Evaluation on use of half-cell potential for measuring corrosion potential of steel bars in reinforced concrete subjected to carbonation

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Abstract

This paper describes corrosion activity of reinforcing steels in reinforced concrete which was attacked by carbonation. The half-cell potential (HCP), corrosion current density (i_{corr}) and depth of carbonation were measured to investigate the corrosion status of the reinforcing steels. Six fly ash concrete (FA) mixtures with water to binder ratios of 0.4, 0.5 and 0.6 were compared to three mixtures of ordinary Portland cement concrete (OPC). The specimens were exposed in a carbonation chamber in which the conditions were controlled at 4 % carbon dioxide concentration, 40ºC, and 55±5% RH. Results demonstrated that HCP measurement was not appropriate for being used to investigate probability of steel corrosion due to carbonation. When carbonation front extended to surface of steel bars, i_{corr} suddenly jumped to more positive values. However, the HCP showed different tendency when compared with i_{corr}. HCP showed almost constant values even though steel bars had corroded by carbonation. This study clearly indicates that HCP measurement may not be appropriate for being applied to investigate probability of steel corrosion due to carbonation. On the other hand, i_{corr} and depth of carbonation showed good correlation in detecting corrosion initiation in laboratory measurement.

1. Introduction

Many reinforced concrete structures in Bangkok are subjected to carbon dioxide, which significantly degrades the structural performance due to the occurrence of corrosion of the steel reinforcement. In general, reinforcing steel is protected from corrosion by passive film due to high alkalinity of concrete pore solutions, having pH values between 12.5 and 13.5 [1]. If the carbonation depth exceeds the concrete cover thickness, the reinforcement that has been protected by the alkalinity (passive film) of the concrete will be destroyed by carbonation and corrosion will start on the reinforcement. When steels corroded, there were usually signs of deterioration on the concrete surface such as rusting, cracking, and spalling. If these deterioration signs appear on the structure, it is too late to provide preventive maintenance and may result in high cost of repair works. Therefore, monitoring the condition of structures should be done at

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proper time before visible deterioration appears on the structures.

A non-destructive technique by half-cell potential measurement (HCP) is generally used to estimate the possibility of corrosion of reinforcing steels. One the recommendations used to interpret the measured HCP values is given by ASTM C876. In this guideline, the probability of corrosion of the reinforcement is expected to be less than 10% if the potential is higher than -200 mV, whereas potential values lower than -350 mV indicate a high probability (>90%) of active corrosion. The half-cell values between these limits indicate areas where the corrosion activity is uncertain. Although HCP measurement is widely used to monitor the corrosion state of reinforcement, the HCP measurement can be misinterpreted by ignoring various factors such as concrete moisture content, chloride content, cement type, carbonation of the concrete, concrete cover thickness, etc [2]. Moreover, the HCP readings depend on several factors such as temperature, relative humility of environment during test, stray current, the pre-wetting time, etc [3,4].

It is well accepted that HCP is effective for being used to evaluate corrosion potential in chloride induced condition. However, there has been still few studies to evaluate the use of HCP in case of carbonation. This paper presents the characteristics of half-cell potential measurement on reinforced concrete specimens exposed to carbon dioxide in a laboratory carbonation chamber. The carbonation depth of each mix proportions was monitored by chemical test. The corrosion status of reinforcing steel was monitored HCP measurement and i_{corr}measurement. The results of HCP measurements were compared with i_{corr} and carbonation depth in order to confirm the corrosion starting time of reinforcement. The applicability and limitation of HCP measurement for being applied to carbonated reinforced concrete were investigated through experiment works conducted in this study.

2. Experimental program

2.1 Materials and mix proportions

The cement used in making concrete specimens was ordinary Portland cement (Type I). The mineral admixture used in this study was fly ash (FA) from Mae Moh power plant in the north of Thailand. Chemical compositions and physical properties of the cement and fly ash are given in Table 1. The coarse aggregate was 9.5 mm maximum size crushed limestone with a bulk specific gravity of 2.69 and water absorption of 0.25%. The fine aggregate was river sand with a specific gravity of 2.58 and water absorption of 1.01%. The mix proportions of concrete tested in this study were designed by varying the water to binder ratios from 0.4 to 0.6. Table 2 shows the quantities of the constituent materials used for each mix proportion in this study.

Table 1 Chemical compositions and physical properties of cement and fly ash.

Chemical compositions	Cement	Fly ash
Silicon dioxide (%)	20.48	43.88
Aluminum oxide (%)	5.25	24.31
Iron oxide (%)	3.82	12.51
Calcium oxide (%)	65.00	11.18
Magnesium oxide (%)	0.95	2.73
Sulfur trioxide (%)	1.90	1.43
Insoluble residue (%)	0.13	-
Sodium oxide (%)	0.01	0.78
Potassium oxide (%)	0.40	2.78
Titanium dioxide (%)	0.25	0.47
Phosphorus pentaoxide (%)	0.05	0.13
Free Lime (%)	0.75	-
Gypsum Content (%)	5.60	-
Physical Properties		
Specific gravity (g/cm^3)	3.15	2.08
Loss on ignition (%)	1.17	0.17
Blaine Fineness (cm^2/g)	3350	3460
Water requirement (%)	100	95.60

Table 2 Concrete mix proportions

Designation	w/b	Cement, kg/m^3	FA, kg/m^3	Water, kg/m^3	Sand, kg/m^3	Gravel, kg/m^3
0.4OPC	0.4	454	0	182	720	1032
0.4FA20	0.4	348	87	174	720	1032
0.4FA50	0.4	204	204	163	720	1032
0.5OPC	0.5	399	0	199	720	1032
0.5FA20	0.5	307	77	192	720	1032
0.5FA50	0.5	181	181	181	720	1032
0.6OPC	0.6	355	0	213	720	1032
0.6FA20	0.6	274	69	206	720	1032
0.6FA50	0.6	163	163	196	720	1032

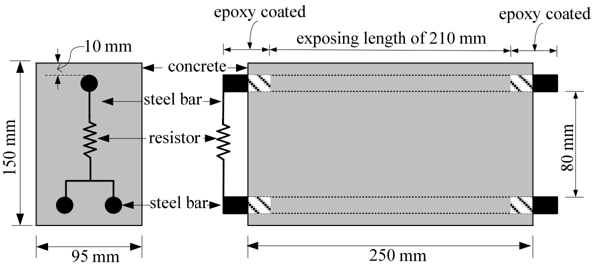

Figure 1 Schematic illustration of a specimen

2.2 Specimens and test procedures

The concrete specimens were cast in a natural condition room. At 24 hours after casting, all concrete specimens were demolded and moisture-cured for 27 days. After 28 days, all specimens were exposed to carbon dioxide in the chamber with the control condition of 4% carbon dioxide concentration, 40°C and 55±5% of relative humility. The dimension of concrete specimens is 95 mm ×250 mm ×150 mm, which was modified from ASTM G190 as shown in Fig.1. Three deformed bars (SD40 according to TIS 24) with a diameter of 12 mm and a length of 310 mm was embedded in each specimen: one bar at the top with a concrete cover thickness of 10 mm and two at the bottom, with a distance of 80 mm from the top bar. All of the reinforcing bars were polished by using a wire brush to remove rust existing on the surface and then degreased by acetone. After that, steel bars were coated with epoxy at both ends to provide the middle exposing length of 210 mm. After demolded, top bar was electrically connected with the bottom bar by using a 100 Ω resistor. In addition to the concrete prisms, corresponding cube specimens with the size of 100 mm × 100 mm × 100 mm were casted to determine the depth of carbonation.

The prism specimens were measured for half-cell potential following ASTM C 876. The specimens were made wet by wet cloth in order to reduce the fluctuation of HCP values. After being made wet for 1 hour, the HCP values were measured immediately. In this study, corrosion current density (i_{corr}) was also measured to compare with the HCP results. This i_{corr} measurement technique was modified from the ASTM G109 to determine the corrosion current density. Corrosion current (I) was measured indirectly as a voltage drop across the 100 Ω resistor connected externally between the top and bottom reinforcing bars. The corrosion current was calculated based on Ohm's law and then converted to corrosion current density as shown in Eq. (1) and Eq. (2).

$$V = IR \tag{1}$$

where V is the voltage drop across the resistor (μV), I is the current (μA), and R is a resistor (100 Ω in this study). Voltmeter is a high impedance type with a resolution of 0.01 mV as recommended by ASTM G109. Then, corrosion current density (i_{corr}) was calculated as shown in Eq. (2).

$$i_{corr} = \frac{I}{A} \tag{2}$$

where i_{corr} is the corrosion current density (μA/cm^2) and A is the surface area of exposed steel. In this study, the exposed steel has the surface area of 79.168 cm^2 (surface area of the middle portion without epoxy coat).

The criteria to indicate the corrosion starting time is the rapid increase of i_{corr}. Depths of carbonation were also monitored to compare with the measured i_{corr}. At the age of carbonation depth measurement, specimens were split and cleaned to remove dust from the fresh surface. The depths of carbonation were determined by spraying on a freshly broken surface with a phenolphthalein solution. The average carbonation depth was calculated from eight measurement points on every side of the specimen. Measurement of HCP, i_{corr} and depth of carbonation were conducted every 7 days.

3. Results and discussion

Figs. 2-4 show the effect of fly ash (FA) replacement on the carbonation depth in the concrete mixes made with water to binder ratios of 0.6, 0.5 and 0.4, respectively. The results show that, when percentages of fly ash replacement increase, carbonation depths also increase. It could be explained that calcium hydroxide, which was a product of hydration, was reduced by carbon dioxide from environment and then converted to calcium carbonate (carbonation area). In addition, concrete made with high percentage of fly ash ratio resulted in low calcium hydroxide due to the consumption of calcium hydroxide by pozzolanic reaction. The details of the mechanisms can be found elsewhere [5,6,7]. Many researchers recommended that, if the carbonation front extended to the steel bar surface, corrosion of reinforcing steel could start. From these criteria, if the carbonation front extended beyond the concrete cover thickness (10 mm), the top reinforcing bar was corroded. The corrosion starting time of each mix proportion by the carbonation depth criterion is presented in Table 3.

After 77 days of exposure to carbonation all concrete specimens were monitored by using the half-cell potential method to determine the corrosion initiation time. The results of half-cell potential measurement were obtained every 7 days. The results of HCP measurement are shown in Figs. 5-7.

Fig. 5 shows that all specimens with w/b=0.6 had almost equal HCP values before carbonation (at 0 day of exposure). After that, half-cell potential showed values ranging from -50 to -250 mV when time of exposure increased. At 7 days of exposure, specimen 0.6FA50 started to show a higher negative potential value than specimens 0.6FA20 and 0.6OPC. But the specimen 0.6OPC showed a higher negative potential value than 0.6FA20. After 7 days of exposure, half-cell potential of all specimens showed

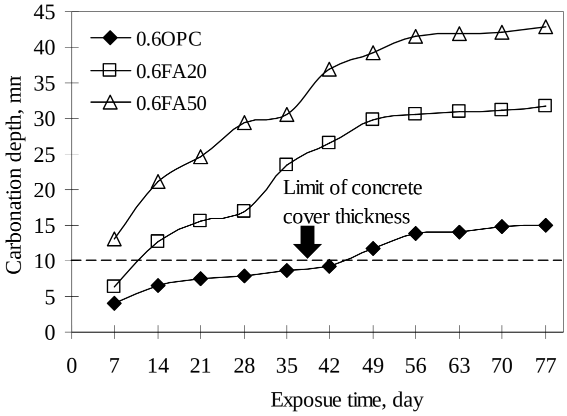

Figure 2 Carbonation depths of specimens with w/b=0.6

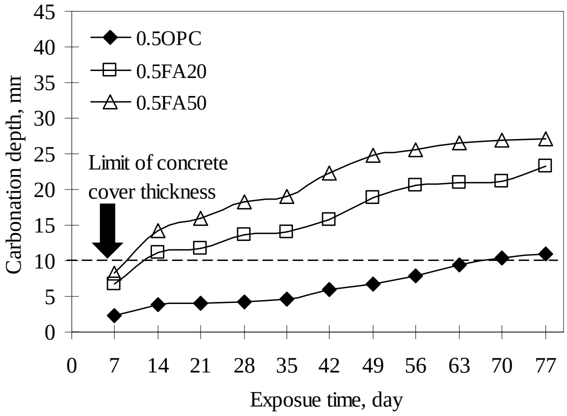

Figure 3 Carbonation depths of specimens with w/b=0.5

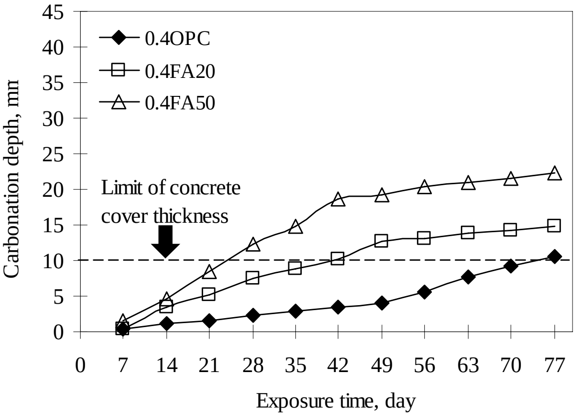

Figure 4 Carbonation depths of specimens with w/b=0.4

Table 3 Corrosion starting time of concrete specimens by carbonation and i_{corr} criteria

Binder	By depth of carbonation, days	By i_{corr}, days
0.4OPC	74	> 77
0.4FA20	41	42
0.4FA50	24	35
0.5OPC	67	> 70
0.5FA20	12	14
0.5FA50	9	14
0.6OPC	44	49
0.6FA20	11	14
0.6FA50	5	7

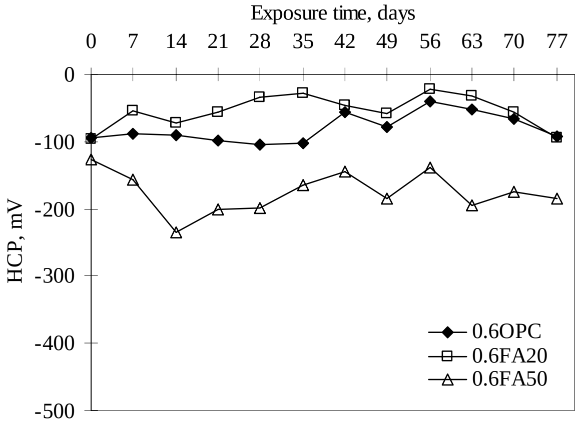

Figure 5 Half-cell potential of specimens with w/b=0.6

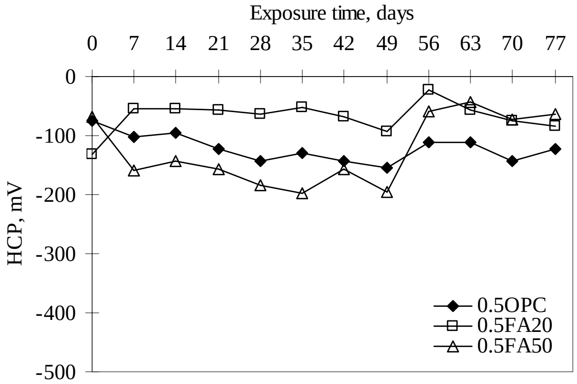

Figure 6 Half-cell potential of specimens with w/b=0.5

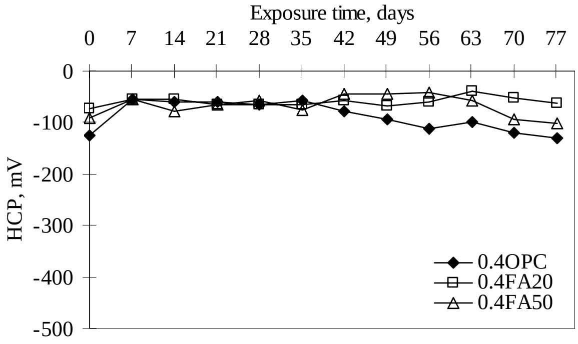

Figure 7 Half-cell potential of specimens with w/b=0.4

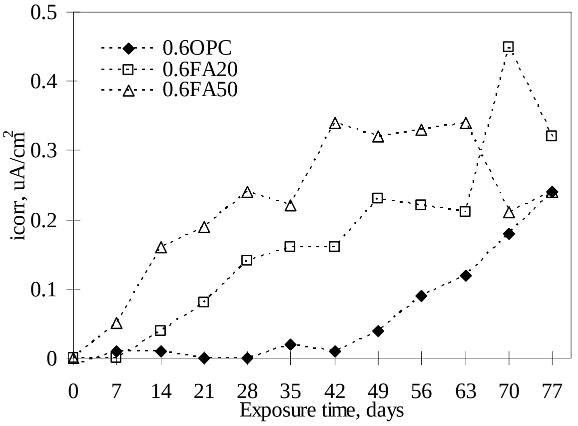

Figure 8 Corrosion current density of specimens with w/b=0.6

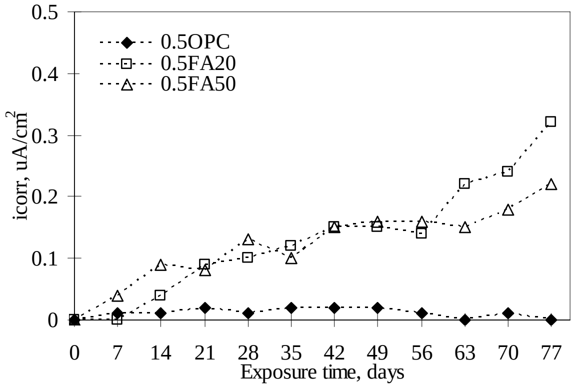

Figure 9 Corrosion current density of specimens with w/b=0.5

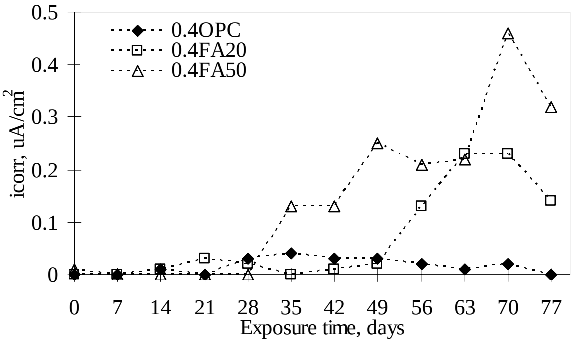

Figure 10 Corrosion current density of specimens with w/b=0.4

almost stable values when exposure times increased. In the same way, concrete specimen with w/b=0.5 (Fig. 6) had similar tendency of HCP values with the specimen with w/b=0.6 (Fig. 5). However, specimen with w/b=0.4 showed almost equal and constant HCP values for all fly ash replacements at all tested ages (Fig. 7). All HCP data in Figs. 5-7 indicated no severe corrosion of the reinforcing steels if compared with the numerical criteria of ASTM C876.

To detect corrosion, macro-cell corrosion current was measured and then converted to corrosion current density. Figs. 8-10 show the results of corrosion current density of all tested specimens after exposure to carbon dioxide. From Fig. 8, it was observed that before the exposure, there was (at 0 day of exposure) no current flowing between the top bar and the bottom bars in all specimens. At 7 days of exposure, 0.6FA50 showed a corrosion current density of 0.05 $\mu A/cm^2$, but 0.6FA20 and 0.6OPC still showed almost zero corrosion current density values. At 14 days of exposure, corrosion current density of 0.6FA20 was higher than that 0.6OPC. After that, 0.6OPC started to show rising values at exposure time of 49 days. The i_{corr} values in case of carbonation show gradual increase with values not so high in all specimens. Generally, the i_{corr} values in specimens exposed to chloride are much higher after starting corrosion [8]. This is because the corrosion of steel bars in concrete due to carbonation is micro-cell corrosion (uniform corrosion). The ratio between area of anode and cathode are equal and also very small. The criterion for determining corrosion starting time in case of carbonation is the jumping of i_{corr} value. The results of corrosion starting times decided using the i_{corr} criterion are shown in Table 3. The results of corrosion starting times decided by the i_{corr} criterion get along well with the results of carbonation depth. The jumping of corrosion current density for different specimens started by the order: 50%FA before 20%FA before 0%FA.

From the presented results, it can be observed that half-cell potential is not good for being used to detect corrosion in case of carbonation. This is because the half-cell potential values did not change even when carbonation front had already reached the steel or i_{corr} started to rise. From Fig. 2, at 7 days of exposure, specimens with water to binder ratio of 0.6 and 50% fly ash replacement showed larger carbonation depth when compared to the thickness of concrete cover (10 mm). However, at the same time, half-cell potential only indicated the value of -156 mV as seen in Fig. 5. After that, half-cell potential showed rather constant values. This indicated that the reinforcing steel already started corrosion by carbonation when refer to depth of carbonation. However, half-cell potential value still showed passive condition when referring to ASTM C876.

In addition, half-cell potential and corrosion current density showed different tendencies. When carbonation front extended to reach the reinforcing steel, corrosion current density showed value increase. After that, corrosion current density continuously increased when exposure time increased. Nevertheless, half-cell potential showed almost constant values when carbonated front extended to reach the reinforcing steel and later. The measured half-cell potential is likely to be affected by the high resistivity and lower porosity of the carbonated concrete.

4. Conclusions

This paper presents experimental results regarding HCP to measure steel corrosion in concrete due to carbonation. Based on the experimental results presented in this paper, the following conclusions can be made:

1. Water to binder ratio had influence on corrosion starting time of steel bars in concrete. The corrosion starting time of high w/b ratio concrete started sooner than low w/b ratio concrete.
2. Corrosion current density showed slow increase due to micro-cell corrosion in carbonated specimens. Because anode and cathode areas are small, amount of flowing electrons are also small.
3. Corrosion current density showed increase values when carbonation front extended to the surface of the steel bars. But half-cell potential show almost constant values.

Then, half-cell potential measurement is considered not appropriate for monitoring corrosion risk of reinforced concrete subjected to carbonation.

4. The numerical criteria from ASTM C876 are not particularly suitable for assessing the corrosion risk of reinforced concrete subjected to carbonation.

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