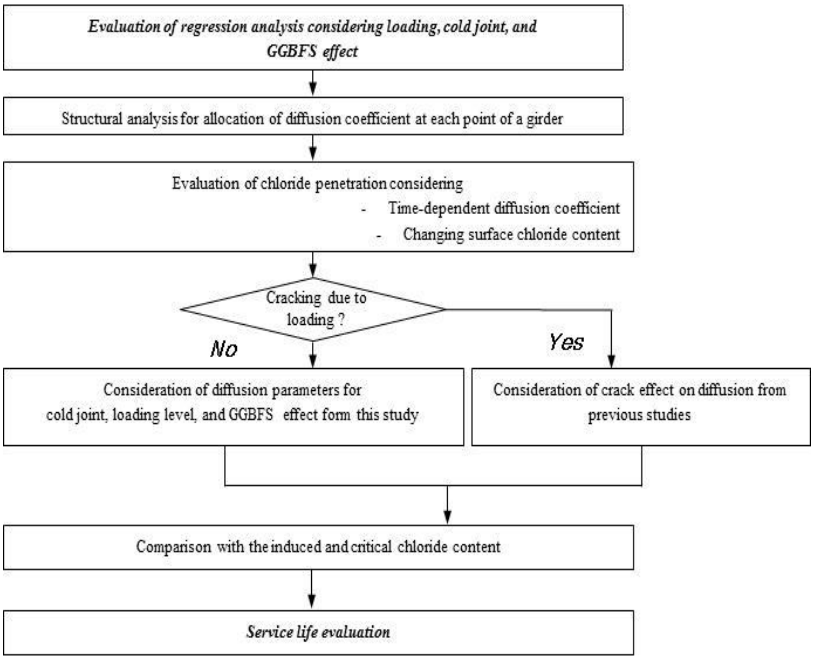


Fig. 2 Flowchart for service life evaluation

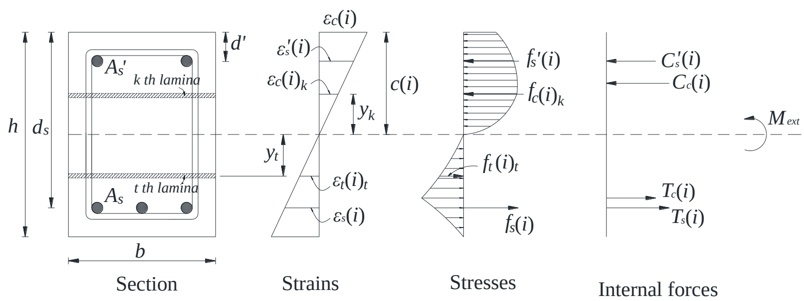
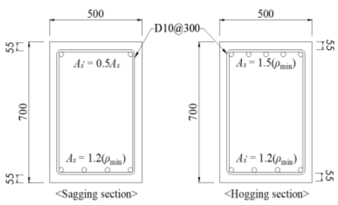


Fig. 3 Generalized distribution of strains and stresses along the beam section for a given external moment

Table 4 Structural design parameters and section geometry of continpus-2 span RC girder

Parameters	Value	Section geometry
F_{ck}	30.0 MPa	
f_y	400.0 MPa	
$(A_{s'})_{sag.}$	567.9 mm^2	
$(A_s)_{sag.}$	1,135.8 mm^2	
$(A_{s'})_{hog.}$	1,135.8 mm^2	
$(A_s)_{hog.}$	1,703.6 mm^2	
d'	510.0 mm	
d	649.0 mm	
E_c	27,537.0 MPa	
$\rho_{\min}$	0.0035	

The analysis conditions are determined as case 1- Service loading and case 2-cracking moment loading.

equation model proposed by Yang *et al*. (2014). Tensile stresses of concrete until cracking are calculated using the Hook's law. The steel constitutive relations are regarded as a perfect elasto-plasticity material.

For a given external moment (M_{ext}), the beam section is subdivided into small element to formulate the section lamina method. The depth $[c(i)]$ of neutral axis and concrete strains $[\varepsilon_c(i)]$ at the extreme fibers for a given M_{ext} are determined from the equilibrium conditions of internal forces and equivalent condition of internal and external moments, respectively, as presented in Fig. 3. For an assumed $\varepsilon_c(i)$, $c(i)$ can be readily obtained through a numerical approach such bi-section method. Once $\varepsilon_c(i)$ and $c(i)$ are determined for a given M_{ext}, the strains and stresses at each layer of concrete and steel reinforcing bars can be calculated from the considered Bernoulli's principle and each material constitutive equation. The algorithm presented in Fig. 4 can be easily realized by a computer coding. The calculation results are plotted in Fig. 5. The location of construction joint is assumed at 3.0 m from left and right support where the maximum moment (positive) is applied. The induced compressive and tensile stress increase from 2.71 MPa to 3.34 MPa and -2.53 MPa to -3.81 MPa, respectively when applied load increases from service load (14.2 kN/m) to cracking load (17.6 kN/m).

3.3 Exposure conditions

In order to simulate service life for the structure, determination of durability design parameters is required. Life 365 program is adopted for solving Fick's 2nd Law.

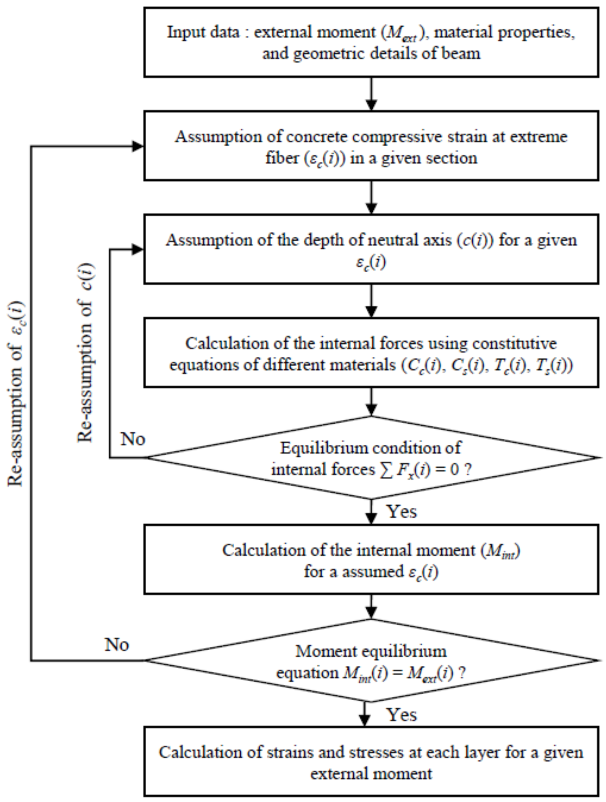
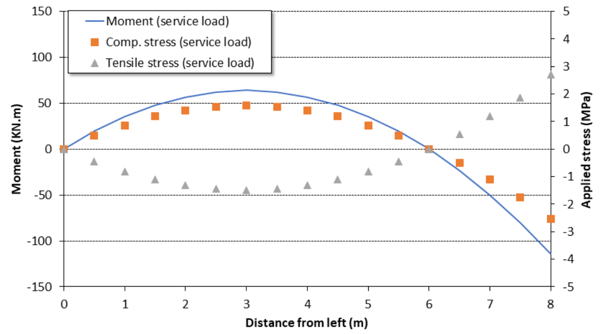
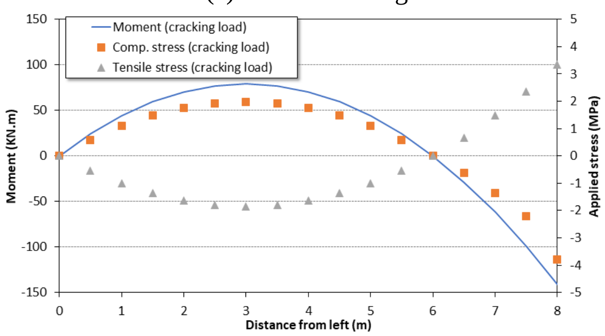


Fig. 4 Non-linear analytical approach for determining stresses and strains of beam section



(a) Service loading



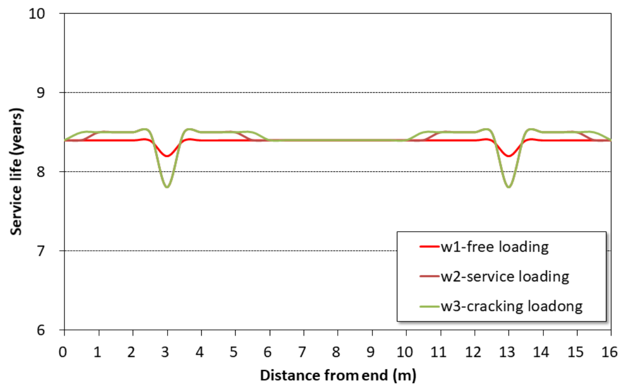
(b) Cracking loading

Fig. 5 Stress variation with loading conditions

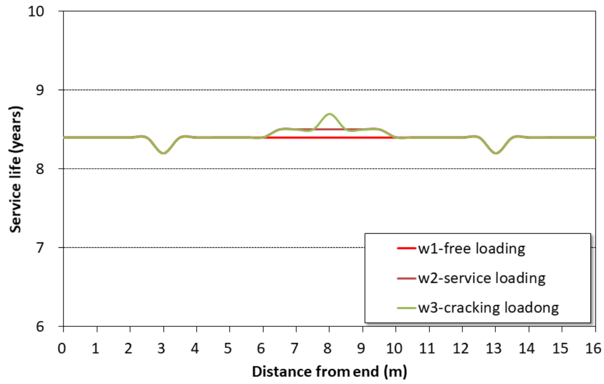
Surface and critical chloride content are assumed as 5.0 kg/m^3 and 1.2 kg/m^3 referred to Concrete Specification (JSCE 2007). The built-up period for outer chloride saturation is assumed as 10 years (Thomas and Bentz 2002).

Table 5 Analysis conditions for service life prediction

Cover depth (mm)	Surface chloride content (kg/m^3)	Built up period (years)	C_{cr} (kg/m^3)	m	Monthly temperature (℃)
55.0	6.0	10	1.2	0.2 (OPC) 0.428 (GGBFS)	-6.7-20.5



(a) Top surface



(b) Bottom surface

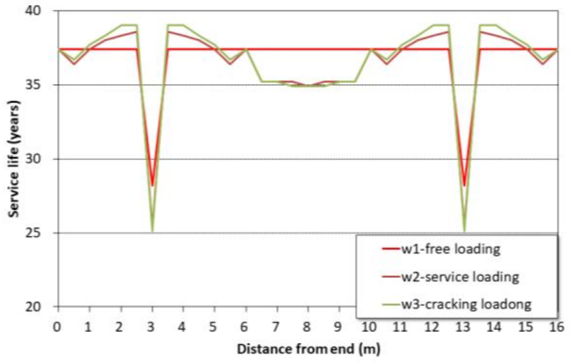
Fig. 6 Service life variation in OPC concrete

Time effect on diffusion is very critical to service life prediction but the results are dependent on long term exposure test and field investigation. Many researches have been performed for quantitative evaluation of time effect on diffusion (Thomas and Bentz 2002, Tang and Joost 2007, Poulsen 1993, Kwon *et al.* 2009, Lee *et al.* 2017, Tsao *et al.* 2015). In the work, m (time exponent) for OPC and GGBFS are assumed as 0.2 and 0.428 based on the previous researches (Thomas and Bamforth 1999, Thomas and Bentz 2002). The governing equations for chloride behavior with Fick's 2nd Law and time-dependent diffusion coefficient are listed in Eq. (1) and Eq. (2).

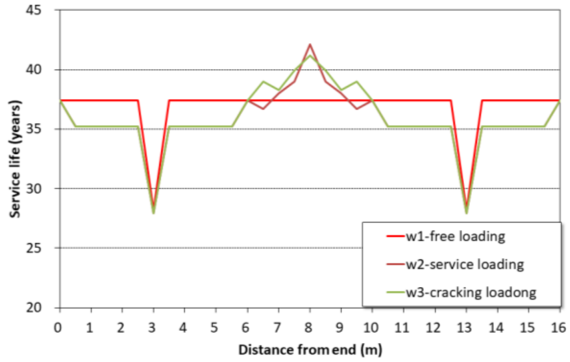
$$C(x,t) = C_S\left\{1 - erf\left(\frac{x}{2\sqrt{D(t)t}}\right)\right\} \tag{1}$$

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m \tag{2}$$

where C_S is surface chloride content and erf is error function. x and t are cover depth and exposure period. D_{ref} is the diffusion coefficient at the reference time (t_{ref}). The analysis conditions for service life are listed in Table 5.

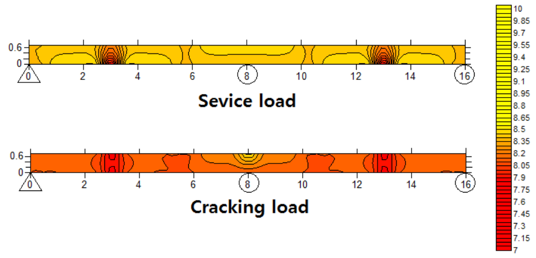


(a) Top surface

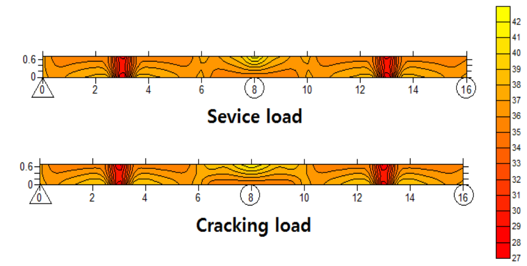


(b) Bottom surface

Fig. 7 Service life variation in GGBFS concrete



(a) OPC concrete



(b) GGBFS concrete

Fig. 8 Service life contour with increasing loading considering material type

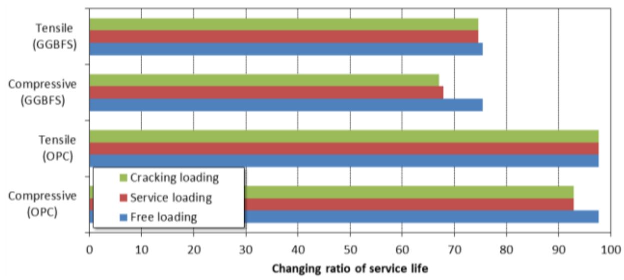


Fig. 9 Changing ratios of service life in cold joint concrete with loading

4. Service life and investigation of the effects

4.1 Service life simulation

In the section, service life in 2 span continuous-girder is evaluated considering effects of loading and cold joint. The cold joint is prepared at 3.0 m from the each support since the applied shear force is 0.0. Two loading cases of service and cracking loading are considered. In order to compare the effect of GGBFS in service life, concrete with OPC and 40% replacement of GGBFS are evaluated, respectively. The results are shown in Fig. 6 for OPC and Fig. 7 for GGBFS concrete, respectively. The contours of the results are shown in Fig. 8.

In the tensile zone, service life decreases with enlarged diffusion coefficient. In the compressive zone, service life slightly increases due to reduced diffusion coefficient since the applied stress is calculated through elastic analysis.

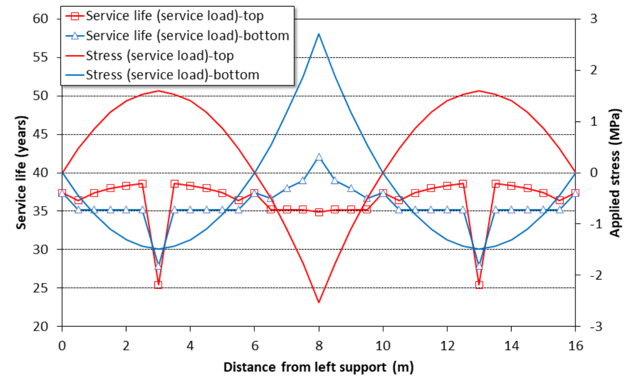
4.2 Effects of cold joint, loading conditions, and GGBFS on Service life

4.2.1 Material types and cold joint

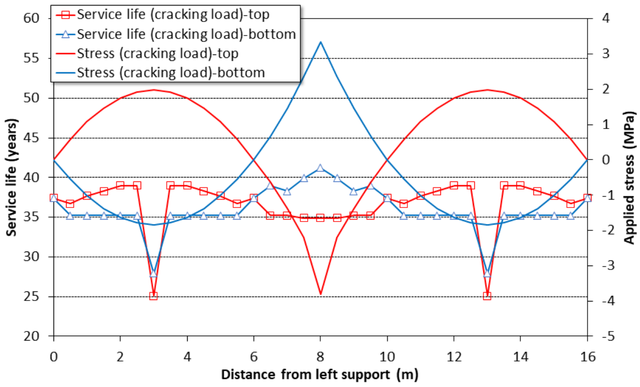
The range of service life is evaluated to be 7.8~8.7 years in OPC concrete and 25.1-42.1 years in GGBFS concrete, respectively. Many researches have reported the enhanced resistance to chloride ingress in GGBFS replaced concrete through reduction of porosity due to enlarged CSH formation (Song and Kwon 2009, Tang and Nilsson 1992), chloride binding effect (Ishida *et al*. 2007, Arya and Newmann 1990), and reduction of chloride diffusion (Thomas and Bamforth 1999, Thomas and Bentz 2002, Jang *et al*. 2017). In the service life analysis in equation (2), time-parameter in GGBFS concrete is considered as 0.428, which directly delays the chloride penetration significantly. With increasing loading in compressive zone, service life in cold joint area decreases from 8.4 years to 7.8 years in OPC while it decreases from 37.4 years to 25.1 years in GGBFS concrete. The significant reduction in service life in cold joint is also evaluated in tensile zone, which shows a drop from 37.4 years to 27.9 years. Despite of GGBFS replacement, a special attention of reduction in service life should be paid in cold joint area. The changing ratios of service life to free condition are plotted in Fig. 9, which shows 74.6-75.4% of decreasing service life in cold joint clearly.

4.2.2 Loading effect and cold joint

The diffusion coefficients are much dependent on the applied loading. In the tensile zone, decreasing service life due to linear increase in diffusion coefficient with applied stress is evaluated, however more complicated trend of service life is observed in the compressive zone with cold joint. COV (Coefficient of variation) of service life in OPC with loading conditions are below 2.0%, which is a very small variation, so that those in GGBFS concrete are



(a) Service load condition



(b) Cracking load condition

Fig. 10 Service life and applied stress in GGBFS concrete

investigated with applied moment and stress. The COV level in GGBFS is evaluated to be 6.1-9.0% and the service life with applied stress is shown in Fig. 10. The shape of applied stress is similar as the service life in the concrete without cold joint. The changing ratios of service life at the location where maximum and minimum stress are induced are plotted in Fig. 11.

As shown in Fig. 11, service life changes with 93.3-105.1% compared to free condition without cold joint. Considering cold joint effect, service life decreases to 67.1% at the location of 3.0 m where maximum positive moment is applied. In the bottom surface, 3.0 m (maximum negative moment) and 8.0 m (maximum positive moment) location show 94.1% and 112.6% of changing ratio, respectively. Regarding cold joint effect, 74.6% of decreasing ratio of service life is evaluated. The effect of loading and cold joint are evaluated to be 5.1-12.6% and 25.4-32.9% of service life, respectively.

5. Conclusions

In the work, the chloride behavior before cracking stage is evaluated considering cold joint and loading levels, and the changes in service life under various conditions such as loading, cold joint, and GGBFS properties are obtained. If crack occurs with increasing loading level, the diffusion significantly increases with crack width and depth, however the diffusion before cracking load is applied is employed for the work. The proposed technique can be applied to the

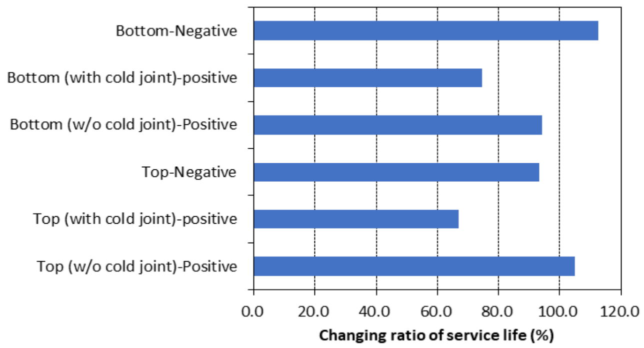


Fig. 11 Changing ratios of service life with maximum and minimum stress

service life estimation from free stress condition to the loading condition causing allowable crack width if crack effect on diffusion is continuously considered. The conclusions on effects of loading conditions and cold joint on service life exposed to chloride ingress are as follows.

- Diffusion coefficients in cold joint concrete cured for 1 year are measured under loading conditions. In the tensile region, increasing diffusion trend is observed regardless of cold joint presence. A slight reduction of diffusion to 30~40% of loading levels and enlarged diffusion over 50% of loading levels is evaluated in the compressive region. The results from 1 year-cured concrete are consistent with the previous test results from 91 days-cured concrete, and show overall reduction of diffusion due to time effect. The changing diffusion ratios from 91 days to 1 year of curing period, 89.3% (OPC without cold joint), 87.2% (OPC with cold joint), 78.3% (GGBFS without cold joint), and 78.8% (GGBFS with cold joint) are evaluated, respectively.
- Through normalization of diffusion coefficient with loading conditions, cold joint, and mineral admixture effect, service life in RC continuous beam is simulated. In order to consider the applied stress, non-linear analysis is performed for 16.0 m of RC girder with 2 span-three supports. When increasing loading to cracking moment, service life in cold joint area decreases from 8.4 years to 7.8 years in OPC while it decreases from 37.4 years to 25.1 years in GGBFS concrete in compressive zone. The significant reduction in service life in cold joint is also evaluated in tensile zone, which shows a drop to 74.6~75.4%. The reduction of service life with the effect of cold joint and tensile stress should be considered in maintenance plan even if GGBFS which shows excellent resistance to chloride ingress is used for the structures.

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