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New experiment recipe for chloride penetration in concrete under water pressure

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Abstract. Chloride penetration is considered as a most crucial factor for the determination of the service life of concrete. A lot of experimental tools for the chloride penetration into concrete have been developed, however, the mechanism was based on only diffusion, although permeability is also main driving forces for the chloride penetration. Permeation reacts on submerged concrete impacting for short to long term durability while capillary suction occurs on only dried concrete for very early time. Furthermore, hydrostatic pressure increases in proportional to measured depth from the surface of water because of the increasing weight of water exerting downward force from above. It is thought, therefore, that the water pressure has a great influence on the chloride penetration and thereby on the service life of marine concrete.In this study, new experiment is designed to examine the effect of water pressure on chloride penetration in concrete quantitatively. As an experiment result, pressure leaded a quick chlorides penetration by a certain depth, while diffusion induced chlorides to penetrate inward slowly. Therefore, it was concluded that chloride should penetrates significantly by water pressure and the phenomena should be accelerated for concrete exposed to deep sea. The research is expected as a framework to define the service life of submerged concrete with water pressure and compute water permeability coefficient of cementitious materials.

Keywords: chloride penetration; permeation; water pressure; service life; chloride profile

1. Introduction

Chloride penetration is a main cause of deterioration of marine concrete and considered as most deterministic factor for the service life prediction of the structures(Haque and Kayyali 1995, Glass and Buenfeld 2000, Liang *et al.* 2002, Pritzl *et al*. 2014, Yoon 2014a). The estimated cost of repair or rehabilitation and replacement of deteriorated concrete structures will be huge in the coming decades and, therefore, a clear understanding of the phenomenon is of crucial importance. The current state of knowledge on the subject was eminently presented in a lot of papers, however, the mechanism was dealt with only diffusion(Castellote and Andrade 2006, Baroghel-Bouny *et al*.

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Table 1 Experiment method of chloride penetration (Stanish *et al*. 1997)

	Accelerating testing			Natural testing
	RCPT	Dhir's test	RCM	Solution Immersion
Code	ASTM C 1202	-	NT Build 492	AASHTO T356
Condition	Steady state	Steady state	Non-steady state	Non-steady state
Data	Total passed charge	Diffusion Index, (Diffusivity)	Migration Coeff. (Diffusivity)	Chloride Profile,
Testing time	6 hours.	6 hours	a day	At least a year
Thickness of samples	50 mm	50 mm	50 mm	unlimited
Reliability	Poor	Normal	Good	Excellent

Table 2 Transport mechanisms for chloride penetration in concrete (Yoon 2014b)

	Capillary suction	Diffusion	Permeation
Driving force	Surface tension	Concentration difference	Pressure difference
Governing law	Laplace law	Fick's 1st and 2nd law	Darcy's law
Equation	$F = -\frac{k_p}{\eta}\frac{dp_w}{dx}$ where, K_p: moisture permeability coefficient $\frac{dp_w}{dx}$: gradient of pore water pressure p_w η: viscosity of water	$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right)$ where, D: diffusion coefficient c: concentration	$Q = K A i$ where, Q: water charge K: permeability coefficient A: cross section area i: pressure gradient
Material Coeff.	k_p	D	K
Governed portion	Tidal zone	Atmospheric zone Tidal zone Submerged zone	Submerged zone
Impact to life	Very short term	Middle to long term	Short to Long term
Experiment method	ISAT	NT Build 492 AASHTO T259 ASTM 1202 Dhir's test, etc.	This study

2007, Karkar 2011, Morga and Marano 2014, Park and Choi 2012). Some of researches suggested surface resistivity in order to save time and experiment labor for an indirect method of chloride penetration (Ghosh and Tran 2014, Yoon *et al*. 2015)

Meanwhile, the chloride penetration in concrete is very slow process, although the ability of chloride ions to penetrate the concrete must be known for design as well as quality control process. It cannot be determined directly in a timeframe that would be useful as a quality control measure. In order to assess chloride penetration, a test method that accelerates the process is needed, to allow the determination of penetration values in a reasonable time. Therefore, a lot of experimental tools for the chloride penetration in concrete have been developed. However, the mechanism is based on only diffusion, although permeability is also main driving forces for the chloride penetration as well (Table 1).

Chloride ions permeability is one of the intrinsic properties of concrete to be assessed independently, so as to know the long term durability and serviceability of concrete structures under marine environment. The fluid transport in aqueous into concrete takes place through pore spaces in the cement paste. A variety of different physical and chemical mechanisms may govern transport of the media into concrete, depending on the substance flowing and its local concretization, the environmental conditions, the micro-structural properties of concrete, the pore radius or width of micro-cracks, the degree of saturation of the pore system and the temperature (Najigivi *et al*. 2013). Those transport mechanisms can be divided into three driving forces; capillary suction, diffusion, and permeation, as shown in Table 2 (RILEM 1997). Since the transport parameters are influenced by micro-structural properties of cementitious materials, those parameters have interrelationship (Halamickova *et al*. 1995, Basheer *et al*. 2001).

The severity of marine exposure varies considerably depending on the nature of the marine environment in which a structure is located. Accurate estimation of concrete durability need to take cognizance of the severity of exposure since durability performance depends on the material properties of concrete and environmental conditions that the material must withstand. Permeation reacts on submerged concrete impacting for short to long term durability while capillary suction occurs on only dried concrete for very early time. Furthermore, hydrostatic pressure increases in proportional to measured depth from the surface of water because of the increasing weight of

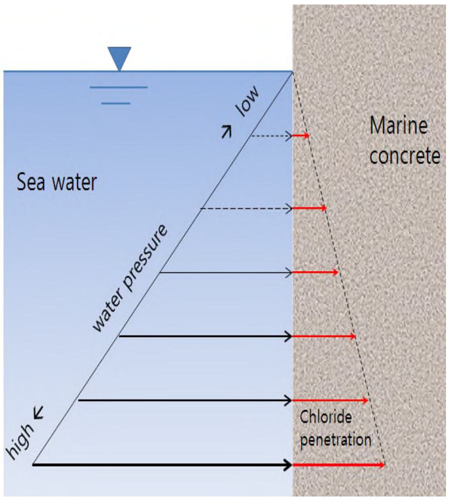


Fig. 1 Water pressure with depth from sea level

Table 3 Mixing proportion of concrete

w/c	Unit weight (kg/m^3)			
	Water	Cement	Sand	Gravel
0.45	185	411	706	1001
0.50	185	370	720	1021
0.55	185	336	732	1038

water exerting downward force from above, as shown in Fig. 1. Assuming the density of sea water to be 1,025 kg/m^3 (in fact it is slightly variable), water pressure can be calculated and increases by 1 atm with each 10 m of depth approximately. Therefore, it is very important to understand the effect of permeation on chloride penetration in concrete and the impact on its service life. Furthermore, although permeation can be a decisive driving force for chloride penetration into concrete, there are rare of its experimental recipes.

With the technical background, new experiment, called YOON's test (Yoon 2014b), is designed. The experiment method is designed to quantify the effect of water pressure on chloride penetration in concrete. The new experiment is intended for estimating water permeability coefficient, gas permeability coefficient, and chloride intrusion by permeation. In this study, one of the functions of Yoon's test, chloride intrusion by pressure is introduced. The thickness of concrete specimen is recommended as 50 mm in general accelerating experiments. In the specimen cracked by mode I stress, maximum crack width can be produced up to 0.12 mm (Yoon and Schlangen 2014). This means that it is impossible to examine the chloride penetration through a large crack exceeded 0.12 mm by means of the experiments. Yoon's test was invented to examine chloride penetration behavior through a large crack in concrete because concrete sample with the thickness of maximum 300 mm is available for the setup.

2. Experiment program

2.1 Preparation of samples

The samples of Ordinary Portland concrete with three different w/c ratios, 0.45, 0.50, 0.60, were produced (Table 3). Concrete was cast into cylinder moulds with a diameter 100 mm, which are moist cured at 20°C for 24 hours, followed by water immersion with temperature 20°C until YOON'S test.

2.1.1 Experiment for water pressure

Yoon's test is represented in Fig. 2. The experiment tool consists of permeation cell, gas/water/seawater reservoirs, and pressurizer with maximum compressive pressure of 1.5 MPa. Computer is linked with the Yoon's test for monitoring the strength of pressure, amount of water, elapsed time, and so on. Chloride solution with 0.5 mol was filled with the reservoir. Before the exposure of chloride solution, all specimens were saturated to prevent capillary suction. For a week, the test was conducted at a pressure of 0.65 MPa, which was equivalent to water pressure to simulate 60 m depth approximately from sea water level.

2.2 Measurement of chloride penetration depth and chloride profile in concrete

After Yoon's test, two methods were used to estimate chloride penetration. First, 0.1N $AgNO_3$ indicator was applied on the fresh fractured surfaces of the specimens to measure chloride penetration depth (Baroghei-Bouny *et al*. 2007). Secondly, for improving data accuracy, micro-profiler grinding kit was used to take concrete powder at suitable increments. The specimen was drilled along the vertical direction from the surface(see Fig. 3). Two samples were taken from each mixture. Water soluble chloride content was then measured with the concrete powder (AASHTO T 260-97).

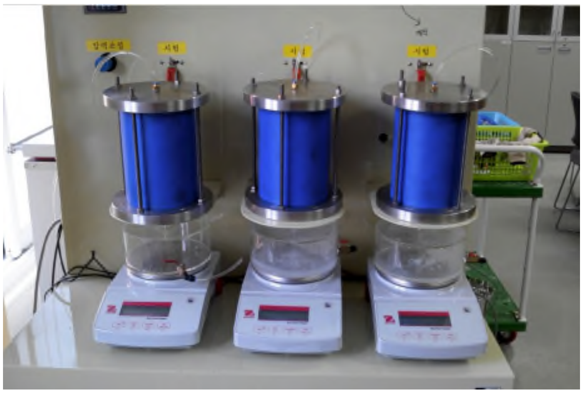


Fig. 2 Yoon's test

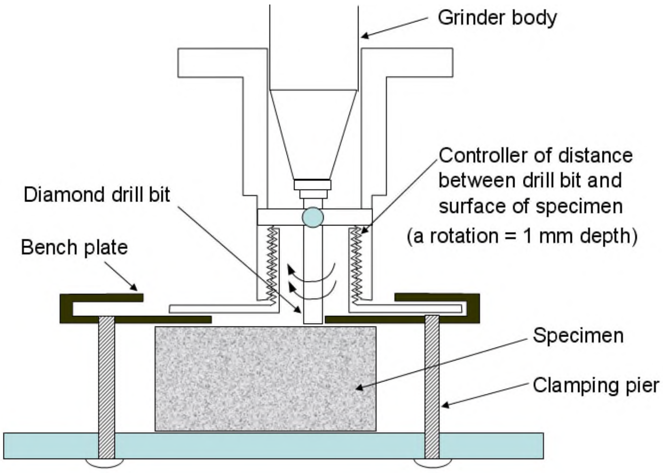


Fig. 3 Schematics diagram of micro-profiler kit to get concrete power at interval distance from the surface

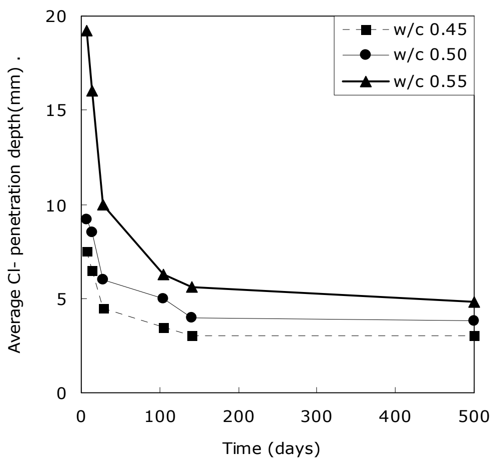
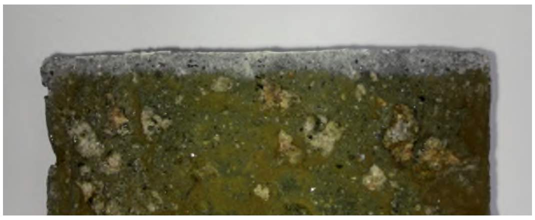
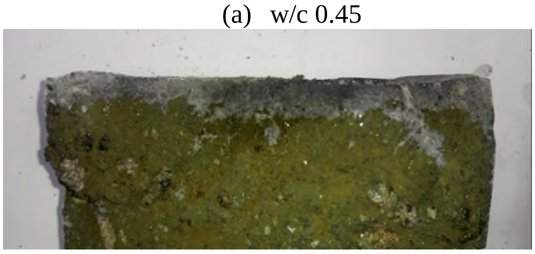


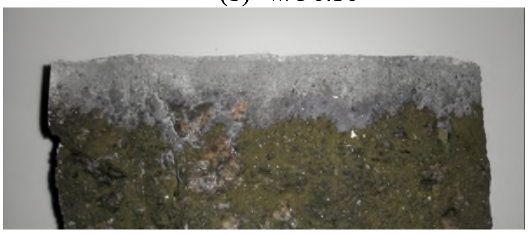
Fig. 4 Chloride penetration depth



(a) w/c 0.45



(b) w/c 0.50



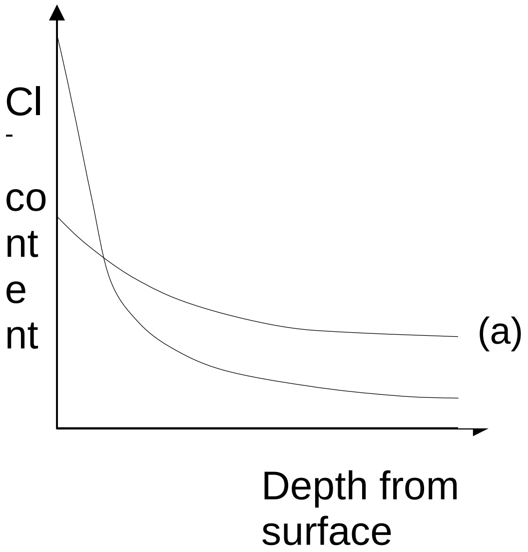
(c) w/c 0.55

Fig. 5 Chloride penetration depth at 28 days cured concrete

3. Results and discussion

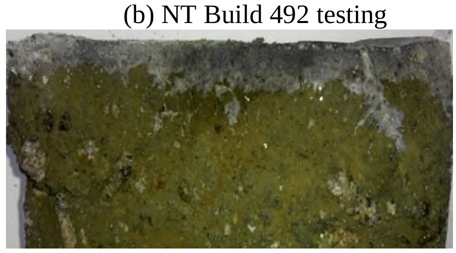
Fig. 4 shows the chloride penetration depth of concrete samples cured for 500 days. As expected, chloride penetration depth increased for concrete with high w/c ratio (Fig. 5). For concrete with w/c 0.50, the border line of chloride penetration depth had a specific chloride content, 7×10^{-4} g per concrete weight. In the meantime, chloride penetration depth tends to decrease with elapsed time because of the development of micro-structure of cement due to the on-going hydration of the cement (Bamforth 2004, Mangat and Molloy 1994, HETEK 1996). However, the trend was definitely slowing down after 100 days.

Fig. 6 presents the profile of chloride penetration with various testing methods. Border line at chloride penetration depth in concrete under NT Build 492 testing and permeation testing of this study was clear, while that of concrete under immersion testing was very ambiguous. Since NT Build 492 testing is done by means of electrical power for short time, chlorides penetrate inwards very rapidly for a short time. For permeation testing suggested in this study, chloride penetrates rapidly by high pressure. However, for natural immersion testing, main driving force is diffusion which is performed for a long time. For these reasons, NT Build 492 testing and permeation testing of this study showed a steep slope of the chloride profile as shown in (b) and (c) of Fig. 6, while, normal profile of concrete under natural immersion test was shown in (a) of Fig. 6. This means that chloride penetration is governed by the behaviour of diffusion which is progresses slowly in natural condition. This should lead to a gradual slope of chloride profile with depth, connecting with ambiguous border line at the depth of chloride penetration.



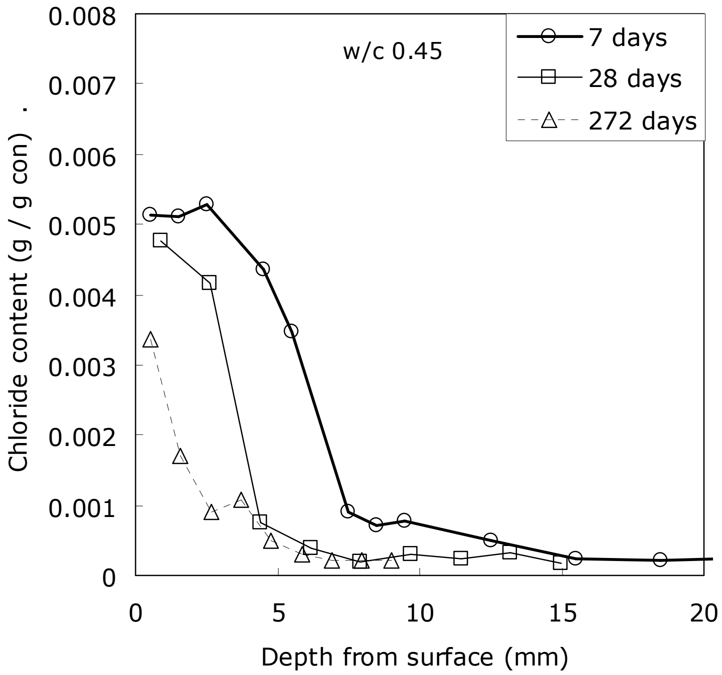
(a) Natural immersion testing

(b) NT Build 492 testing



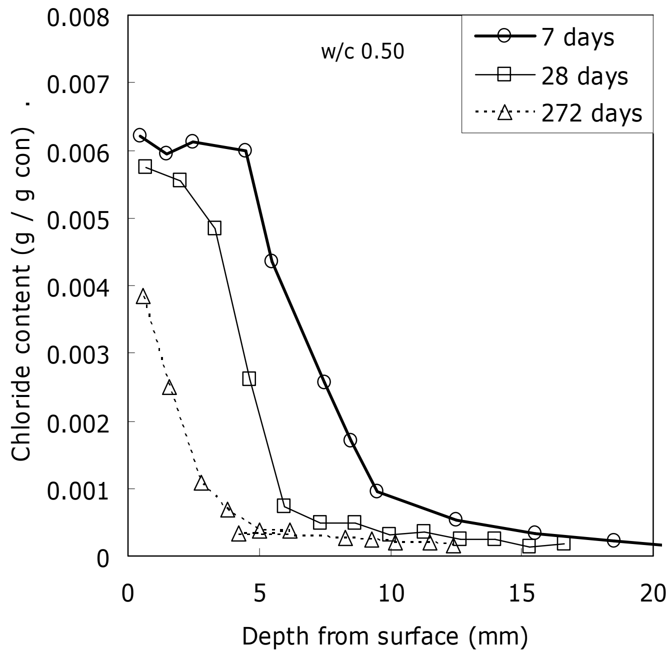
(c) This study

Fig. 6 characteristics of chloride profile with mechanism of chloride penetrations

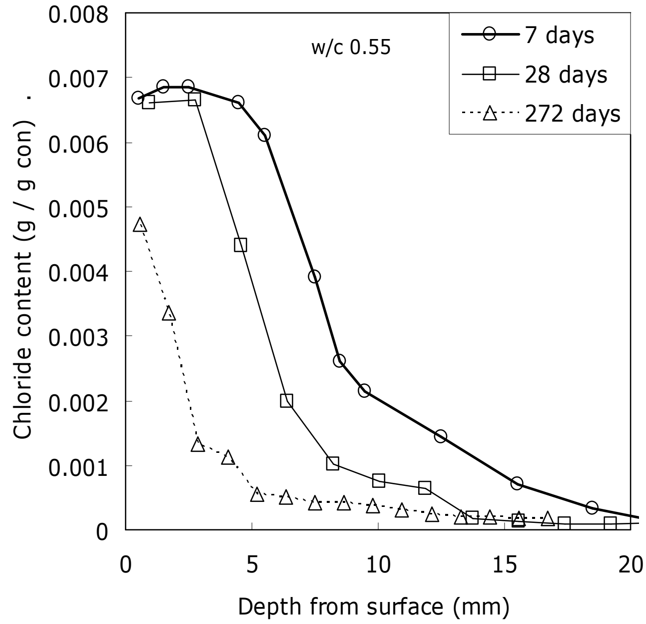


(a) w/c 0.45

Fig. 7 Chloride profile of concrete



(b) w/c 0.50



(c) w/c 0.55

Fig. 7 Continued

Fig. 7 shows the chloride profile with depth from the surface of concrete with various w/c ratios. For 28 days cured concrete with w/c 0.50, chloride content had largely diminished from 3 mm depth, however, the trend was stopped from 6 mm. Thus, the concrete from surface to 6 mm was contaminated by chloride ions. For the behavior of chloride penetration, water pressure was different with traditional diffusion. Chlorides move inward by pressure to a some extent. This means that pressure leads a quick chlorides penetration up to 6 mm, while diffusion induces a slow penetration. Therefore, it can be concluded that chloride should penetrates significantly by water pressure and the phenomena should be accelerated for concrete exposed to environment with high pressure, for instance, deep sea. However, this does not mean significant reinforcement corrosion in concrete under the deep sea because of rarefied dissolved oxygen in the deep seawater. Nevertheless, it is necessary to define chloride penetration in concrete under the deep sea in order to estimate the service life of concrete accurately.

Despite the fact that there have been some uncertainties on the results, it is obvious that high pressure can lead to rapid chloride penetration in concrete. The computational term of water pressure should be added to predict the chloride profile of submerged concrete precisely in previous service life models.

5. Conclusions

In this study, new experimental recipe, Yoon's test, was suggested. the following conclusions were obtained based on the results of the experiments.

- The penetration depth of concrete under permeation environment was obtained by $AgNO_3$ solution. Accelerating testings including the permeation testing of this study can provide with clear penetration depth because of a steep slope of chloride profile with depth from surface. However, in natural immersion condition, the depth of the chloride penetration was ambiguous because the mechanism is a diffusion to induce a rate of slow penetration for a long time. This should lead to a gradual slope of chloride profile with depth.
- In examining of chloride profile, the chloride penetration of concrete under permeation was not governed by Fickian behaviour. Chlorides moved inward by pressure to a some extent. Chloride concentration of concrete from surface to penetration depth was significantly high, however, chloride concentration was low at healthy zone which was not affected by permeation. Thus, chloride ions should penetrate significantly by water pressure and the phenomena should be accelerated for concrete exposed to deep sea.

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