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Testing of the permeability of concrete box beam with ion transport method in service

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Abstract. The permeability is the most direct indicator to reflect the durability of concrete, and the testing methods based on external electric field can be used to evaluate concrete permeability rapidly. This study aims to use an experiment method to accurately predict the permeability of concrete box beam during service. The ion migration experiments and concrete surface resistivity are measured to evaluate permeability of five concrete box beams, and the relations between these results in service concrete and electric flux after 6 hours by ASTM C1202 in the laboratory are analyzed. The chloride diffusion coefficient of concrete, concrete surface resistivity and concrete 6 hours charge have good correlation relationship, which denote that the chloride diffusion coefficient and the surface resistivity of concrete are effective for evaluating the durability of concrete structures. The chloride diffusion coefficient of concrete is directly evaluated permeability of concrete box beam in service and may be used to predict the service life, which is fit to engineering applications and the concrete box beam is non-destructive. The concrete surface resistivity is easier available than the chloride diffusion coefficient, but it is directly not used to calculate the service life. Therefore the mathematical relation of the concrete surface resistivity and the concrete chloride diffusion coefficient need to be found, which the service life of reinforced concrete is obtained by the concrete surface resistivity.

Keywords: permeability; concrete beam; surface resistivity; chloride diffusion coefficient; in service

1. Introduction

There are many large scale infrastructures in service such as water pipelines, bridges, highway flyovers and modern elevated structures of light rail transport in the world. The box beam is commonly used for them. Normally the box beams are made of steel or concrete, which in china the most box beams are made of concrete (Wang *et al*. 2011). Therefore the reinforced concrete box beam is a large common component and its durability is very important for these infrastructures safe. The permeability of concrete is an important part of its durability (Mcarter *et al*. 2005, Meira *et al*. 2010, Homwuttiwong *et al*. 2012), and the evaluation permeability of concrete is used by mainly electrical parameters method, including steady state migration test, non-steady state migration test and other fast determination penetration method (Hong *et al*. 1999, Andrade *et al*. 1993, Tang 1996). The chloride concentration in the concrete and the chloride

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diffusion coefficient of concrete can be determined to evaluate the permeability of concrete and the finite element method has been applied to calculated the chloride diffusion coefficient of concrete(Sajal *et al.* 2014). Most of the testing methods are only used in the laboratory, and the actual surface of concrete structures is affected by environmental factors, for example boundary effects, steel of the barrier and the fluctuation of concrete materials (Desouza *et al*. 1998, Long *et al*. 2001), the chloride diffusion coefficient is not different with the result of laboratory (Guzmán 2011, Kim 2014). If the concrete surface is drilled for testing, it is bad to concrete structure in service. How to measure the permeability of concrete structures in service with nondestructive methods(Yang *et al.* 2014) , the ion transport method that is based on the steady state test is proposed (Basheer *et al*. 2005), and this method is modified to define the characteristic of steady stage with experiment results (Yang *et al*. 2009).At the same time the effect of concrete pore solution on the test results is also studied that the effects of nitrate ions and hydroxyl ions on the test results is be ignored. The surface resistivity of concrete is the most early used by Florida Department of Transportation to evaluate concrete permeability (Florida 2004), and the relationships between the surface resistivity of concrete and other indicators of concrete permeability still need further to be studied for reliability(Ghafoori 2013). Therefore the chloride diffusion coefficient and surface resistivity of concrete in service is measured for evaluation permeability of concrete box beam and the relation results in service with the electric flux in laboratory is studied in this paper. The service life of concrete box beam is calculated in ocean atmosphere based the measuring permeability results in service.

2. Theoretical basis for the test

2.1 The coefficient of chloride diffusion for steady state

The electric field force of chloride ion in the electrolyte solution is

$$F_i = ze_0 \frac{U}{l} \tag{1}$$

where F_i is the electric field force, N; z is ionic valence; e_0 is the electron charge, 1.6 × 10^{-19}C; U is the voltage between the electrodes, V; l is the distance between the electrodes, m.

Chloride ion migration rate is

$$v = u F_i \tag{2}$$

where v is the ion migration speed, m/s; u is the electrical mobility of chloride ions, $m^2/(s \cdot J)$.

At the same time the Einstein equation

$$D = u \frac{RT}{F} e_0 \tag{3}$$

where D is the chloride diffusion coefficient, m^2/s; F is the Faraday constant, 9.65 × 10^4C/mol; R is an ideal gas constant, 8.31 J / (K · mol); T is the absolute temperature, K.

The chloride ion migration rate is derived in Eq. (4) from equations (1), (2) and (3)

$$v = z \frac{U}{l} \frac{DF}{RT} \tag{4}$$

when Chloride ion in concrete migration process is reached steady state, the amount of chloride ions move per unit time as shown in Eq. (5)

$$J_{out} = vAC \tag{5}$$

where J_{out} is the amount of chloride ions move per unit time; A is the surface area of chloride ion migration, m^2; C is the chloride ion concentration in the inner chamber, mol/l.

For the outer chamber the unit time moving amount of chloride ions is calculated by Eq. (6)

$$J_{in} = \frac{dc}{dt}V \tag{6}$$

where V is the outer chamber volume, 6.5 × $10^{-4}m^3$; $\frac{dc}{dt}$ is the change rate of chloride ions concentration with time in outer chamber, mol/(l·s).

In steady state migration phase, according to the law of conservation of chloride ions there is Eq. (7).

$$J_{out} = J_{i} \tag{7}$$

Therefore the coefficient of chloride diffusion is obtained by Eq. (8)

$$D = \frac{RT}{zCFU}V\frac{l}{A}\frac{dc}{dt} \tag{8}$$

where $\frac{l}{A}$ is fixed parameter for the instrument, 3.74/m; U is 60V.

2.2 The surface resistivity of concrete

The principle of concrete surface resistivity is used the four electrodes as shown in Fig. 1.

$$\Delta U = U_1 - U_2 = \frac{\rho I}{\pi a} - \frac{\rho I}{2\pi a} = \frac{\rho I}{2\pi a}$$

$$\rho = 2\pi a \frac{\Delta U}{I} \tag{9}$$

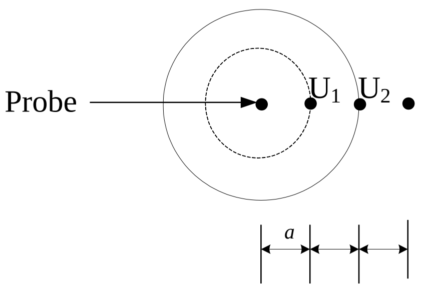

Fig. 1 The surface resistivity principle

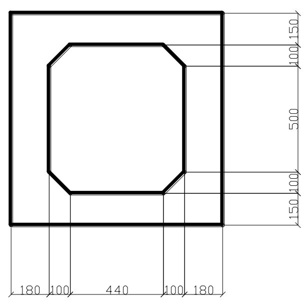

Fig. 2 Concrete box beam

Table 1 Raw materials chemical composition (mass percent, %)

	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	MnO	TiO_2	Na_2O	K_2O	Loss
Portland cement	21.5	4.6	64.0	0.9	2.09	3.37	0.12	-	-	0.6	3.2
Fly ash	52.4	32.1	2.1	0.5	0.3	4.1	0.2	0.6	0.2	-	1.0

Table2 Concrete proportion（kg/m^3）

Concrete beam	Portland cement	Fly ash	Sand	Stones	Water	Admixture	Water-binder- ratio	28d compressive strength(MPa)
1	288	72	774	1026	180	5.04	0.50	37.5
2	302	76	778	1032	170	6.04	0.45	38.5
3	340	85	742	1025	170	6.80	0.40	44.2
4	389	97	684	1026	170	7.77	0.35	49.9
5	413	103	662	1035	165	9.28	0.32	57.7

where ρ is the surface resistivity of concrete, KΩ ·cm; a is an electrode spacing, cm; ΔU is the intermediate electric potential difference between two electrodes, V; I is the electric current, mA.

3. Experiment

3.1 Materials

The ordinary Portland cement is complied with the Chinese National Standard GB175-2007 PO42.5 and the fly ash as Class II according to the Chinese National standard GB1596-91 is also used. Their chemical compositions are showed in Table1.The Crushed limestone with a size range of 5~31.5 mm and natural river sand with a fineness modulus of 3.0 are used as coarse and fine aggregate. A polycarboxylic superplasticizer is used to prepare concrete mixtures.

The proportion of concrete box beams are shown in Table 2 and the box beam size is 7.6 m × 1.0 m × 1.0 m, which the cross-sectional shape of box beam is shown in Fig. 2. The minimum thickness of the side is 180 mm, the upper and lower surfaces of the minimum wall thickness is 150 mm. The compressive strength of concretes at 28 days is given in Table 2, which is measured with rebound test because the rebound method has been verified to meet the precision requirement of the field test.

3.2 Test method

The ion transport meter with two concentric chambers is made of stainless steel, which the inner electrode is a cathode chamber, the outer chamber of the electrode as an anode material for the ordinary low carbon steel as shown in Fig. 3. When test begins, the meter is fastened to the concrete sample surface. The inner chamber is filled with 0.55mol/l NaCl solution, the outer chamber is filled with deionized water. The chloride ion is moved from concrete surface to the outer chamber under 60V DC electric field. The outer chamber is provided with a conductivity sensor for measuring the conductivity.

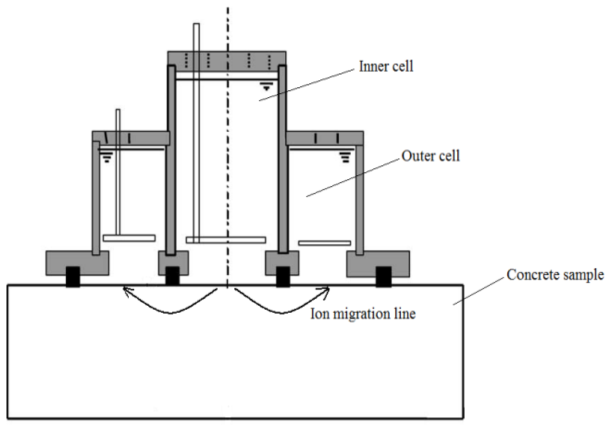

Fig. 3 Ion transport operation principle

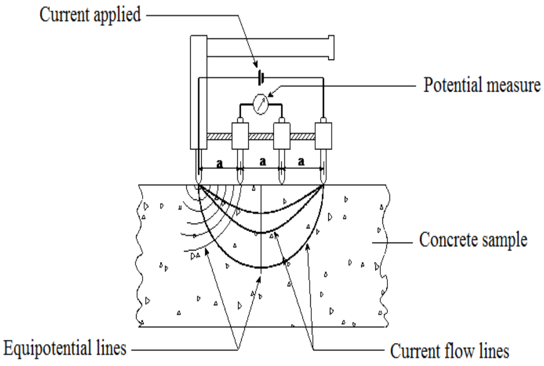

Fig. 4 Concrete conductivity meter principle

(a) Chloride diffusion coefficient

(b) Surface resistivity

Fig. 5 Testing in service

The surface resistivity of concrete is measured with Railey CRT-1000 type, which is produced by United States, voltage 12V, Wenner array sensor spacing 50 mm. The structure and working principle is shown in Fig. 4.

The concrete surface is saturated with deionized water for 24 hours prior to the test to achieve a similar concrete surface saturated state and the testing in service is shown in Fig.5. There are three points for the chloride diffusion coefficient test that are averaged, and ten points for the concrete surface resistivity averaged them.

4. Results and discuss

4.1 Measuring the coefficient of chloride diffusion

The variation curves of conductivity in outer chamber of ion transport are shown in Fig. 6 for five concrete box beams. As it is seen in the test beginning, the chlorine ions are still not formed the steady state phase. After more 120 minutes, the linear stage is obviously, but when the time of the ion concentration increases, the relation between the concentration of the ion and conductivity is also not linear. Therefore the steady state time of the conductivity changes are from 120 minutes to 300 minutes after beginning. The rate of change of conductivity with time is shown in Fig. 7. The ion transport test solution is measured with the electric conductivity of the solution of the chloride ion concentration conversion, general conductivity of the electrolyte with a strong increase in the number of conductive particles is increased, when the concentration increases to a certain extent, the positive and negative ions are increased to prevent the ion interaction the movement, the conductivity is reduced.

In low concentrations, the conductivity and the concentration of ion can be considered a linear relation. Therefore when the concentration of outer chamber chloride ion is measured in the steady state phase, each 5 ml solution is determined chloride ion concentration by potentiometric titration. Firstly the electrical conductivity with the chloride ion concentration increasing is increased, and then the trend is flat, which is with strong electrolyte conductance theory. This indicates that the

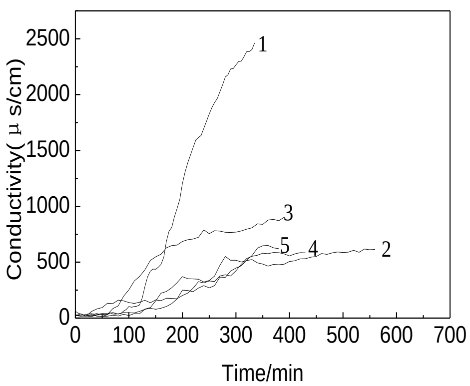

Fig. 6 Outer conductivity change with time

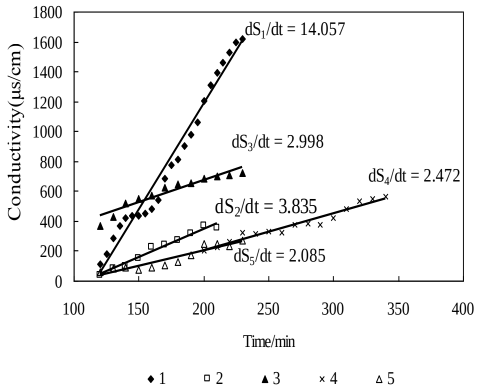

Fig. 7 Conductivity under steady stage with time

concentration of chloride ion still increases in ion transport unsteady test phase over time. In the steady state stage the chloride concentration is relatively low, and it can be considered linear relationship between the conductivity and the concentration of ion. The linear relationship between them in this study is basically showed in Eq. (10).

$$\frac{dc}{dt} = 4.9 \times 10^{-6} \times \frac{dS}{dt} \tag{10}$$

where $\frac{dS}{dt}$ is the rate of change of conductivity with time, *uS*/ (cm•s).

The temperature of the solution is given by the internal temperature sensor, and in the steady state the temperature of the solution is mainly affected by ambient temperature, and the high temperature makes the chloride ion diffusion coefficient increase. When the temperature T and $\frac{dc}{dt}$ value are substituted into the Eq. (8) for each box beam concrete, the chloride diffusion coefficients of concretes are calculated as shown in Fig. 8. The coefficient of chloride diffusion of concrete box beam in service with ion transport field testing is much smaller than the value of RCM test method (Yang *et al*. 2009), and there are two main reasons that one is the RCM sample preparation which the damage generated on the concrete surface cracks increase the chloride diffusion coefficient and the other reason is that the protective cover concrete is basically the mortar with less coarse aggregate because of the steel bar barrier , therefore the cover concrete has little permeability than inner concrete. At the same time these studies indicate that there is certain the linear relation between them.

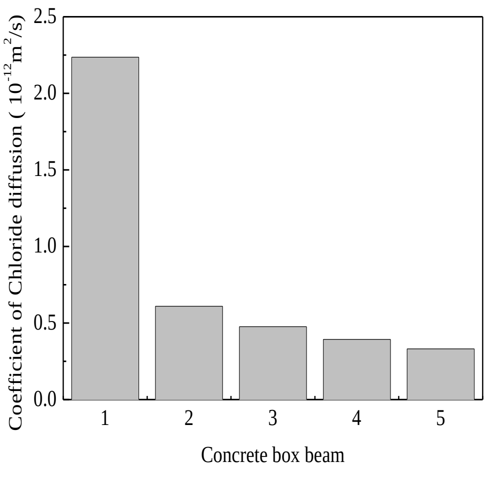

Fig. 8 The chloride diffusion coefficient of concrete box beams

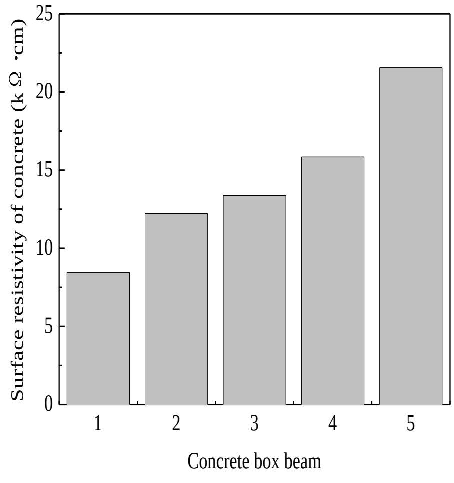

Fig. 9 The surface resistivity of concrete box beams

4.2 Measuring the coefficient of Chloride diffusion

Before measuring the concrete surface resistivity of concrete, the electrode is suck water saturated sponge. The test result is shown in Fig. 9, and the permeability of concrete is stronger, the surface resistivity of concrete is smaller.

The chloride diffusion coefficient of concrete box beam 1 is obviously greater than that of the other box beams because its Portland cement amount is lowest and the water-binder-ratio is highest in five box beams. At higher water-binder-ratio stage, the chloride diffusion coefficient reduces obviously water with binder ratio deceasing, but when the water-binder-ratio drops to a certain stage, the diffusion coefficient of chloride ion does not obviously decrease. This reason is that the permeability of concrete is mainly affected by water-binder-ratio at higher water-binder-ratio stage, but at lower water-binder-ratio stage the permeability of concrete is also affected by other factors such as the binder fitness, amount and activity. Therefore from box beam 2 to box beam 5 the chloride diffusion chloride of concrete decreases slowly.

4.3 The correlation of chloride ion diffusion coefficient and concrete surface resistivity

The relation between the chloride diffusion coefficient of concrete and surface resistivity is showed in Fig.10. Although they are obtained by the two different principles, they all measure the permeability of protective cover concrete. When the surface resistivity increases, the chloride ion diffusion coefficient decreases, their relation is non-linear. The correlation of surface resistivity and chloride diffusion coefficient of concrete makes the surface resistivity of concrete to be used in the engineering because the surface resistivity of concrete is easy to be measured

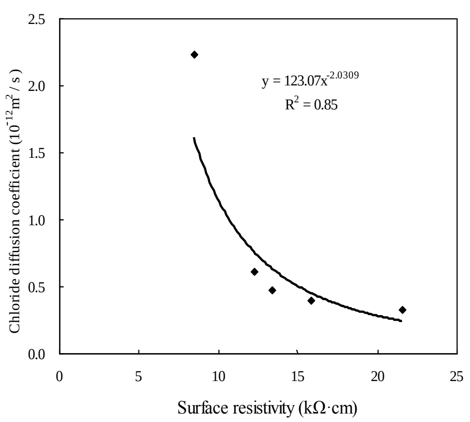

Fig. 10 The relation of the chloride diffusion coefficient and surface resistivity of concrete

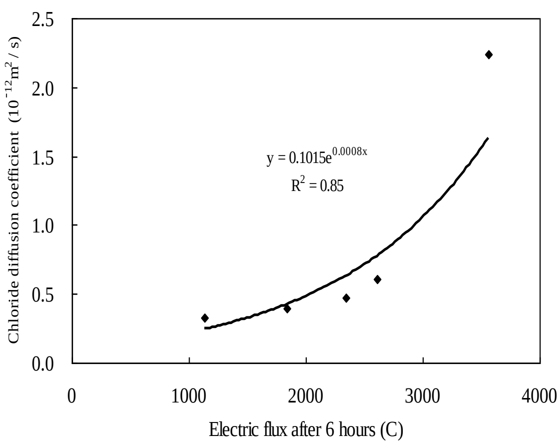

Fig. 11 The relation of the chloride diffusion coefficient and the electric flux after 6 hours of concrete

4.4 The correlation of chloride diffusion coefficient, surface resistivity and electric flux

Rapid chloride penetration test based on ASTM C1202 has been faced by some criticisms including the movement of other ions, production of heat and thus accelerating the ion movements and so on. Now many study results also denote that the containing a large amount of slag concrete, ultra low water-binder-ratio concrete and adding steel fiber concrete cannot be evaluated their permeability by the electric flux method.

In this study, the five concretes are common concretes and are evaluated permeability by ASTM C1202 method in laboratory. The main purpose is to analyze the field test method whether evaluating permeability of concrete.

According to the ASTMC1202-97 electric flux method, there are six hours of electric charge for concrete specimens with diameter of 95 ± 2 mm, 51 ± 3 mm thick. The specimens of concrete are prepared from the surface layer of concrete box beam, and the specimens must first be vacuum saturated. The measuring results show the correlation of the chloride diffusion coefficient and the electric flux in Fig.11, and the correlation of the concrete surface resistivity and the electric flux is shown in Fig.12. It can be seen that the chloride diffusion coefficient and the concrete surface resistivity in service has better relevance with electric flux in laboratory. So the concrete permeability results in service are valid.

4.5 The application of measure results

The reinforced concrete life in the marine environment is often calculated with the chloride diffusion coefficient of concrete, which the steel bar caused by chloride reach critical chlorine concentration for damage of the steel surface protective film (Shin *et al.* 2011). The service life of concrete can be obtained according to Flick's second law as Eq. (11) (Wang *et al.* 2012)

$$T = \frac{x_{cr}^2}{4D}[erf^{-1}(\frac{C_s - C_{cr}}{C_s - C_0})]^{-2} \tag{11}$$

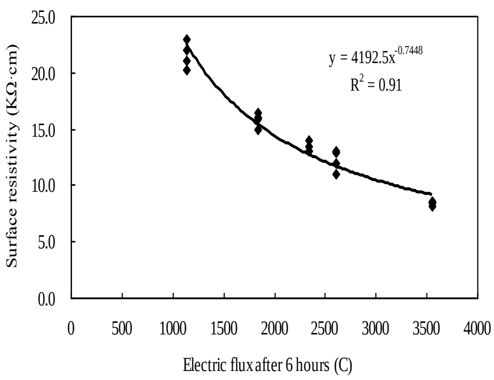

Fig. 12 The relation of concrete surface resistivity and the electric flux after 6 hours of concrete

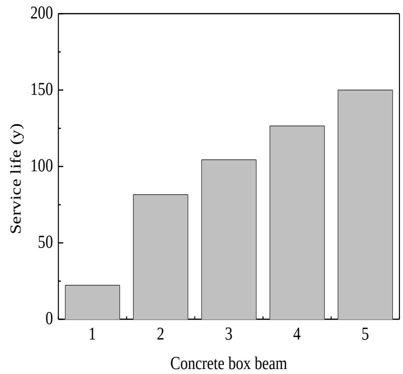

Fig. 13 The service life of concrete box beam

where x_{cr} is the thickness of the concrete cover layer, 50 mm; C_s is the chloride concentration of concrete surface; C_{cr} is the critical chloride concentration caused steel bar corrosion; C_0 is the initial chlorine ion of concentration concrete; erf^{-1} is inverse of error function.

When the box beams work in the marine atmosphere, the parameter value $C_s = 1.1\%$, C_{cr} =0.32%, $C_0 = 0$, the service life of reinforced concrete box beams are shown in Fig.13. If the chloride ion induced corrosion is only considered，the service life of box beam 1 is about 22 years or so .The general results of field observations is accordance with field observation, so this method is directly able to evaluate the existing reinforced concrete service life.

5. Conclusions

The determination of permeability of concrete box beam in service is obtained and there are some results as fellows.

1) The chloride diffusion coefficient of concrete is directly evaluated permeability of concrete box beam in service and is used to predict the service life. This method is non-destructive, which is fit to engineering applications. Now this method is only used in the plane surface of concrete, and does not measure the curve concrete.

2) The analysis of the chloride diffusion coefficient of concrete, concrete surface resistivity and concrete 6 hours charge has good correlation relationship, which denotes that the chloride diffusion coefficient and the surface resistivity of concrete is effective for evaluating the durability of concrete structures.

3) The concrete surface resistivity is easily available, and may directly evaluate the concrete permeability. Although the concrete surface resistivity is not used to calculate the service life, the mathematical relation of the concrete surface resistivity and the concrete chloride diffusion coefficient is found, which can change the concrete chloride diffusion coefficient and the service life of reinforced concrete is obtained.

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