The accelerated method for estimating corrosion of reinforced concrete structure in seawater

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ABSTRACT

The corrosion of concrete for offshore structures is generally caused by the penetration of chloride ion deriving from the salts in seawater. Up to now, lots of researches have been done concerning the corrosion of concrete by seawater and durability of concrete. However, the investigation for corrosion of reinforced concrete structure by seawater are relatively rare, because of the needs for long term tests (at least 3 to 5 years usually). The structures sited in the intertidal zone always accompany severer deterioration by seawater. Under such environmental conditions, frequent wetting and drying will aggravate the effect of sulfate attack, while the crystallization of sea salts in the concrete on evaporation may also contribute to expansive forces. For these reasons above, the purpose of this paper is to study the corrosion of reinforced concrete structure in the intertidal zone by a accelerated method presented.

The critical variables considered in this research include the temperature and concentration of seawater. During the experimental period (1 year), the specimens were cured in wetting and drying situation (for each circle, submerged by seawater for 24 hours and then drying at 70℃ for the following 24 hours), and this repeatedly cyclic procedures is to accelerate the corrosion of reinforced concrete structure by seawater. According to the experimental results, the increased concentration and temperature of seawater would accelerate deterioration of concrete obviously. The duration of testing could be shortened about 75% by using the sweater with 10 times the concentration. As the curing temperature increased, the corresponding strength concrete at earlier age would increase, and which could reduce the corrosion of reinforced concrete.

Keywords: durability of concrete, the accelerated method to estimate corrosion of concrete**,** corrosion of concrete by seawater

1. Introduction

For reinforced concrete structures, the major factors against durability could be attributed to the deteriorated concrete quality and corrosion on the embedded reinforcing bars in general. Those causing decay on concrete properties could be further divided into two aspects

originated from the internal (intrinsic essence of concrete) and external (environmental conditions) effects. The internal factors of concrete include water to cement ratio (*w/c*), the type of cement, aggregate, and the use of mineral (such as fly ash, silica fume, and blast furnace slag) and chemical admixture, etc. Besides, the external conditions are influenced by the environmental humidity and temperature, concentration of carbon dioxide (CO_2), and other detrimental substances, which would lead to certain changes in chemical and physical properties of concrete itself, and thus the expansive cracking and connected porosity are likely to occur inside concrete. On the other hand, the appearance of steel corrosion is primarily in connection with the penetration of chloride ions, carbonation, and oxidation-reduction reaction which will generate the expanded products resulting in cracking in concrete and increase the exposed extent of steels. Under such vicious circles, the likelihood that unfavorable ions penetrating into concrete will be gradually enhanced [1].

2. Experimental programs

2.1 Materials

2.1.1 Cement

ASTM Type Ⅰ Portland cement was used. The chemical compositions and physical properties of the cement are given in Table 1.

Table 1 Chemical compositions and physical properties of cement

Chemical composition							Physical properties	
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI	Specific gravity	Specific surface
19.8%	5.88%	3.61%	62.85%	3.64%	2.13%	0.74	3.15	3400 cm^2/g

2.1.2. Aggregates

The fine aggregates were local natural river sand with fine modulus of 2.88, absorption of 1.28% and density (SSD) of 2.61 g/cm^3. The coarse aggregates were crushed quartzite with maximum nominal size of 20 mm, absorption of 1.12%, and density (SSD) of 2.62 g/cm^3.

2.1.3. Artificial seawater

In this study, the chemical compositions of artificial seawater compounded conform to the specification of ASTM D1141-90 summarized in Tables 2. There were three types of concentration of artificial seawater (1, 5 and 10 times) used for the subsequent tests.

Table 2 Chemical composition of artificial seawater

Compound	NaCl	$MgCl_2$	Na_2SO_4	$CaCl_2$	KCl	$NaHCO_3$	KBr	H_3BO_3	$SrCl_2$	NaF
Concentration (g/L)	24.53	5.20	4.09	1.16	0.695	0.201	0.101	0.027	0.025	0.003

2.2. Mixture proportions

As shown in Tables 3, two target strengths of 20 and 35 MPa (210 and 350 kgf/cm^2) at 28 days with the target slump of 120 mm were decided for mixture proportions. The criteria for mix proportioning selection were that the concrete should be readily available, and not require any reactive admixtures to reach the target strength and slump both.

Table 3 Mixture proportions (kg/m^3)

Batch	Air content	*w/c*	Cement	Water	Aggregate	
					Fine	Coarse
N20*	1.5%	0.68	300	203	718	1078
N35*	1.5%	0.50	390	195	645	1078

*20 and 35 designates the target strength of 20 MPa and 35 MPa respectively.

2.3. Curing conditions

The curing conditions for all specimens exposed were shown in Table 4. After casting, all specimens were left in molds for 24 hr. After 24 hr, the specimens were demolded and moved into a curing pool. The temperature of water in the curing pool was maintained at 20℃. After 7-day water curing, partial specimens (except for control ones still left behind) were changed to be cured in seawater by repeatedly wetting and drying circles (curing condition A~E). For each circle, the specimens were submerged by seawater for 24 hours and then drying at 70℃ for the following 24 hours.

Table 4 Curing conditions

Curing condition	Cyclic curing by seawater (wetting & drying)					Standard curing by water
	A	B	C	D	E	Control
Temperature (℃)	20	20	20	40	60	20
Multiples of seawater concentration	10	5	1	10	10	—

2.4. Specimen dimensions and testing details

2.4.1. Compressive strength test

Compressive strength tests were performed on Φ100×200 mm concrete cylinder at age of 28, 56, 90 and 180 days. For each age, the compressive strength was averaged from three specimens tested.

2.4.2. Electric resistance test

Electric resistance tests were also performed on concrete cylinders at the same age of compressive strength tests. The electric resistance values were measured by a resistivity

meter on the specimen surface.

2.4.3. Permeability test

For permeability tests, the testing specimens (Φ100×200 mm concrete cylinder) and ages (28, 56, 90 and 180 days) were identical with compressive strength and electric resistance tests. The period during test would take one hour and the pressure of water applied on specimens was 0.1 MPa (1 kgf/cm^2). All specimens should be treated as oven dry at 80℃ and weighted before permeability tests. Then the permeability of specimens could be determined by the extent of increased weigh measured after testing from the initial oven-dry condition.

2.4.4. Carbonation test

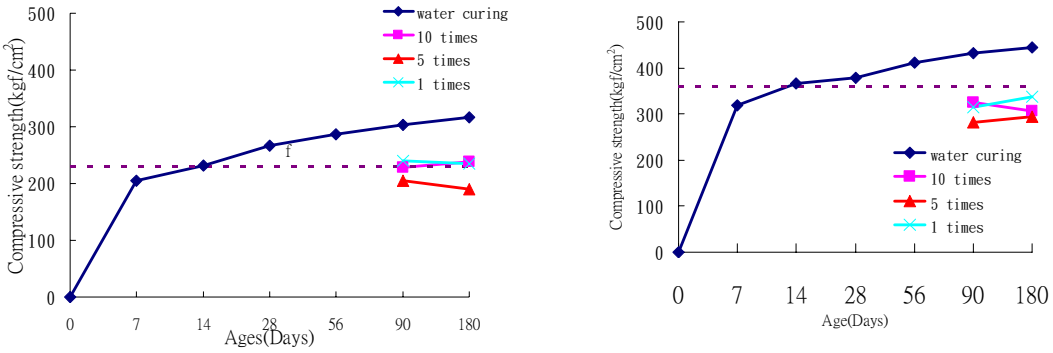
The carbonation tests were conducted on the split concrete cylinder specimens by seawater curing at the tested ages. The phenolphthalein solution (1% phenolphthalein in alcohol) was sprinkled on the broken surface of specimens. The color of phenolphthalein solution would change to be purple-red if the carbonation occurring in concrete. The degree of carbonation for specimens could be obtained by measuring the depth from the broken surface of specimens (with purple-red color) to the interface without being colored.

3. Results and discussion

3.1. Compressive strength

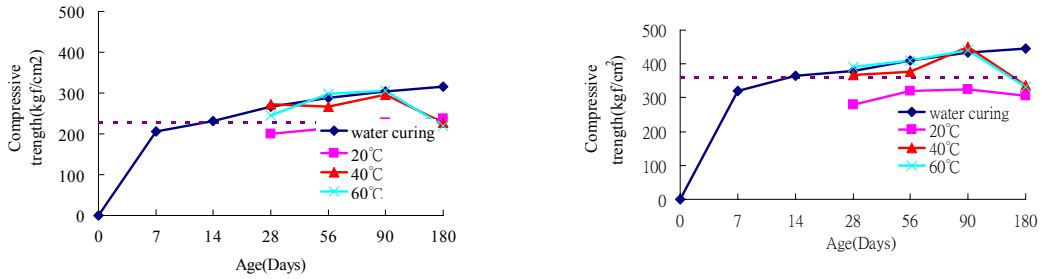
The compressive strengths of concrete with varied curing situation are shown in Figs.1 and 2. From Fig.1(a) and (b), after the age of 90 days, the compressive strength of specimens cured by seawater were lower than that by standard-water curing about 25%~40%. This strength reduction could be attributed to that the chemical compounds in seawater (such as NaCl, $MgCl_2$, $MgSO_4$, and $CaSO_4$) would decompose the C-S-H gels in cement paste, reduce the pH values of concrete (with CH crystals separated out), and cause the secondary expansion (with ettringite formed). However, for curing temperature of 20℃, there were no obvious differences between the development of compressive strength and seawater concentration could be found in Fig.1(a).

In Fig.2, for the specimens cured by high temperature seawater (40 and 60℃), the compressive strength are close to that with standard-water curing until the age of 90 days. However, after 90 days, the 180-day compressive strength of specimens cured by high temperature seawater compared with those with standard-water curing reduced to only 70%. This is probably because the high curing temperature would increase the rate of hydration to form the hydration products incompletely in cement paste and make concrete tend to possess higher strength at earlier age. Nevertheless, this tendency is harmful to the long-term strength development of concrete because the rapid initial hydration and the formation of defective hydration products will bring about the larger amount of capillary pores existing in cement paste.



(a) N20 specimen (b) N35 specimen

Fig.1 The development of compressive strength for cured at 20℃ with varied seawater concentrations (1, 5 and 10 times)



(a) N20 specimen (b) N35 specimen

Fig.2 The development of compressive strength for cured at varied temperatures (20, 40, and 60℃) with 10 times seawater concentrations

3.2 Electric resistance test

The electric resistance value of concrete with varied curing situation are shown in Figs.3 and 4. According to Fig.3, for curing temperature of 20℃, the electric resistance value of specimens which were cured in high concentration seawater of 10 times are the lowest of that with varied concentration seawater. As the concentration of seawater increased, the electric resistance value of concrete would reduce obviously. But, after the age of 28 days, the electric resistance values of specimens with varied curing situation change slightly.

According to Fig.4, for high concentration seawater of 10 times, the electric resistance value of specimens which were cured in normal temperature seawater of 20℃ are the lowest of that with varied concentration seawater. But, the 180-day electric resistance value of specimens treaded to get identical. This is probably because the high curing temperature would increase the rate of hydration to form the hydration products incompletely in cement paste and make concrete tend to possess higher strength at earlier age. Nevertheless, this tendency is harmful to the long-term strength development of concrete because the rapid initial hydration and the formation of defective hydration products will bring about the larger amount of capillary pores existing in cement paste.

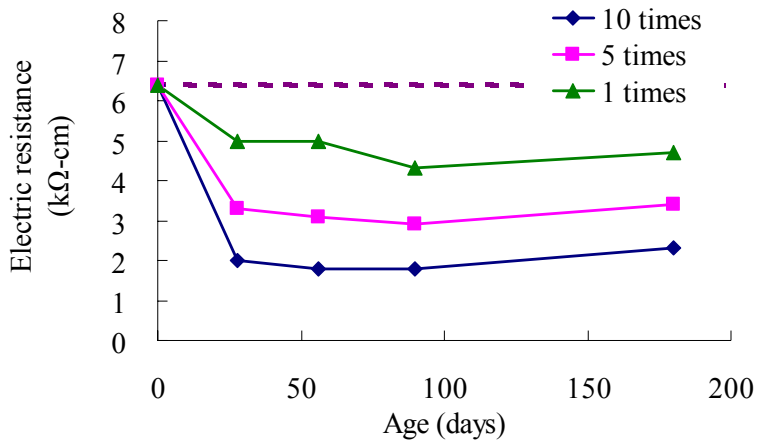


Fig.3 Relations between electric resistance and age of N20 specimens for cured at 20℃ with varied seawater concentrations (1, 5 and 10 times)

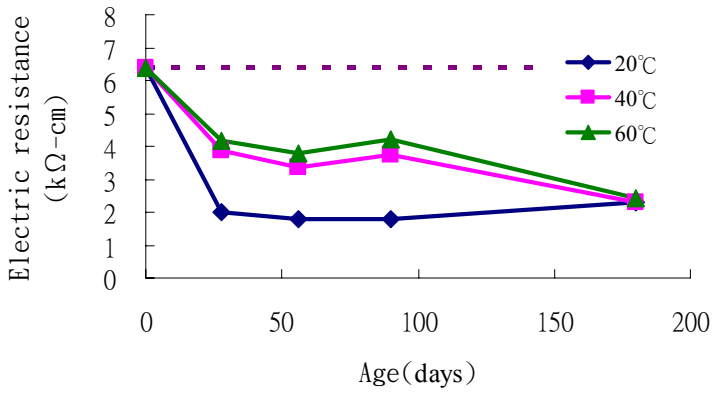
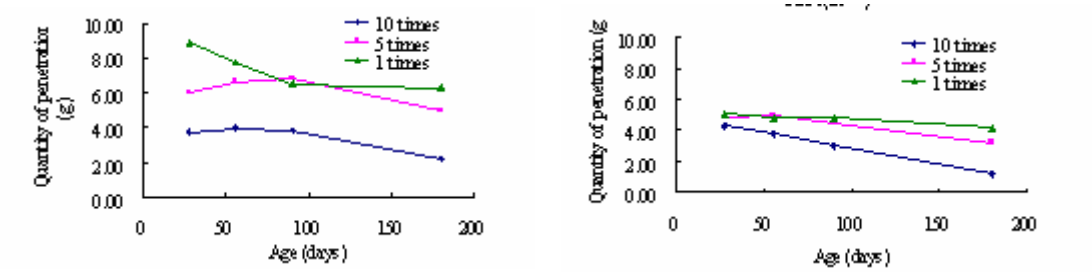


Fig.4 Relations between electric resistance and age of N20 specimens for cured at varied temperatures (20, 40, and 60℃) with 10 times seawater concentrations

3.3. Permeability of concrete

The permeability of concrete with varied curing situation are shown in Fig.5(a) and (b). According to Fig.5 (b), for curing temperature of 20℃, the ;ermeability of specimens which were cured in high concentration seawater of 10 times only reach 40% of that with curing in normal concentration seawater. And as the concentration of seawater increased, the permeability of specimens reduced. Compared with Fig.5(a) and (b), the high compressive strength concrete possessed lower permeability. This is probably because the internal structure of high strength concrete would be denser than that of low strength concrete.



(a) N20 specimen (b) N35 specimen

Fig.5 Relation between permeability and age for cured at 20℃ with varied seawater concentrations (1, 5 and 10 times)

3.4. Carbonation test

The carbonation depths of concrete with varued curing situation are shown in Table 5 and Table 6.It is known that carbonation is a chemical reaction that takes place between hydration product and CO_3^-. However, seawater possess only few CO_3^-, so the carbonation rate of concrete with curing in seawater were very slower. According to Table 5, for curing temperature of 20℃, carbonation depths of specimens which were cured in high concentration seawater of 10 times were the thinnest of that with varied concentration seawater. And as the concentration of seawater decreased, the carbonation depths of specimens increased. According to Table 6, for high concentration seawater of 10 times, as the temperature of seawater increased, the carbonation depths of specimens decreased.

Table 5 Carbonation depths (20℃)

Concentration of seawater	Mix no.	Carbonation depth（mm）			
		28 days	56 days	90 days	180 days
10 times	N20	0.0	4.4	0.0	8.1
	N35	0.0	3.7	0.0	4.5
5 times	N20	0.0	4.7	0.0	9.4
	N35	0.0	4.3	0.0	3.1
1 times	N20	0.0	5.8	12.3	16.1
	N35	0.0	3.6	9.1	11.5

Table 6 Carbonation depths (concentration of 10 times)

Temperature of seawater	Mix no.	Carbonation depth（mm）			
		28 days	56 days	90 days	180 days
20℃	N21	0.0	4.4	0.0	8.1
	N35	0.0	3.7	0.0	4.5
40℃	N21	0.0	3.1	3.0	6.1
	N35	0.0	2.3	2.5	5.2
60℃	N21	0.0	3.3	3.7	5.3
	N35	0.0	2.2	2.1	4.8

4.Conclusions

a. With high concentration (10 times) seawater at room temperature (20℃) for cyclically wetting and drying curing, the rates of reductions in compressive strength and electric resistance of concrete would increase apparently with the age. As for the comparisons of varied seawater concentrations (1, 5, and 10 times), the effects on compressive strength and electric resistance of concrete are not obvious.
b. With high temperature (60℃) seawater for cyclically wetting and drying curing, due to the higher strength development at earlier age, the compressive strength and electric resistance of concrete possess lower reduction rates. Until the age of 180 days, only 70% in contrast to the compressive strength of the specimens with standard-water curing.
c. Based on the results of carbonation tests, the effects of cyclically wetting and drying curing by seawater on the carbonation of concrete are insignificant.
d. From the results of permeability tests, it can be seen that the values of water penetrating into concrete specimens would increase with the increasing concentration of seawater. This means that, in spite of the internal structure of concrete corroded by seawater resulting in the strength reduction, the pores caused by erosion would be filled with salt crystals from seawater, and which would make the values measured by permeability tests insensitive to reflect the behavior of concrete suffering from corrosion.
e. For submerged with room temperature (20℃) and standard seawater (1 time concentration) under cyclically wetting and drying, the conditions of concrete corroded could be accelerated. The rate of concrete corroded could reach to above 4 times in terms of the results of visual inspection from specimen surface, compressive strength, and electric resistance tests.

References:

1. Clear, K. C., and Hay, R.E., "Time-to-Corrosion of Reinforcing Steel Slabs, Vol.1:Effect of Mix Design and Construction Parameters," Inter. ReportNo.FHWA-RA-73-32, Federal Highway Administration, Washington, D.C.,pp.103-105,1973.
2. Page, C. L., Short, N. R., and Holden, W.R., " Influence of Different Cements on Chloride-Induced Corrosion of Reinforcing Steel," Cement and Concrete Research,Vol.16, No.1, pp.79-86, 1986
3. Pressler, E.E., Brunauer, S., Kantro, D.L., and Weise, C. H., " Determination of the Free Calcium Silicates," Analutical Chemistry, V.ol. 33, No.7, pp.877-882,1961
4. Mehta, P.K. and Aitcin, P.C., "Effect of Coarse-Aggregate Characteristics on Mechanical Properties of High Strength Concrete, "ACI Material Journal, 1990.
5. ASTM, "1995 Annual Book of ASTM Standard", Vol.04.0104.24,1995.
6. Erik, J. L.D. Sellev, and Terje Nilsen, "Condensed Silica Fume in Concrete", A World Review," 1986.

7. Zhao, T. J. Z.H. Zhou, N.Q. Feng , “An Alternating Test Method of Concrete Permeability,” Cement and Concrete Research, Vol.28, No.1, pp.77-12, 1998.
8. Alexander, M.G. B.J. Magee, “Durability Performance of Concrete Containing 144 Condensed Silica Fume,” Cement and Concrete Research, Vol.29, pp.917-922, 1999.