สมาคมคอนกรีตแห่งประเทศไทย
Thailand Concrete Association

Journal of Thailand Concrete Association
วารสารวิชาการสมาคมคอนกรีตแห่งประเทศไทย

FACTORS AFFECTING NEAR SURFACE TESTS OF IN-SITU CONCRETE STRUCTURES FOR CARBONATION-INDUCED CORROSION

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ARTICLE INFO:

Received: July 5, 2012
Received Revised: Aug. 15, 2012
Accepted: Aug. 25, 2012

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ABSTRACT :

Corrosion in RC members leads to reduction in strength and serviceability of the structures. Several non-destructive testing techniques can be employed to evaluate the possibility of reinforcement corrosion relatively quickly and cost-effectively. However, due to uncontrollable variations of structures conditions in the field, the reliability and validity of the test results are in doubt. This paper examines the effects of surface conditions, concrete moisture content, ambient conditions, and carbonation depth on the rebound number, half-cell potential, two and four-probe resistivities, and linear polarization resistance. Eighteen reinforced concrete buildings located in Bangkok metropolitan areas which are ten years or older were sampled. Statistical analyses were performed to determine the significance of each effect on the non-destructive test values. The effects and relationship of each factor were shown on this paper.

KEYWORDS : Corrosion, Carbonation, Non-destructive test, Reinforced Concrete.

1. Introduction

Corrosion of reinforcement in reinforced concrete (RC) building affects the strength, serviceability and reliability of the structures. For Bangkok metropolitan area, the majority of corrosion in RC buildings is caused by carbonation reaction due to high concentration of carbon dioxide. If the corrosion problem is left undetected, the corrosion could propagate which leads to reduction of steel cross-section and spalling of concrete cover. Repair of severely corroded reinforcement is often difficult and expensive. If the corrosion problem can be detected in the early stages, only minor repairs or preventive maintenance is required, which is more economical. There are various non-destructive techniques (NDT) that can be used for the assessment of the corrosion activity and sign of deterioration in concrete. These NDT tests can be performed quickly and routinely with relatively small costs. However, due to uncontrollable variations of structure's conditions in the field, the reliability and validity of these test results are in doubt.

The objective of this research is to determine the effects of surface conditions, concrete moisture content, ambient conditions, and carbonation depth on the non-destructive test results, including rebound number, half-cell potential, two and four-probe resistivities, and linear polarization resistance.

The scope of this research is limited to conventional reinforced concrete buildings located in Bangkok metropolitan areas which are ten years or older.

2. Background

2.1. Carbonation-induced corrosion

Carbonation reaction is a process in which carbon dioxide in the atmosphere reacts with dissolved calcium hydroxide in the pore water of concrete, resulting in the formation of calcium carbonate

(Equation1). The consumption of calcium hydroxide decreases the pH of concrete from approximately 13.4 to 8.3, leading to a breakdown of the passive layer around reinforcement that protects it from corrosion[1].

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \quad (1)$$

The corrosion reaction of steel is an electrochemical reaction in which ferrous ions are dissolved into the pore water in the anode sides react with water and oxygen to form rust ($Fe_2O_3 \cdot H_2O$).

2.2. Non-destructive tests for signs of corrosion

Corrosion activity in reinforced concrete structures can be measured either directly from various characteristics of the corrosion process, or can be predicted indirectly based on several aspects of the concrete quality [2].

The most common method for direct measurement of corrosion activity is half-cell potential. This method measures the difference in electrical potentials between the embedded steel in concrete and the reference electrode immersed in specified electrolytic solution. A value more negative than -350 mV indicates a high likelihood of active corrosion while a value more positive than -200 mV indicates a high likelihood that no corrosion is occurring at the time of the measurement [3].

Another method for measured the corrosion activity is linear polarization resistance (LPR), which determines the corrosion rate of reinforcement by measuring the change in the open-circuit potential of the short-circuited electrolytic cell when an external current is applied to the cell. The slope of a linear relationship between voltage (E) and applied current (I) over the cross-sectional area of reinforcement bar (A) is called the polarization resistance (R_p), which is directly related to the corrosion current density (I_{corr}) :

Corrosion risk can also be related to the concrete properties and environmental conditions [4, 5]. Quality of concrete, especially near the surface, plays an importance role in corrosion resistance of reinforced concrete structures. A non-destructive surface hardness tests can be used to evaluate the quality of concrete. Concrete with large pores or cracks, which allows for faster transport of carbon-dioxide and water, usually lower surface hardness compared with concrete with smaller pore systems[6]. The most common equipment for this test is a rebound hammer, which is inexpensive and can be performed very quickly. However, the result obtained may be affected by surface hardening from the carbonation reaction near the surface, which makes it impossible to relate the rebound number to the original concrete strength [2].

The extent of carbonation reaction can be measured by spraying a freshly exposed surface of the concrete with 1% phenolphthalein solution. Phenolphthalein is a pH indicator, which turns pink at a pH higher than 9.0 and remains colorless at pH below 9.0 [7]. The carbonated concrete, having pH of about 8.3, will become pink upon contact with the solution [8].

The electrical resistance of the concrete controls the ease at which ions migrate through the concrete between anodic and cathodic sides and therefore affects the corrosion rate. This could be tested indirectly by measuring the electrical resistance of concrete. The resistivity value can be measured by two-or four-probe resistivity apparatus [2]. However, the carbonation reaction reduces the conductivity of concrete by converting hydroxide ions in the pores to an insoluble calcium carbonated ($CaCO_3$). Thus, the validity of this method is questionable for carbonation-induced corrosion.

3. Experimental Program

3.1. Sample Selection Protocol

Samples in this study were collected from buildings in three locations within Mahidol University located in Bangkok metropolitan areas namely Phayathai, Salaya and Siriraj campuses. The buildings in these campuses were classified by their ages into five categories as 10 to 19 years, 20 to 29 years, 30 to 39 years, 40 to 49 years, and 50 years or more. Then, preliminary visual investigations were made for these buildings to select only one or two buildings for each age category for each zone. The criterion used for the selection of the sampled buildings included accessibility of the building, signs of deterioration, and space available for the tests. In some campuses, no building older than 40 years was available; as a result, no collection was made in these age categories. A total of eighteen reinforced concrete building was chosen for sample collection. Table 1 summarizes number of buildings sampled from each category.

For each building, at least three locations within the building were selected for the test with different levels of corrosion damages, i.e. from mild to severe, based on signs of corrosion damages from visual inspections.

Table 1 Number of Sampled Buildings.

Building Age (Years)	Zone		
	Phayathai	Salaya	Siriraj
10-19	1	2	2
20-29	1	3	1
30-39	2	1	2
40-49	2	-	-
>50	-	-	1

3.2. Testing and Data Collection

First, the basic information of each building collected such as visual appearance, surface preparation, member type, and exposure condition at each test location.

For each selected location, signs of deterioration and cracks were identified by visual inspection. A crack microscope was used for measurement of crack width. Then a cover meter was utilized to find the location and cover of reinforcing bar. After that, a moisture content of concrete was measured by a moisture meter. Then, non-destructive tests were performed. Figure 1 shows the schematic layout of the testing positions on each selected location. Each test was performed along the reinforcing bar except the two and four-probe resistivity tests.

The quality of the cover concrete was evaluated by surface hardness test using a rebound hammer followed by two-probe resistivity. After that, 50 mm. holes were drilled to the level of reinforcement bar.

Then the half-cell potential method was tested conforming to ASTM C876 [3]. Next, 1% phenolphthalein solution in alcohol was sprayed into the hole. The depth to which the concrete does not change its color was measured to 1 mm precision and recorded as a carbonation depth for that hole. Then, the linear polarization (LPR) was performed following ASTM G59 guidelines [9]. Finally, the four-probe resistivity method (adapted from ASTM G57 [10]) was performed. In addition, ambient temperature, relative humidity and carbon dioxide (CO_2) concentration during the test were collected at each test point using appropriate sensors. Figure 2 show some of the test apparatus.

3.3. Data Analysis and Interpretation of Results

Basic information of buildings and the data collected from the tests were analyzed using PASW Statistics software. Analysis of variance (ANOVA), linear regression, and logistic regression techniques were used for finding the contribution of various factors in the measurements of the tests. The details of the analysis can be found in a Statistics textbook [11].

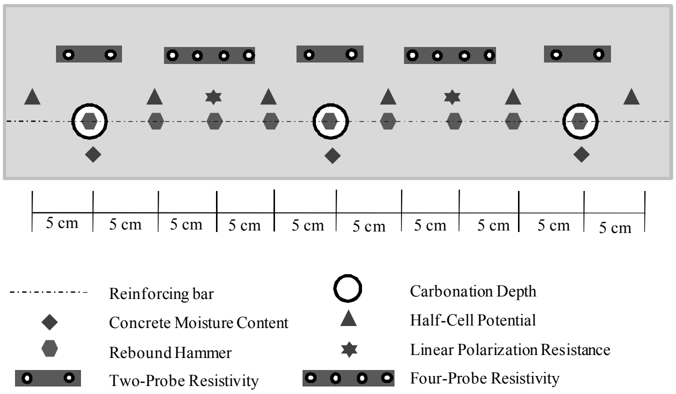


Figure 1 Schematic testing position for each test.

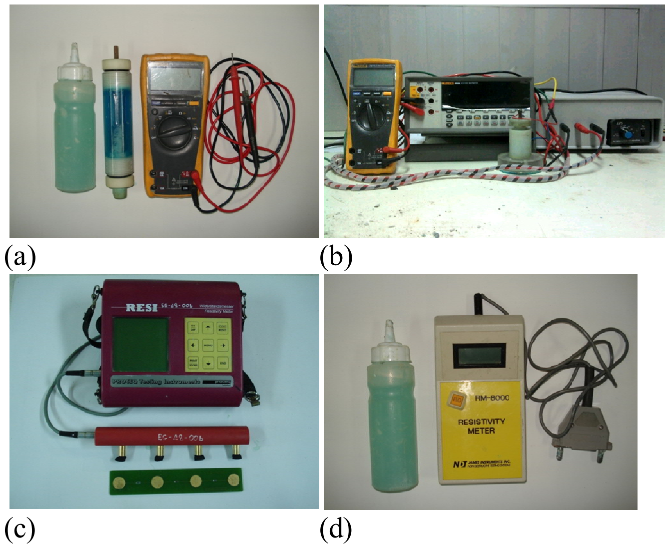


Figure 2 *Test apparatus (a) Half-cell potential apparatus, (b) LPR apparatus, (c) Four-probe resistivity apparatus, (d) Two-probe resistivity apparatus.*

4. Result and Discussion

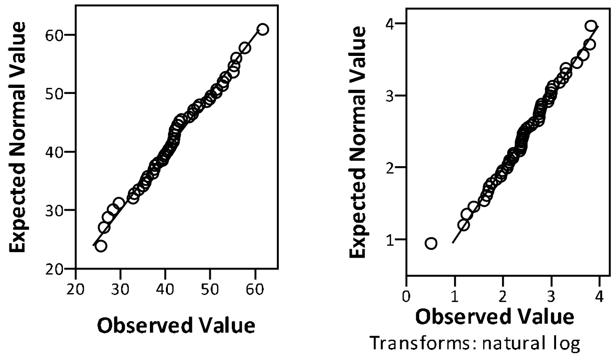
4.1. *Distribution of data*

In many statistical analysis procedures, the dependent variable must be normally distributed. Thus, it is necessary to check the distribution of each variable against normal distribution. A probability plot was used [11]. If the data follows normal distribution, the point should align along a straight line; otherwise a lognormal distribution is then checked. This is done by transforming the data using natural log and plot in a normal probability plot. If the points follow a straight line, the variable is lognormally distributed and the log of the data will then be used in the analyses where normal distribution is required. For variables that do not follow either normal or lognormal distribution. They are classified as other.

Table 2 summarizes the statistical distribution of the variables collected.
Figure **3** shows the example of probability plot for normal and lognormal variables.

Table 2 Distribution of variables.

Variable	Distribution		
	Normal	Log normal	Other
2-Probe Resistivity			●
4-Probe Resistivity			●
Age	●		
Carbonation Depth		●	
CO_2 Content		●	
Concrete Moisture	●		
Half-Cell Potential	●		
I_{corr}		●	
Rebound Number	●		
Relative Humidity	●		
Temperature			●



(a) rebound number (b) carbonation depth

Figure 3 Probability plot.

4.2. Environmental Condition

4.2.1. Temperature and Relative Humidity
Because all the samples in this research were collected from buildings within Bangkok metropolitan areas, the temperature and relative humidity among the zones were not expected to be substantially different. Much larger variations can occur from daily or seasonal variations, and also whether the test point is air-conditioned or open-air. Nonetheless, the temperature and relative humidity were collected to investigate their effects on the values of other tests. From the collected data, the average outside temperature and relative humidity for all zones were 32.2 ˚C and 61.3%, respectively. The range of temperature and relative humidity at the test points were between 22-34 ˚C and 55-77%, respectively.

4.2.2. Carbon-Dioxide Concentration
Figure 4 shows the average CO_2 concentration for each zone classified by open-air or having air conditioner. The result shows that Siriraj zone had the highest CO_2 concentration whereas Salaya zone had the lowest concentration. The result agrees with the observation that the Siriraj zone had highest building density and had the most traffic congestions around the area comparing to the other zones. On the other hand, Salaya zone had very low building density with a lot of trees and lowest traffic.

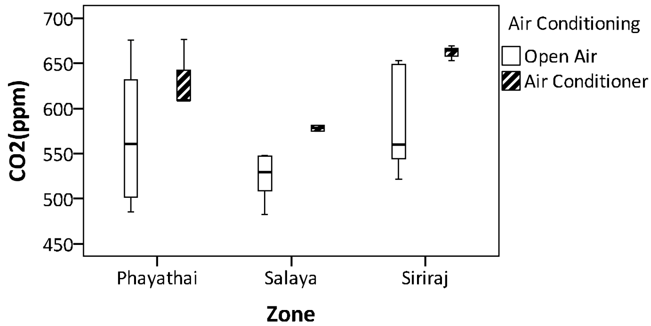


Figure 4 Average carbon-dioxide concentration vs. zone.

When comparing the CO_2 concentration between the case of air conditioning and open-air at each zone, it was found that the CO_2 concentration of the air-conditioned area was significantly higher than that in the open-air area. Air conditioning prevents the exchange of CO_2 caused by breathing of building's occupants to the outside atmosphere. These observations are confirmed by the linear regression analysis of the logarithm of CO_2 concentration with zone and air conditioning, which shows a significance level (p-value) of less than 0.001.

4.3. Near-Surface Concrete Moisture
Figure 5 shows the relationship between concrete moisture content with ambient relative humidity for points with and without air conditioner. It can be observed that for point with air conditioner, the moisture content increases as the relative humidity increases. However, for the open-air conditions, no relationship was found between the concrete moisture and the relative humidity. This is because concrete moisture changes very slowly while the ambient relative humidity may fluctuate throughout the day.

Furthermore, linear regression analysis found no relationship between the concrete moisture and possibility of water contact, surface finisher or member type.

4.4. Carbonation Depth

Figure 6 shows a relationship between the carbonation depths and the age of the building. Even with all the variabilities, a positive relationship can be observed. A linear regression analysis revealed that age is a significant factor for prediction of the carbonation depth, However, no effect was found for the CO_2 concentration. This is because carbonation is a process occurred during a period several years. The CO_2 concentration measured during at any time may not be good representative of the average CO_2 concentration throughout the life time.

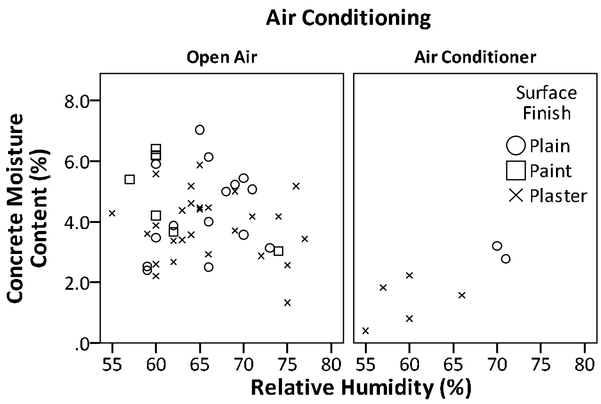


Figure 5 Concrete moisture content vs. relative humidity.

In this research, a general zone variable was found to be more significant than the CO_2 in relation to the carbonation depth. Buildings in Siriraj zone appeared to have higher value of carbonation depth than those in the other zones. The effect of surface finish on the carbonation depth is shown in Figure 7. It can be seen that carbonation depth of painted surface is significantly lower than that of plain concrete surface. This is because paint filled the surface voids and prevented the CO_2 diffusion into the concrete. When compared between paint and plastered (usually with paint applied as well) surface, the carbonation depth of plastered surface was found to be slightly lower and had larger variability. The lower and more variable quality of mortar plaster appear to offset the effect of paint in this case. The observation is confirmed by the linear regression analysis of the logarithm of carbonation depth with age of building, Siriraj zone, and surface finish, which shows a significant (p-value) of less than 0.05.

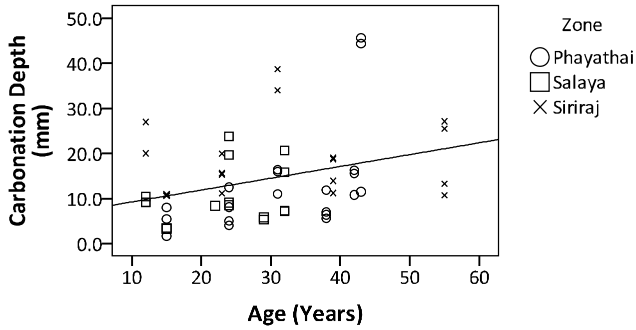


Figure 6 Carbonation depth vs. age of building.

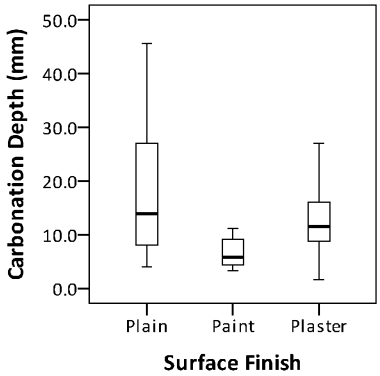


Figure 7 Carbonation depth vs. type of surface finish.

4.5. Rebound Number

Rebound number of plastered surface was found to be significantly lower than those of plain and painted surfaces, as shown in Figure 8. This is expected because mortar plaster has lower surface hardness and elastic modulus than concrete due to the absence of coarse aggregate. On the other hand, rebound numbers of plain and painted surfaces were not significantly different considering the overall variability of concrete quality. Detailed analysis also revealed that the rebound numbers are not significantly different among buildings from different zones because the sample buildings are of similar scale and similar design criteria.

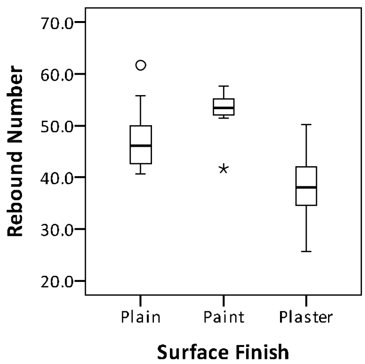


Figure 8 Rebound number vs. surface finish.

Although carbonation reaction increases the surface hardness of concrete [12], the results, as shown in Figure 9, show no trend between the rebound number and carbonation depth because all the samples have already been carbonated.

4.6. *Concrete Resistivity*

From Table 2, concrete resistivities, measured using either two-or four-probe method, do not follow normal or lognormal distribution and contain a lot of points having values close to 100 kΩ-cm (i.e. resistivity too high to be measured). Thus, in this study, the resistivity is treated as dichotomous variable, having the value of 0 and 1. The value of 0 is assigned when the measured is below 90 kΩ-cm and 1 for values greater than 90 kΩ-cm Figure 10 shows the relationship between proportion of samples having resistivities greater than 90 kΩ-cm and the carbonation depth. It can be observed that the proportion of concrete having resistivities greater than 90 kΩ-cm increases as the carbonation depth increases. This is because the carbonation reaction consumes calcium hydroxide ($Ca(OH)_2$) inside the pores and result in calcium carbonated ($CaCO_3$) leading to a reduction in electrical conductivity. Both two- and four-probe methods show similar trend. However, four-probe method is slightly more sensitive to carbonation than the two-probe method.

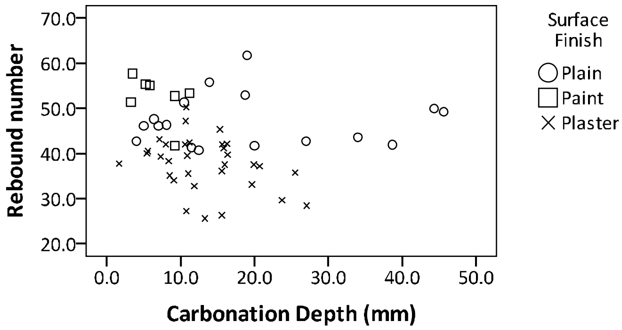


Figure 9 Rebound number vs. carbonation depth.

Concrete resistivity was also found to be influenced by moisture content as shown in Figure 11. It can be seen that the proportion of concrete having resistivities greater than 90 kΩ-cm. decreases as concrete moisture content increase in because of an increasing the conductivity of concrete when water is present in the pores. No statistical significant relationship was found between concrete resistivity and surface finishes. This is partly due to the relatively small number of samples having resistivity below 90 kΩ-cm.

4.7. *Half-Cell Potential and Linear Polarization Resistance*

Figure 12 shows the relationship between half-cell potential and concrete moisture content classified by levels of carbonation depth. It can be observed that half-cell potential tends to decrease as concrete moisture content increases. In addition, half-cell potential tends to be lower in groups with high carbonation depth. However, it is not possible to determine whether this is a factor affecting the test or that reinforcement in concrete having high moisture content and high carbonation depth are corroding, which leads to lower half-cell potential. Nonetheless, the linear regression found no significant effects of age, surface finish, water contact, or exposure conditions.

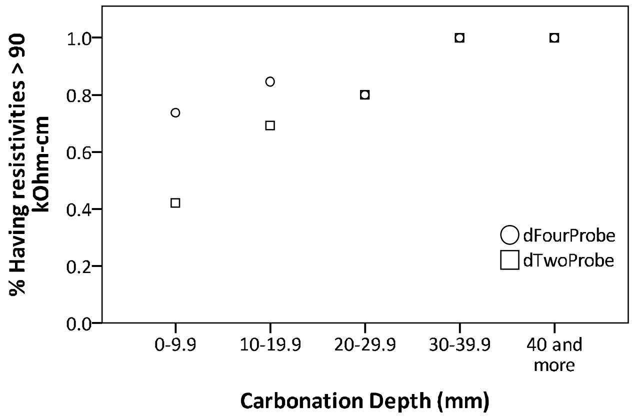


Figure 10 Percent of sample having resistivities more than 90 kOhm-cm vs. carbonation depth.

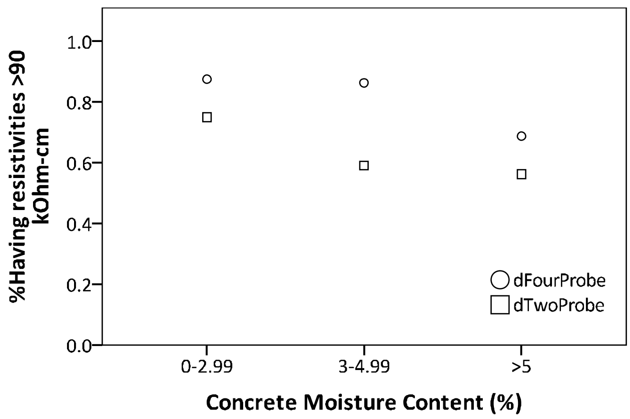


Figure 11 Percent of sample having resistivities more than 90 kOhm-cm vs. concrete moisture content.

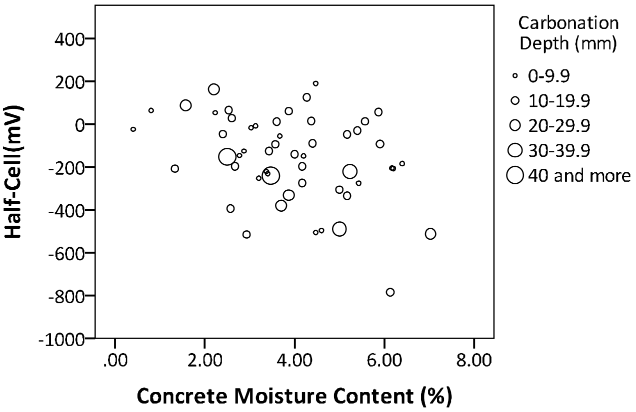


Figure 12 Half-cell potential vs. concrete moisture.

For linear polarization resistance test, it was found that the samples having plastered finish yield significantly lower I_{corr} than other groups of surface finishes. This possibly due to the gaps between plaster and substrate concrete caused by drying shrinkage of plaster impede the current flow. These values are then excluded from the analysis. On the half-ell potential; Figure 14 shows the relationship between I_{corr} and concrete moisture content classified by carbonation depths for only plain and painted surface. Unlike the half-cell potential, the result shows no clear trend between the I_{corr} and moisture content or carbonation depth due to the small number of samples left.

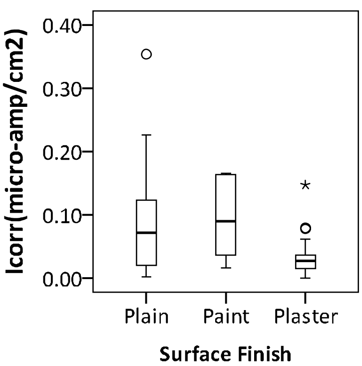


Figure 13 I_{corr} for different surface finishes.

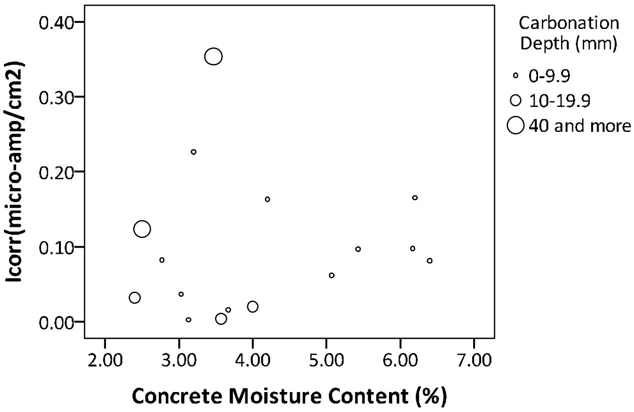


Figure 14 I_{corr} vs. concrete moisture.

5. Conclusions

In this study, the effects of surface conditions, concrete moisture content, ambient conditions, and carbonation depth on the non-destructive test results in concrete structures are evaluated. The following conclusions can be drawn from the result of this study.

1. Carbon-dioxide concentration is affected by zone of the building and whether it is air conditioned or not.
2. Near-surface concrete moisture content is affected by ambient relative humidity only under air conditioner. No relationship was found between concrete moisture content and possibility of water contact, surface type, or member type.
3. The carbonation depth is affected by the age of building, zone, and type of surface finish.
4. Rebound number of plastered surface was found to be significantly lower than those of plain and painted concrete.
5. Concrete resistivity, measured using either two-or four-probe method, is affected by carbonation depth and concrete moisture content.
6. Half-cell potential can be affected by concrete moisture content and carbonation depth, but is insensitive to surface finish.
7. I_{corr} can not be measured reliably on a plastered surface.

Acknowledgements

The authors would like to acknowledge the support provided by the National Research Council of Thailand.

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