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Full paper

Attenuation of Ground Penetrating Radar Signal Amplitude in Monitoring Reinforced Steel Corrosion

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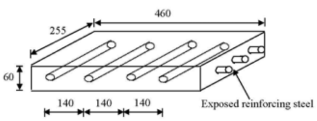
Graphical abstract



Abstract

In this study, the reduction of ground penetrating radar (GPR) signal amplitude magnitudes were measured to monitor the reinforcing steel corrosion in concrete slab. Geophysical Survey System Incorporation (GSSI) BridgeScan system which includes a SIR-3000 Windows, based on portable GPR data collection with 1.6 GHz ground-couple antenna has been used to generate electromagnetic waves and analysis of the signal on a slab sample. Four 16 mm diameter reinforcing steel were embedded in a 255 mm x 455 mm x 60 mm grade 40 concrete slab in the transverse direction and three in the longitudinal. The slab was immersed in concentrated sodium chloride solution (8 g/l) for three months to simulate the corrosive environment on the reinforced slab. The average signal amplitude decreases from 1139.75 dB (at day 7) to -404.25 dB (at day 61) and finally drop to -782.75 dB (at day 93) as the corrosion process progressing. The presence of corrosion activity on the reinforcing steel was confirmed based on the potential difference reading by Half Cell (HC) which shows that the reinforcing steel experienced probability of corrosion level by more than 90 % after 61 and 93 days. GPR method is found to be a promising approach as it possesses high sensitivity towards changes in amplitude at par with high potential changes in HC method in corrosion detection.

Keywords: Corrosion; reinforced concrete slab; ground penetrating radar; electromagnetic wave; half-cell

■1.0 INTRODUCTION

Bridge deck structures made of concrete material are commonly used in many bridge constructions in Malaysia. Othman et al. (2002) estimated that 81% of 7002 bridges along the Federal roads in Peninsular Malaysia were constructed from reinforced concrete. If such structure had been designed properly, constructed and periodically maintained, the corrosion of steel is not a problem. Unfortunately, this large number of concrete bridge structures has the tendency to display symptom of deterioration due to corrosion of reinforcing steel especially when exposed to watery environment.

King and Mahmud (2009) observed that the deteriorations in concrete member were often visualized by the formation of cracking and spalling. The former and the latter deterioration modes were obviously detected on bridge deck component during the routine inspection. One of the probable cause of this problem is due to the corrosion of reinforcing steel and this has been reported by Bhargava et al. (2006) and Val et al. (2009).
Non-destructive methods have been used to monitor and access the severity of the corrosion problem. The methods proven to be fast, inexpensive and does not involve damage on the structure. Hamid et al. (2009) used impact echo method to study the probability of reinforcing steel corrosion using the pressure waves generated on the concrete surface. They concluded that the amplitude attenuation measurement can be used to determine the corrosion activity of steel rebars. However, this method may not be suitable to be applied on large areas such as bridge deck as it is a time consuming task.

GPR is an excellent non-destructive method that can be used to evaluate bridge deck condition in easier and faster manner (Scott et al. 2003). Over the years, various research works on using GPR to access bridge deck corrosion-induced damaged have been explored. These research explorations relate the weak return signals with the corrosion effects resulting from chloride ion (Barnes and Trottier, 2004) and measuring the effect of moisture and chloride on radar signals (Hugenschmidt and Loser, 2008). Currently, Kabir (2011) had examined and compared the efficiency of GPR and digital half-cell potential (HCP) method in detecting the reduction of corroded reinforcing steel diameter and corrosion degree level estimation. Cui and Husten (2011) found that the combination of rust accumulation, water and chloride ion surrounding the reinforcing steel resulted in the increasing of GPR image blurring with the increasing of corrosion duration. However, measurements of the GPR wave attenuation due to blurring situation have not received much attention by the researchers.

Therefore, in this study, a research work was conducted to measure the GPR waves variation due to corroded reinforcing steel in concrete slab structures without having to hack the structure nor it need not to be in saturated condition as in the case of HCP method.

■2.0 EXPERIMENTAL PROGRAMME

2.1 Materials and Method

The concrete slab with size of 460 mm × 255 mm × 60 mm of grade 40 with water to cement ratio of 0.39 was prepared. Four numbers of 16 mm diameter high yield reinforcement was embedded in the middle slab thickness. Figure 1 shows the isometric view of the sample and Figure 2 shows the schematic diagram of the reinforced concrete slab. The rebars were designed at 140 mm centre-to-centre distance and this spacing is (s) more than sufficient for the electromagnetic waves to penetrate between the rebars (s ≥ wavelength, λ). In Figure 2, the rebar marked with label A to D are the transverse rebar and the longitudinal rebars were marked with label X,Y and Z. The rebar designated as A,B,C and D represent the embedded rebars that will be measured by GPR and rebar marked by X,Y and Z represent the embedded rebar that will be measured by HCP. Rebar marked by X, Y and Z were left exposed on their right ends to allow the portion to be electrically connected to the voltmeter for electrical potential measurement by half cell.

After three days, the samples were removed from the moulds and the samples were immersed in the 8g/l sodium chloride. This was done for simulating the corrosion process of the reinforcing steel within three months duration.

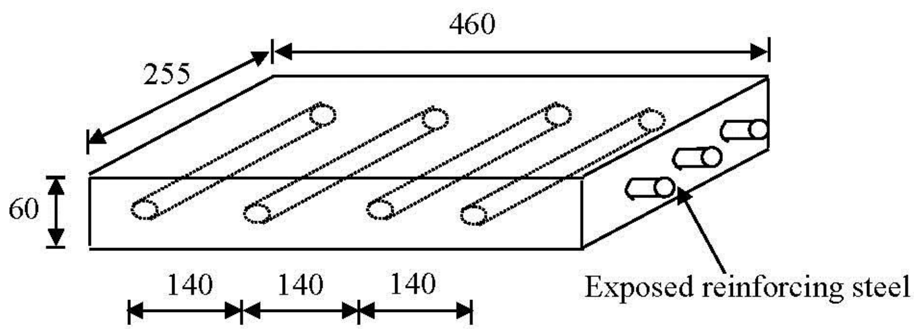


Figure 1 Isometric view of slab sample (All units are in mm)

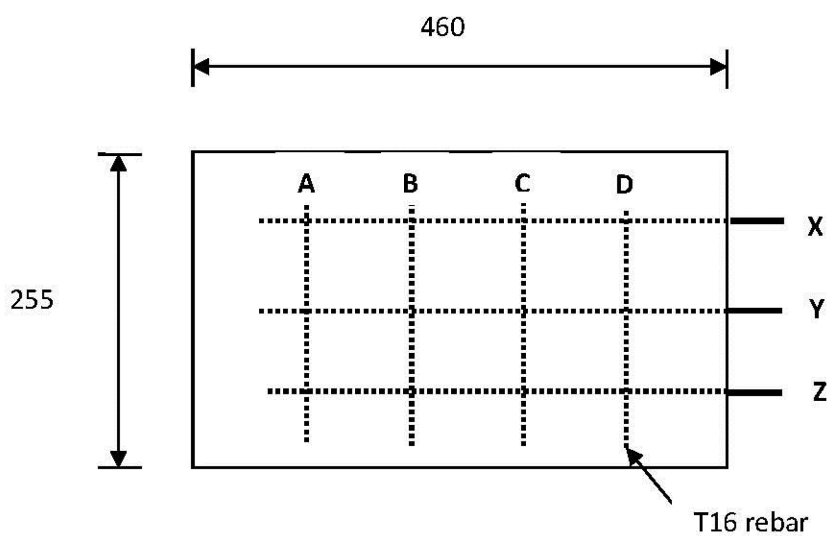


Figure 2 Schematic diagram of the reinforced concrete slab (All units are in mm)

2.2 Monitoring of Corrosion Using GPR

Figure 3 shows the GPR system used to monitor the corrosion activity. An aluminium sheets were placed under the sample to ensure that GPR was able to detect the bottom surface of the sample. The procedure stated in ASTM D6432-11 was followed. High yield reinforcements were allowed to corrode under accelerated condition and the measurement of signal amplitude was recorded prior to accelerate corrosion process. The reinforcing steels were washed by water without damaging the corroded part prior to testing. The slab was left to dry for several hours before it was scanned in the longitudinal direction as shown in Figure 4. A computer program, RADAN v6.6, was used to process the captured image by time-zero correction and migration analysis to obtain the value of signal amplitude of each reinforcing steels. This procedure was repeated at days 61 and 93.

All signals will be extracted and analyses by using MATLAB software. Attenuation of peak-to-peak amplitude for both GPR direct waves and the reflected waves is normalized with respect to the peak-to-peak amplitude of the waves recorded in air and is calculated using the following equation:

$$A = -20\log\left(\frac{A_c}{A_a}\right) \quad (1)$$

where

A_c = peak-to-peak amplitude of radar signal relative to concrete

A_a = peak-to-peak amplitude of wave signal in air.

Figure 5 shows the measured direct wave and the reflected wave.

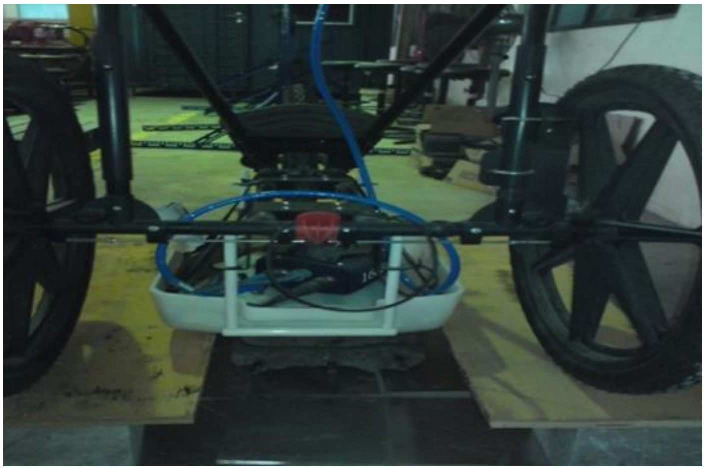


Figure 3 Ground Penetrating Radar equipment

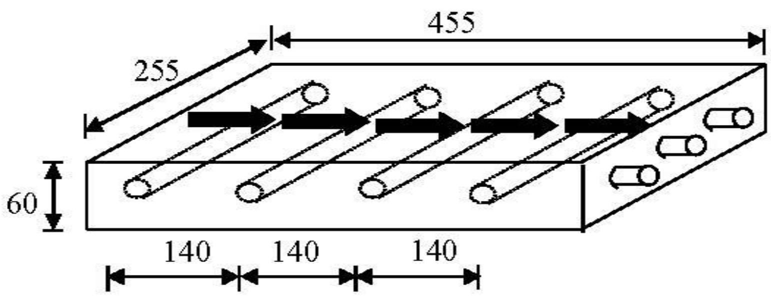


Figure 4 Direction of GPR scanning (All units are in mm)

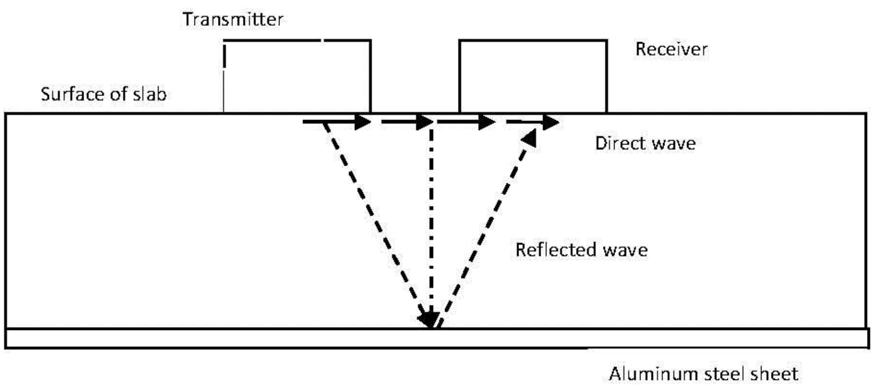


Figure 5 Direct and Reflected wave

2.3 Monitoring of Corrosion Using HCP

HCP Method is based on the standard specification outlined in ASTM C876-09. The sample was taken out from the salt solution and washed with water. The exposed steel bar was connected to the positive terminal that served as the cathode and the other end of the lead wire was connected to the negative terminal of the voltmeter. The silver-silver chloride electrode (Ag/AgCl) or probe was connected to the same lead wire will be used to measure electrical potentials values on the concrete surface with increment of 25 mm along the rebar X,Y and Z as shown in Figure 6. Prior to commencing of electrical potential measurement, the concrete surface has to be wetted and pre-wetted probe sponges with low electrical contact solution was attach to the tip of the probe to provide electrical continuity between the probe and the concrete surface. The probe's sponge was placed on the concrete surface for at least 5 minutes until the potential reading was stable. The average electrical potential measurements were compared with potential difference values empirically developed in ASTM C876-09 to indicate probabilities of corrosion. The similar procedure was repeated on 7, 61 and 93 days.

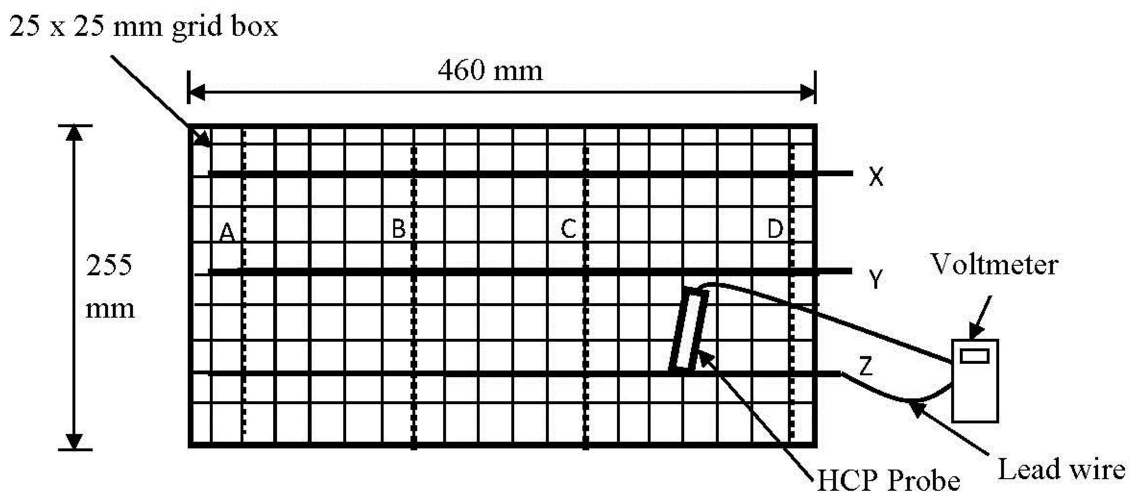


Figure 6 HCP difference measurement along the rebar using half cell probe

■3.0 RESULTS and DISCUSSIONS

3.1 Variation of GPR Wave Amplitude on Reinforcing Steel

The concrete slab samples were scanned by the GPR to capture the internal image of the concrete and its reinforcing steel at 7, 61 and 93 days. An image displayed in Figure 7 shows the resulting four hyperbolas shape, i.e. inverted U shapes after 61 days which can be seen as white-black band at approximately 2.4 ns (nanoseconds) in the image. The appearance of the inverted U shapes images was formed by the reflection of the electromagnetic waves on the top of rebars surface back to receiver antenna when the wave propagates inside the concrete from the emitting antenna. The bottom surface of the slab appeared at approximately 8 ns as black-white-black band.

Table 1 shows the amplitudes of GPR wave signals for each bar on different ages. The wave velocity is chosen to be fixed at 0.12 m/ns as the default dielectric concrete used in the GPR settings is 6, which is the typical values for concrete structures (Qiang et al. 2011). Figure 8 shows the plot of the amplitudes of GPR wave reflection (dB) of the reinforcing steel versus the duration of corrosion process. The average of the amplitude magnitude drastically decreases from 1139.75 dB to -404.25 dB after 56 days of immersion and followed by further amplitude reduction to -782.75 dB after 93 days. Strong wave reflection with the magnitude of 1139.75 dB was observed on the non-corroded reinforcing steel, but as the corrosion is developing on the reinforcement surface, weaker amplitude reflections with the magnitude of -404.25 dB after 56 days and -782.75 dB after 93 days are recorded.

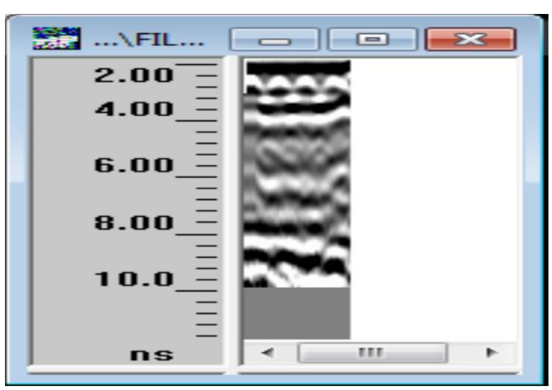


Figure 7 Captured GPR Image after 61 days

TABLE 1 Amplitudes of GPR wave signals for each bars on different ages

Age (days)	Rebar	x(m)	y(m)	z(m)	Amplitude (dB)	Average amplitude (dB)	Wave Velocity (m/ns)	Time (ns)
0	A	0.0175	0.000	0.18	1100.00	1139.75	0.12	2.70
	B	0.1575	0.000	0.16	1064.00		0.12	2.50
	C	0.2975	0.000	0.17	1226.00		0.12	2.62
	D	0.4375	0.000	0.18	1169.00		0.12	2.70
61	A	0.0175	0.000	0.17	-596.00	-404.25	0.12	2.56
	B	0.1575	0.000	0.16	-239.00		0.12	2.72
	C	0.2975	0.000	0.17	-214.00		0.12	2.64
	D	0.4375	0.000	0.17	-568.00		0.12	2.62
93	A	0.0175	0.000	0.14	-909.00	-782.75	0.12	2.15
	B	0.1575	0.000	0.14	-672.00		0.12	2.19
	C	0.2975	0.000	0.14	-608.00		0.12	2.11
	D	0.4375	0.000	0.15	-942.00		0.12	2.31

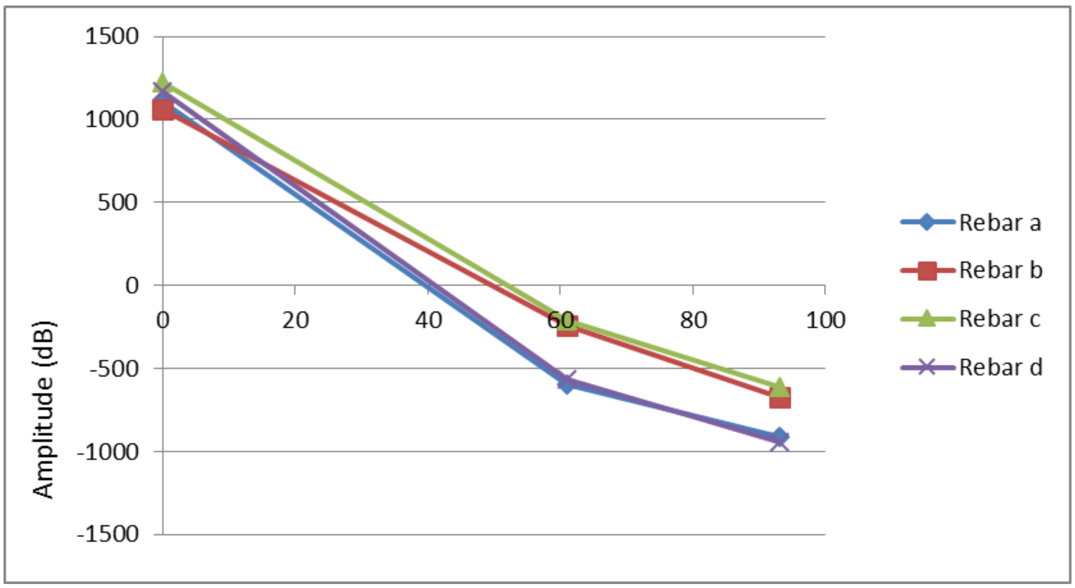


Figure 8 Amplitudes of GPR signals at reinforcing steels versus duration of immersion

The first 56 days shows substantial reduction in amplitude at average 1544 dB followed by a slight reduction of amplitude at average 378.5 dB for the next 32 days. This shows that very rapid wave attenuation occurred within 61 days. Taking the average amplitude at 93 days minus the average amplitude at initial date of test as total reduction (1922.5 db), the percentage reduction of amplitude at 61 days is 80.31% (average of 25.31 dB/day). Later, the attenuation rate reduced to 11.83 dB/day for the remaining 32 days. Rebar B and C show lower reduction in amplitude, thus lower corrosion activities due to their locations away from the edges compared to rebar A and D. This could be attributed by the number of covers at each rebar that will influence the degree of chloride penetration for the rebar corrosion. There are three number of covers at edges of the concrete that nearby rebar A and D (9.5mm for side cover, 30 mm for top and 14 mm for bottom cover). Rebar B and C posses two number of covers that were located on top and bottom of the concrete surface. Figure 9 shows the dimension of the side cover, top cover and the bottom cover of the concrete.

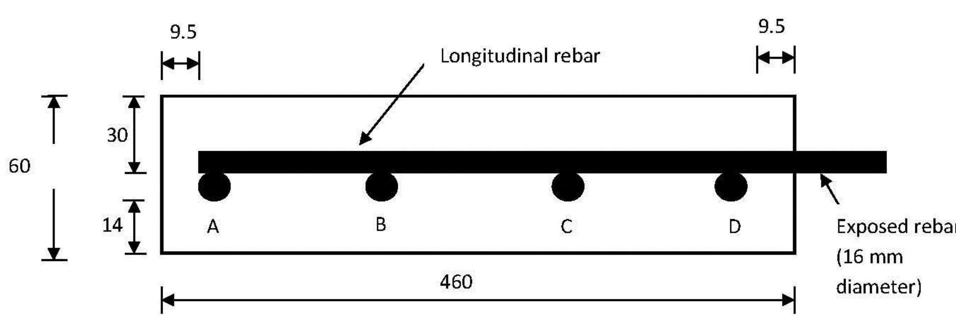


Figure 9 Dimension of side, top and bottom cover (All units are in mm)

As the amplitude attenuation also are affected by the moisture in the slab and the chloride content of the slab, the large reduction in amplitude could not be attributed to the corrosion activity alone. Further research need to be done where effect of both moisture and chloride content need to be studied separately and normalized.

3.2 Variation of Potential Difference with Half Cell

The exposed surface of the longitudinal reinforcing steel labelled x, y, and z were tested for potential difference due to corrosion at 7, 61 and 93 days respectively. The potential difference (mV) of each longitudinal bar on the testing day is shown in Table 2. On day one, the average potential difference measured was 2.67 mV, indicating there was no corrosion process on the reinforcing steel. However, at day 61 and 93, the average potential difference value reduces drastically to -530 mV and -646.3 mV correspondingly, showing that the corrosion activity is active. ASTM C876-09 suggested that the corrosion damage probability is estimated to be more than 90% after 61 days and after 93 days

Table 2 Potential difference of longitudinal reinforcing steels

Age (days)	Electrical Potential (mV)			Average Potential (mV)
	X	Y	Z	
0	**003**	**002**	**003**	**2.76**
61	**-537**	**-520**	**-533**	**-530.0**
93	**-648**	**-645**	**-646**	**-646.3**

3.3 Comparison between GPR Method and HCP Method

From the results of GPR and Half-cell methods, it was observed that both methods were able to measure the probability of reinforcing steel corrosion in concrete slab. As the corrosion probability increases, the amplitude and potential difference values reduced. The percentage of amplitude reduction is 80.3 % between days zero to 61 and reduced by 19.7% from days 61 to 93. The percentage reduction of the potential difference is found to be approximately equal (80%) to the percentage amplitude reduction for the similar immersion duration. This shows that GPR wave amplitude had the similar sensitivity as the HCP method in estimating the rebar probability of corrosion. Even though the GPR attenuation and HCP potential difference with time are also affected by moisture intrusion and chloride intrusion into the concrete, both show very large sensitivity towards these three factors that affected their measurement. GPR has better advantages in its capability to scan large area at quicker time and promises better potential in researches in quantifying rebar corrosion.

■4.0 CONCLUSIONS

The following conclusions can be derived from this study;

a) The corrosive environment of reinforcing steel affect the amplitude of GPR waves by 1544 dB reduction after 61 days of accelerated corrosion process (the percentage reduction of amplitude at 61 days is 80.31% (average of 25.31 dB/day) and 378.5 dB from day 61 to 93 (average of 11.83 dB/day).
b) The level of corrosion probability was observed to be more than 90% after 61 days and after 93 days by HCP measurement (at day 61 and 93, the average potential difference value reduces drastically to -530 mV and -646.3 mV correspondingly).
c) Even though the GPR attenuation and HP potential difference with time are also affected by moisture and chloride intrusion into the concrete, both methods show very large sensitivity towards these three factors (including rebar corrosion) that affect their measurements. GPR has better advantages in its capability to scan large area at quicker time and promises better potential in researches of quantifying rebar corrosion.

Acknowledgments

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