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Cement and Concrete Research 34 (2004) 2037–2044

CEMENT AND CONCRETE RESEARCH

Comparing corrosion measurement methods to assess the corrosion activity of laboratory OPC and HPC concrete specimens

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Received 12 June 2003; accepted 2 March 2004

Abstract

The corrosion of reinforcing steels in concrete is the main reason for the deterioration of bridge decks. An accurate method for measuring corrosion is a fundamental prerequisite for the detection of damaged areas and for planning an effective method for repairing bridge decks. A laboratory study was conducted to estimate the corrosion activity of a reinforcing steel embedded in two types of concrete, ordinary and high-performance, using different corrosion measurement methods. Results indicated that Tafel plot (TP), linear polarization resistance, half-cell potential (HCP), and chloride content methods would assess the same level of corrosion activity in only 24% of specimens.

Keywords: Corrosion; Cycles; Electrochemical properties; High-performance concrete

1. Introduction

The detection and measurement of corrosion in bridge decks are essential in Bridge Management Systems (BMS). The corrosion activity level is used by most highway agencies as the main criterion to determine the proper time and method for bridge deck repair. In addition, monitoring the corrosion rate of a repaired deck could be used to evaluate the effectiveness of different repair methods. Although there are several methods for the diagnosis, detection, and measurement of corrosion in reinforcing steel, there is no consensus regarding which method assesses corrosion levels in reinforced concrete structures most accurately.

Various techniques for detecting and measuring corrosion will provide data on the causes, detection, or rate of corrosion [1]. Because chloride ions are the major contributing factor in the detection of reinforcing steel embedded in concrete, the measurement of chloride content provides data regarding the *causes* of corrosion. Chloride content is determined by obtaining concrete powder samples from different locations and depths and then analyzing them according to the specifications AASHTO T-260, ASTM C1152, and ASTM C1218. Chloride-content results are reported in either percent chloride by mass of concrete or mass of cement.

The main corrosion detection method is the half-cell potential (HCP) measurement. The ASTM C876 standardised test method for conducting corrosion potential tests on uncoated reinforcing steel in concrete employs HCP measurement. It is a nondestructive test that collects an enormous quantity of data from a large structural area. Most highway agencies in North America use a type of HCP, which incorporates copper/copper sulphate electrode (CSE) for measuring corrosion in bridge decks. One who interprets HCP data must consider factors such as variation in the moisture content, chloride concentration, and concrete electrical resistance, as all of these factors have a significant influence on the readings. For example, very high moisture content can increase the HCP to -1000 mV, while corrosion does not exist at all.

Electrochemical methods could be used to estimate the corrosion rate in concrete structures to show the speed at which reinforcing steels are corroding and, therefore, to identify vulnerable locations. The linear polarisation resistance (LPR) technique provides a simple method for immediately determining corrosion rate. It has long been used in laboratories for measuring the corrosion rates of metals in aqueous environments. The Tafel plot technique (TP) is another electrochemical method for calculating corrosion

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doi:10.1016/j.cemconres.2004.03.008

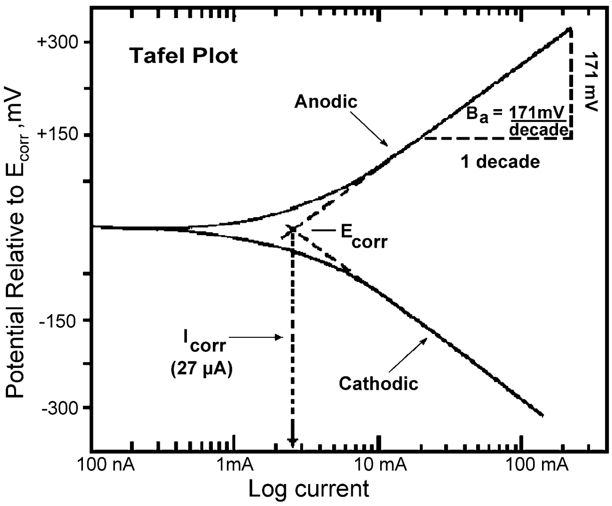

Fig. 1. Idealized TP.

rate based on the intensity of the corrosion current (I_{corr}) and the Tafel slopes. Tafel slopes also could be used to calculate corrosion rate with LPR [2–5].

Both LPR and TP techniques are based upon an application of either steady fixed levels of current, followed by a monitoring of the potential (galvanostatic) or an application of specific potential followed by a monitoring of the current (potentiostatic). The main difference between these two methods is that the change in potential must be kept to less than ± 25 mV for the LPR technique, while the change of potential can go up to ± 250 mV for the TP technique. Another difference between LPR and TP is in the interpretation of testing results for the calculation of corrosion rate. In TP, corrosion rate can be calculated using straightforward substitution of Tafel slope values (β_a and β_c) to get the corrosion current, as shown in Fig. 1 and examined in Eq. (1), then, by calculating corrosion rate using Eq. (2).

$$i = i_{corr}\exp[S_1(E - E_{corr})] - \exp[-S_2(E - E_{corr})] \tag{1}$$

where S_1 = slope of the anodic branch = 2.303/β_a, S_2 = slope of the cathodic branch = 2.303/β_c, β_a = anodic Tafel constant, β_c = cathodic Tafel constant, E_{corr} = the corrosion potential, i_{corr} = the corrosion current in Ampere, E = the potential at any time, and i = the current at any time.

$$\text{Corrosion rate } (\mu\text{m/yr}) = \frac{0.129 I_{corr}\,\text{E.W.}}{dA} \tag{2}$$

where I_{corr} = the corrosion current intensity, in μA/cm^2; A = exposed surface area of the reinforcing steel, in cm; E.W. = the equivalent weight of steel, which is the atomic weight of an element that has the same combining capacity as a given weight of another element, where the standard is 8 for oxygen; and d = the density of the reinforcing steel, in g/cm^3.

To calculate the corrosion rate using the LPR method, I_{corr} is first calculated with Eq. (3), which is based on the Stern–Geary relationship. And then, using Eq. (2), the corrosion rate can be calculated [6,7].

$$I_{corr} = \frac{\beta_a\beta_c}{2.3R_p(\beta_a\beta_c)} \tag{3}$$

where R_p is the polarisation resistance, in kΩcm^2, and β_a and β_c are constants, which could be obtained from a TP. To simplify the above calculation, some researchers have used Eq. (4), with a constant value, B, equal to 26 mV [8–12].

$$I_{corr} = B/R_p \tag{4}$$

2. Objectives and scope

The main objective of this study was to compare the corrosion activity of reinforced laboratory concrete specimens using several corrosion measurement methods. By reviewing the literature, four corrosion measurement methods (TP, LPR, HCP, and chloride content in concrete) were chosen to assess the corrosion activity of reinforcing steel embedded in laboratory concrete specimens. Additionally, a potential correlation between two main field corrosion measurement procedures, the HCP and chloride content, was explored. The laboratory experimental design enabled the acceleration of the corrosion process and the elimination of field variables. Therefore, the only variable remaining was the distinction between measurement methods and/or testing data interpretation.

3. Experimental program

3.1. Materials and concrete mix

Type 10 Portland cement, crushed granite with a nominal maximum size of 20 mm, and siliceous sand with fineness

Table 1
Concrete mixtures proportioning and properties

Materials and properties	Ordinary Portland cement concrete (OPC)	High-performance concrete (HPC)
Cement-type 10 (kg/m^3)	300	495
Water (kg/m^3)	180	165
Fine aggregate (kg/m^3)—fineness modulus = 2.8	675	612
Coarse aggregate (kg/m^3)—maximum size 20 mm	1250	1151
Superplasticizer (ml/100 kg cement)	0	2424
Silica fume (kg/m^3)	0	55
Slump (mm)	125	150
28-Day compressive strength (MPa)	32.5	95.2

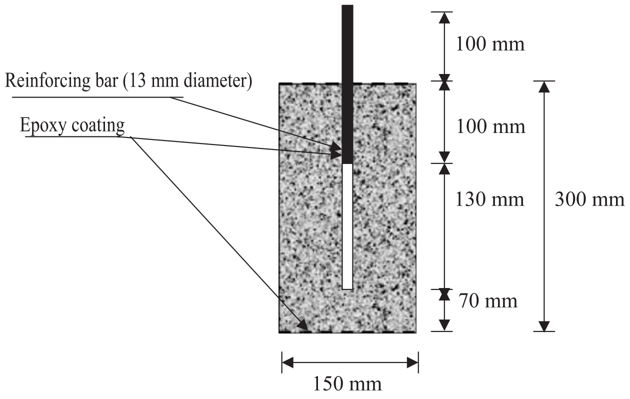

Fig. 2. Reinforced concrete cylinder.

modulus of 2.8 were used in this experiment. The concrete proportioning and some properties of both ordinary Portland cement concrete (OPC) and high-performance concrete (HPC) are shown in Table 1. The concrete cylinder specimens were 150 × 300 mm, with a 13-mm diameter reinforcing steel embedded in the center. This specimen arrangement could simulate a cover depth close to 60 mm. The reinforcing steel complied with ASTM A615 and was sealed with an anticorrosion epoxy coating, SikaTop-Armatec 110 Epocem, except on the area where corrosion was monitored. The base of each cylinder was sealed with impermeable coating, Fosroc-Nitoflor FC140, to insure that the ingress of chloride was coming from the surrounding perimeter only. Fig. 2 shows a typical reinforced concrete cylinder used in this study.

3.2. Laboratory conditionings

This study used 104 reinforced concrete cylinders to investigate the corrosion of reinforcing steel caused by chloride in controlled-exposure laboratory conditions. The chloride solution was made by dissolving the required weight of NaCl in distilled water. The chloride solution concentration was monitored and adjusted regularly. The specimens were subjected to four different concentrations (weight/weight) of chloride solution (0%, 1%, 3%, and 5%). The level of the solution was adjusted so that 250 mm of the specimen's height was in the solution during the test. To accelerate the corrosion of the reinforcing steels, after 28 days of standard curing conditions and two types of preconditioning exposure, all specimens were exposed to cycles of drying and wetting. Two types of specimens, B and E, were used. Type B stands for specimens that are not dried in an oven at 103 ± 2 °C before starting the first cycle of conditioning. Type E stands for specimens subjected to drying in an oven at 103 ± 2 °C before starting the first cycle of conditioning. Each specimen was subjected to cycles of drying for 1 week, followed by wetting for another week; then, it was tested. This procedure was applied to all the specimens, except E0, B0, E3, and B3, in which the specimens were submerged continuously in the solution and

Table 2
Description of conditionings and testing for concrete specimens

Specimen code	Preconditioning[a]		Conditioning process	NaCl concentration exposure[b]	Corrosion testing frequency
	Oven drying	Nonoven drying			
B0		X	Continuously in solution	0	Monthly
E0	X		Continuously in solution	0	Monthly
B1 (1)		X	7 days drying and 7 days wetting.	1	End of each
B1 (2)		X	Drying at 22 ± 2 °C and 80% relative humidity	3	wetting cycle
B1 (3)		X		5	
B2 (1)		X	7 days drying and 7 days wetting.	1	End of each
B2 (2)		X	Drying at 33 ± 2 °C and 94% relative humidity	3	wetting cycle
B2 (3)		X		5	
B3 (1)		X	Continuously in solution	1	Monthly
B3 (2)		X	Continuously in solution	3	Monthly
B3 (3)		X	Continuously in solution	5	Monthly
E1 (1)	X		7 days drying and 7 days wetting.	1	End of each
E1 (2)	X		Drying at 20 ± 2 °C and 80% relative humidity	3	wetting cycle
E1 (3)	X			5	
E2 (1)	X		7 days drying and 7 days wetting.	1	End of each
E2 (2)	X		Drying at 33 ± 2 °C and 94% relative humidity	3	wetting cycle
E2 (3)	X			5	
E3 (1)	X		Continuously in solution	1	Monthly
E3 (2)	X		Continuously in solution	3	Monthly
E3 (3)	X		Continuously in solution	5	Monthly
E4 (1)	X		7 days drying and 7 days wetting.	1	End of each
E4 (2)	X		Drying in oven at 103 ± 2 °C	3	wetting cycle
E4 (3)	X			5	

[a] After 28 days standard curing and before conditioning process.

[b] Weight percent.

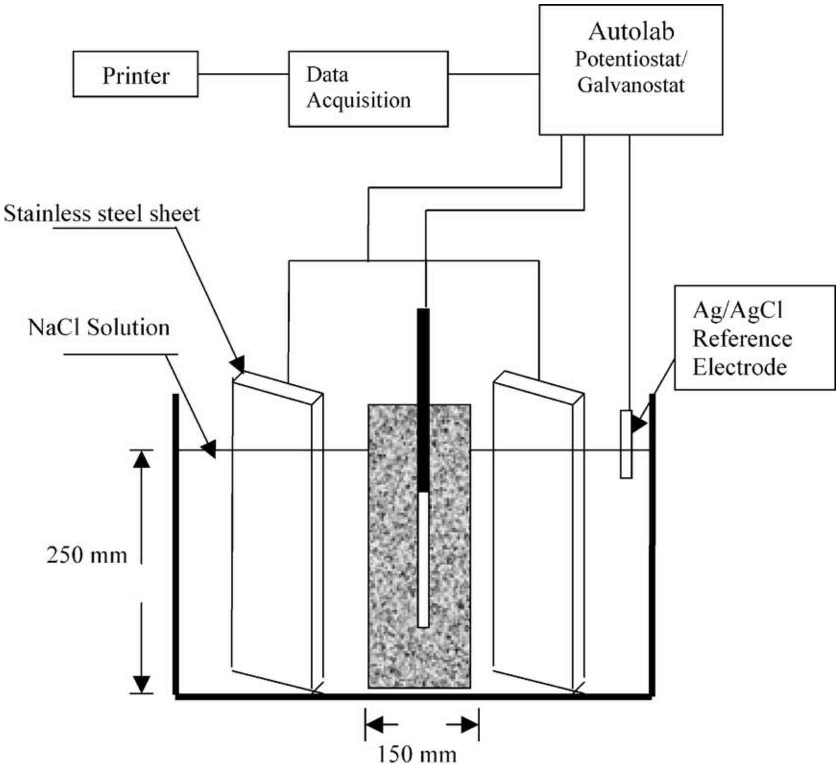

Fig. 3. Schematic diagram of test setup for corrosion rate measurement using LPR and TP techniques.

were tested once every month for corrosion. Table 2 shows the description of the laboratory preconditioning and conditioning exposures for all specimens.

3.3. Testing program

The test setup used for the LPR and TP techniques included a potentiostat/galvanostat, Autolab General Purpose Electrochemical System (GPES) for data acquisition, and a printer. Fig. 3 shows a schematic diagram of the test arrangement for LPR and TP. The exposed surface area, the equivalent weight of steel (E.W.), and the density of the reinforcing steel (*d*) were 53.11 cm^2, 27.93 g, and 7.8 g/cm^3, respectively.

With the Tafel technique, a potential scan was applied to the reinforcing steel in the specimen, extending to a few hundred millivolts (approximately ± 250 mV) either in the cathodic or anodic direction. The potential was plotted against the measured current. Using the LPR method, a controlled potential scan, E_{corr} from -25 to $+25$ mV, was applied to the reinforcing steel in the specimen, and the

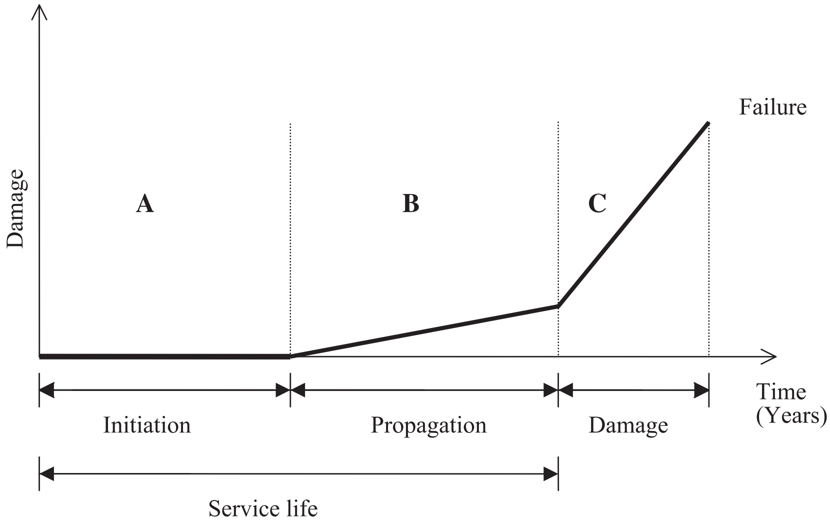

Fig. 4. Relation between the chloride content and the time needed for stages of initiation, propagation, and damage.

Table 3
Corrosion activity ranking system

Testing methods	Threshold	Corrosion activity description	Corrosion activity levels
Tafel plot (TP) and linear polarization resistance (LPR)	$I_{corr} \leq$ 0.2 μA/cm^2	Corrosion rate is negligible and that the steel is in the passive state.	A
	$0.2 \leq I_{corr} \leq$ 1 μA/cm^2	Corrosion has initiated and is proceeding at a moderate rate.	B
	$I_{corr} > 1$ μA/cm^2	High rate of corrosion.	C
Half-cell potential (HCP)	$E \geq -200$ mV	Very low probability of corrosion.	A
	$-350 \leq E < -200$ mV	Corrosion state is uncertain.	B
	$E < -350$ mV	Very high probability of corrosion.	C
Chloride content % by weight of cement	$Cl^- < 0.3\%$	Low corrosion state.	A
	$0.3 \leq Cl^- < 1\%$	Moderate corrosion state.	B
	$Cl^- \geq 1\%$	High corrosion state.	C

resulting current was plotted against the potential. For each test specimen, the polarization resistance (R_p) was obtained following each conditioning cycle. The corrosion rate was calculated based on Eqs. (1)–(3).

By drilling the concrete around the reinforcing steel surface, a water-soluble chloride concentration was ascertained, and powder samples from six different locations were obtained. These samples were subsequently analyzed chemically to calculate the chloride concentration at the surface of the reinforcing steels. Details of the chemical analysis are given in ASTM C1218/C1218M. In addition, potential values were measured using the HCP method based on ASTM G876.

3.4. Establishing corrosion activity levels

The corrosion activity of reinforcing steel was estimated based on corrosion testing results for all specimens. Several researchers have suggested three corrosion levels for reinforcing steel in concrete: initiation, propagation, and damage. Fig. 4 depicts a typical relationship for corrosion activity levels in bridge decks versus time. These corrosion activity levels are used widely to determine the repair time and to select an appropriate repair method for the bridge deck [13–16].

To estimate corrosion activity levels based on testing results, it is necessary to define the threshold values corresponding to different corrosion activity levels. There is not a consensus among researchers regarding such values. During a review of the literature, certain threshold values (for corrosion rate, HCP, and for the percent of chloride in concrete) were selected to estimate the initiation, propagation, and damage states of corrosion. These were designated as A, B, and C corrosion activity levels, respectively. These threshold values and their corresponding corrosion activity levels are summarized in Table 3. For corrosion current intensity (I_{corr}), values between 0.2 and 1 μA/cm^2 have been recommended for the propagation stage (Level B), while corrosion rate values below and above this range represent the initiation (Level A) and damage corrosion activity levels (Level C), respectively [13]. The threshold values selected for the HCP are values suggested by the ASTM C 867. A chloride content of around 0.3% and more

Table 4
The corrosion activity levels for OPC and HPC specimens after 16 cycles

Specimen code and concrete types	Cl^- (wt.% of cement)	I_{TP}	I_{LPR}	HCP ($-$mV)	Corrosion activity level			
		μA/cm^2			Cl^-	TP	LPR	HCP
B0-OPC	0.04	0.21	0.26	120	A	B	B	A
B1(1)-OPC	0.38	2.56	3.42	214	B	C	C	B
B1(2)-OPC	0.49	3.68	4.84	340	B	C	C	B
B1(3)-OPC	0.63	7.26	9.40	475	B	C	C	C
B2(1)-OPC	0.42	3.68	5.13	262	B	C	C	B
B2(2)-OPC	0.65	6.32	8.29	275	B	C	C	B
B2(3)-OPC	0.92	9.40	12.39	380	B	C	C	C
B3(1)-OPC	0.13	1.45	1.79	250	A	C	C	B
B3(2)-OPC	0.42	1.62	2.13	280	B	C	C	B
B3(3)-OPC	0.54	2.14	2.82	322	B	C	C	B
E0-OPC	0.04	0.26	0.30	187	A	B	B	A
E1(1)-OPC	0.49	2.56	2.99	440	B	C	C	C
E1(2)-OPC	1.01	4.70	5.98	525	C	C	C	C
E1(3)-OPC	1.70	6.84	9.23	611	C	C	C	C
E2(1)-OPC	0.52	3.42	3.93	390	B	C	C	C
E2(2)-OPC	1.21	5.98	7.61	511	C	C	C	C
E2(3)-OPC	1.90	7.86	10.60	597	C	C	C	C
E3(1)-OPC	0.32	1.19	1.37	395	B	C	C	C
E3(2)-OPC	0.85	1.88	2.40	490	B	C	C	C
E3(3)-OPC	1.22	3.42	4.61	540	C	C	C	C
E4(1)-OPC	1.34	37.17	42.74	740	C	C	C	C
E4(2)-OPC	3.95	119.65	152.99	670	C	C	C	C
E4(3)-OPC	8.0	145.30	196.58	682	C	C	C	C
B0-HPC	0.008	0.09	0.13	120	A	A	A	A
B1(1)-HPC	0.07	0.68	0.77	117	A	B	B	A
B1(2)-HPC	0.12	1.11	1.37	144	A	C	C	A
B1(3)-HPC	0.16	1.79	2.31	196	A	C	C	A
B2(1)-HPC	0.10	1.28	1.45	78	A	C	C	A
B2(2)-HPC	0.22	1.97	2.48	173	A	C	C	A
B2(3)-HPC	0.28	3.08	4.02	178	A	C	C	A
B3(1)-HPC	0.02	0.38	0.43	150	A	B	B	A
B3(2)-HPC	0.06	0.43	0.51	210	A	B	B	B
B3(3)-HPC	0.10	0.77	1.03	262	A	B	C	B
E0-HPC	0.02	0.13	0.17	105	A	A	A	A
E1(1)-HPC	0.11	1.11	1.28	190	A	C	C	A
E1(2)-HPC	0.15	2.22	2.82	264	A	C	C	B
E1(3)-HPC	0.22	2.74	3.68	344	A	C	C	B
E2(1)-HPC	0.15	1.71	1.97	122	A	C	C	A
E2(2)-HPC	0.19	3.25	4.19	211	A	C	C	B
E2(3)-HPC	0.27	3.68	5.13	212	A	C	C	B
E3(1)-HPC	0.06	0.51	0.59	165	A	B	B	A
E3(2)-HPC	0.09	0.85	1.11	222	A	B	C	B
E3(3)-HPC	0.13	1.19	1.62	344	A	C	C	B
E4(1)-HPC	0.58	17.09	20.09	480	B	C	C	C
E4(2)-HPC	0.87	27.78	35.56	670	B	C	C	C
E4(3)-HPC	1.55	38.72	52.31	660	C	C	C	C

than 1% of the weight of cement at the surface of reinforcing steel are suggested for the initiation and damage stages of corrosion (Levels A and C, respectively) and values between these could be related to the propagation stage (Level B [13]).

4. Results and discussions

Table 4 presents the testing results and corrosion activity levels for OPC and HPC specimens after 16 conditioning cycles.

The testing results, based on the LPR method, are 10% to 30% higher than those obtained by the TP method. A similar difference of 30% was reported in a previous research study [16]. In an interlaboratory test program, involving eight laboratories, the corrosion rate of Type 430 stainless steel in an H_2SO_4 solution was 15% to 25% higher, based on the results obtained by the LPR technique, than those based on the TP technique [17]. Both the TP and LPR methods ranked the same corrosion activity level for OPC and HPC specimens after 16 conditioning cycles. Based upon 46 cases studied encompassing different conditionings and concrete types (OPC and HPC), only in two cases, B3 (3) and E3 (2), did the LPR method estimate the corrosion activity of a specimen one level higher than the TP method did. In both of these cases, the I_{corr} values determined by the LPR method were close to the threshold values. It can be concluded that both TP and LPR methods give similar corrosion activity levels for all types of concretes and conditionings considered in this study. This conclusion was expected because both the TP and LPR methods used the same testing concept. In addition, the calculation of corrosion rate used in LPR was based on a Tafel constant.

There was a consensus regarding the predictions for the corrosion activity level by the chloride content and HCP methods in 70% of OPC specimens and 57% of HPC specimens. HCP predicted one level higher corrosion activity level than the chloride method did in 6 and 10 cases for OPC and HPC, respectively.

In comparing the two concrete types used in this study, OPC and HPC, it was concluded that all testing results based on HCP and chloride content methods were higher for OPC than for HPC. The lower w/c ratio and incorporation of silica fume played a significant role in decreasing the permeability and in enhancing the internal structure of the paste and aggregate. This decreased the corrosion activity of the specimens. No differences in the corrosion activity levels of OPC and HPC specimens, conditioned at 0% chloride solution, were observed. All of these specimens, B0 and E0 for OPC and HPC, respectively, showed a very low probability of corrosion (Level A).

Results demonstrated that preconditioning (oven drying after 28-day standard curing) had no impact on the corrosion activity level of HPC specimens. There was some impact on the corrosion activity level of certain OPC specimens. Both HCP and chloride content showed a high corrosion activity level (Level C) for E4 specimens, regardless of concrete types (HPC and OPC). This was due to the very harsh conditioning process used (cycles of drying in oven at 103 °C) for these specimens. This drying process accelerated the diffusion of chloride in concrete specimens and significantly and consequently caused a high corrosion activity level.

In comparing all the testing methods considered in this study, the same corrosion activity levels were found in 24% of the specimens. Most of these similarities occurred for Type E OPC specimens.

For specimens in which testing methods suggested different corrosion activity levels, the chloride content method estimated the lowest corrosion activity level, while TP and LPR methods predicted the highest corrosion activity level. The HCP method estimated the corrosion activity level to be between these methods.

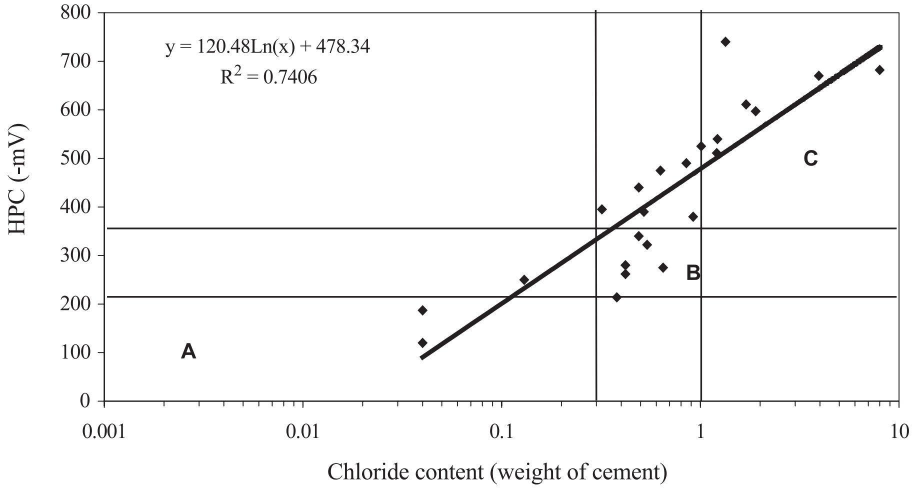

Fig. 5. Relationship between chloride content and HCP results for OPC specimens.

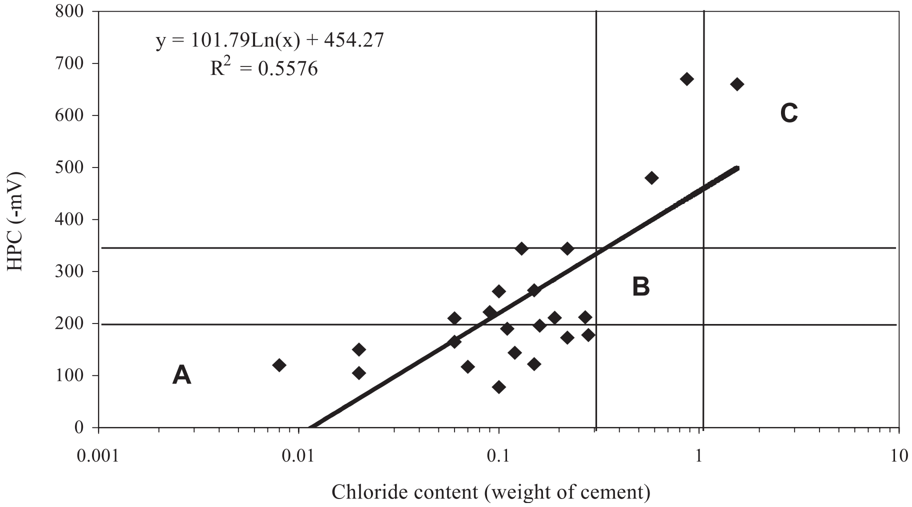

Fig. 6. Relationship between chloride content and HCP results for HPC specimens.

4.1. Relationship between HCP and chloride content

Because the HCP and chloride content methods have been used alternatively by some highway agencies for corrosion measurement, a study was undertaken to find the relationship between HCP readings and chloride content measurements in this experiment. Fig. 5 shows the relationship between chloride content and HCP values for OPC specimens. Eq. (5) summarises this relationship.

$$\mathrm{HCP} = 120.48\mathrm{Ln}(\mathrm{Cl}^-) + 478.34 \quad (5)$$

where HCP is the potential reading, in $-$mV, and Cl^- is the chloride content as percent of weight of cement.

A high correlation between HCP and chloride content methods was found for OPC specimens (R^2=.74). In Fig. 5, the data inside Regions A, B, and C represent specimens in which both methods predicted the same corrosion activity levels. The high number of data in Region C indicates a high corrosion activity level predicted by both methods for OPC specimens.

Fig. 6 shows the relationship between HCP and chloride content values for HPC specimens, and Eq. (6) summarises this relationship. A lower correlation was found for the HPC specimens in comparing Eq. (6) with (5) for OPC; a lower correlation was found for the HPC specimens. Fig. 6 depicts a higher number of specimens in Region A, which means lower corrosion activity for HPC specimens.

$$\mathrm{HCP} = 101.79\mathrm{Ln}(\mathrm{Cl}^-) + 454.27 \quad (6)$$

5. Conclusions

One hundred and four laboratory concrete specimens were conditioned and tested with four common corrosion testing techniques to estimate their corrosion activity levels. All samples were conditioned and tested in laboratory-controlled conditions. Findings from this experiment could provide direction for further studies in corrosion testing techniques comparison. These findings could not be used in real field conditions or in the case of concretes not studied. Some findings from this experiment are summarized below:

1. The four corrosion testing methods used in this study predicted the same corrosion activity level for only 24% of specimens studied. In those cases where specimens were estimated to have different corrosion activity levels, the chloride content method usually estimated the lowest corrosion activity level, while the TP and LPR methods predicted the highest corrosion activity levels. The HCP method usually estimated a corrosion activity level that fell between the estimations offered by the other methods.
2. While the LPR testing results were 10% to 30% higher than TP testing results, both methods suggested identical corrosion activity levels for more than 96% of the specimens studied.
3. A reasonable consistency (close to 65%) was observed between the HCP and chloride content corrosion measurement methods in estimating the corrosion activity levels of concrete specimens. In the remaining cases (35%), the HCP method tended to overestimate the corrosion activity of concrete specimens compared with chloride content methods.
4. HPC specimens showed lower corrosion testing results compared with OPC specimens with both corrosion testing procedures. The lower w/c ratio and the use of silica fume could be the main reasons for lower corrosion activity levels.
5. Cycles of drying specimens drying in the oven accelerate significantly the diffusion of chloride for both OPC and HPC specimens.
6. Mathematical relationships were developed for chloride content and HCP testing results. A higher correlation was

found for OPC specimens compared with HPC specimens. To find a general relationship between HCP and chloride content, testing results still needs more validation based on the consideration of field variables.

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