Jurnal Teknologi

Full paper

Effect of Moisture and Chloride Content on the Direct and Reflected Ground Penetrating Radar Waves Amplitude Ratio in Concrete Slab

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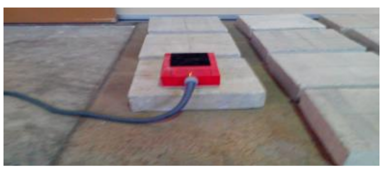
Article history

Received :7 January 2015
Received in revised form :
7 March 2015
Accepted : 8 April 2015

Graphical abstract



Abstract

This paper focused on the effect of various moisture and chloride content on the direct and reflected waves (DW and RW) of Ground Penetrating Radar (GPR) amplitude ratio of concrete slab. The GPR is used in detecting both corrosion agents of 13 numbers of concrete (water/cement ratio= 0.7) slab samples. Radar measurement is employed on a fixed point of the samples to measure two signals referred to as the direct and reflected radar waves amplitudes. Simple signal processing on the collected time domain signal plots is executed by MATLAB® software to compute the attenuation of peak-to-peak amplitude of DW and RW which are normalized with respect to the peak-to-peak amplitude of DW recorded in air. From the analysis, strong linear relationships (R^2 = 0.82 and 0.96) for water content variation of DW and RW are found. However, a very weak linear relationship with R^2 of 0.31 for chloride content variation of DW but a strong linear relationship (R^2 = 0.95) for the RW are established. These findings showed that both moisture and chloride content have a measurable influence on both GPR signals, which enable the GPR utitilisation on detecting the amount of both corrosion agents in concrete. The DW and RW amplitude ratio have the potential usage in mapping problematic zone by moisture and chloride contamination in concrete.

Keywords: Ground Penetrating Radar; moisture; chloride; concrete slab

Abstrak

Kajian ini mengkaji kesan perubahan kandungan lembapan dan klorida di dalam papak konkrit terhadap nisbah amplitud gelombang terus dan terpantul (GT dan GP) Radar Penusukan Bumi (RPB). RPB digunakan untuk mengesan kedua-dua agen pengkaratan dalam 13 sampel papak konkrit (nisbah air/simen = 0.7). Pengukuran gelombang radar dilakukankan pada suatu titik tetap pada sampel untuk mengukur dua jenis isyarat amplitud gelombang radar: GT dan GP. Pemprosesan isyarat mudah menggunakan perisian MATLAB® memplot isyarat di dalam domain masa untuk menghitung pengecilan amplitud puncak ke puncak pada GT dan GP yang mana telah dinormalkan terhadap amplitud puncak ke puncak GT di dalam udara. Hubungan linear yang baik (R^2 = 0.82 dan 0.96) antara kandungan air dengan amplitud GT dan GP telah diperhatikan. Walaubagaimanapun, hubungan linear yang amat lemah (R^2 = 0.31) antara kandungan klorida telah diperhatikan untuk GT. Hubungan linear yang baik (R^2 = 0.95) telah diperhatikan bagi GP bagi kesan perubahan klorida. Dapatan menunjukkan bahawa kandungan lembapan dan klorida memberi kesan signifikan terhadap isyarat RPB, yang membolehkan RPB digunakan untuk mengesan kandungan kedua-dua agen pengkaratan ini di dalam konkrit. Nisbah amplitud GT dan GP ini mempunyai potensi untuk digunakan untuk pemetaan zon bermasalah disebabkan oleh penusukan kelembapan dan klorida pada konkrit.

Kata kunci: Radar Penusukan Bumi; lembapan; klorida; papak konkrit

1.0 INTRODUCTION

The evaluation of moisture and chloride content in reinforced concrete is very relevant for durability assessment of aging structures. The amount of moisture in concrete pores enables the chemical agents such as chloride ion to penetrate the cover of concrete. Once chloride ions reach the rebar surface, they act as catalyst for the rebar corrosion process at the steel surface. As the amount of these two corrosion agents indicate the severity of the rebar corrosion activity, a reliable, rapid and non-destructive tool is required for estimating the moisture and chloride contents in the concrete component.

On concrete structures, Lai *et al*. had mentioned that GPR had been successfully employed as a non-destructive testing (NDT) method to evaluate concrete structures.[1] The successful GPR applications were mainly ranging from the determination of concrete thickness, the detection of embedded rebar location, detection of air void in concrete and the assessment of bridge deck condition.[2,3,4,5] The main advantages of using GPR as reported by ASTM D6432-11 in these research works is non-destructive testing method as there is no damaging procedures are employed on the investigated concrete surface structures.[6] Grid point testing is not required as in impact echo test, and no damaging procedures are employed on the investigated concrete surface as in half cell potential. As such, these provide an opportunity for conducting rapid and repetitive data measurements on the same concrete component. However, GPR has not been successful in quantifying the degree of the severity of the corrosion activity in reinforced concrete. In a recent study conducted by Ghani *et al*., the influence of rebar corrosion activity on GPR signal attenuation has been carried out.[7] They reported that as the corrosion level increased (as also were measured by half cell potential), the GPR amplitude attenuation decrease significantly. However, it should be noted that the value of the attenuation could not only be attributed to the corrosion activity, but also to the amount of chloride in the slab, as the corrosion process was induced by immersing the slab in chloride solution. The effect of varying moisture and chloride content in concrete should be studied separately to quantify the effect of both on the GPR amplitude attenuation.

The effect of concrete moisture in GPR sounding has been studied and reported. It is found by Laurens *et al*. that the GPR amplitude signals increased during hydration and drying of the concrete samples.[8] The inversion of GPR data over varying moisture and chloride contents in concrete samples has also been studied by Kalogeropoulus *et al*. and the results showed that an increase in conductivity and permittivity for increasing moisture and chloride content.[9] The use of GPR signals in determining the freshly mix concrete volumetric water has also been investigated by Chen W. *et al*.[10] Previous researches had utilised the reflected wave (RW) in their studies. However, the use of direct wave (DW) on durability assessments on RC structures has been given little attention by the researchers. Therefore, the potential uses of the DW are studied in time-domain in conjunction with the RW in this paper. The peak-to-peak attenuation of both wave were computed based in the varying moisture and chloride content in concrete. As the amount of moisture and chloride in concrete can indicate the degree of the corrosion severity, this study aim at determining the effect of both corrosion agents content in a concrete slab to the GPR wave attenuation alone, hence the investigation is done on plain unreinforced concrete slab.

2.0 EXPERIMENTAL PROCEDURES

2.1 Materials

Thirteen unreinforced concrete slab samples (very high water-to-cement ratio of 0.70) were prepared in order to obtain a high permeable concrete. The slab dimension is 0.25 m × 0.25 m × 0.07 m^3 and 70 mm in thickness. The mix design composition was prepared based on a British standard and shown in Table 1.[11]

Table 1 Sample mix design composition

Materials	Mix composition (kgm^{-3})
Ordinary Portland cement	402
Coarse aggregates (10 mm)	939
Fine aggregates	1058
Water	286

2.2 Samples Preparation

In this study, seven samples denoted as SW, DS1, DS2, DS3, DS4, DS5 and DS6 were prepared to evaluate the effect of the radar amplitude on moisture content and another six samples denoted as SW, SC10, SC20, SC30, SC40 and SC50 were used to study the effect of chloride content on the radar amplitude. All samples were cured in the curing tank for 28 days. After the curing period, the initial sample weight (w_{dry}) were recorded for all samples and were kept immersed in water and weighted until the recorded weight was constant (fully saturated). The water absorption by capillary absorption from the dried state to the targeted degree of water saturation is controlled in each sample by calculating the percentage of water content using Equation 1,

$$x_1 = \frac{w_{sat} - w_{dry}}{w_{sat}} \times 100\% \quad (1)$$

where x_1 is the percentage of water content, w_{sat} correspond to the weight of saturated sample (kg) and w_{dry} is the targeted weight of dried sample (kg). Table 2 shows that the % moisture content at fully saturated is 10.1%.

The effect of water content on radar signals was evaluated using 7 samples denoted as SW, DS1, DS2, DS3, DS4, DS5 and FD. All samples except SW were dried by drying it in oven at 80°C. The samples were then weighted and dried until the targeted degree of water saturation weight was constant. Thin aluminium foil is used to seal all of the sample surfaces for two months to achieved uniform water distribution inside the samples before drying in an oven The weight of the samples is checked at the end of this procedure in order to ensure there was no weight loss before the radar measurement is carried out. Table 2 shows the percentage of water content used and the description of notation for all samples.

Table 2 Types of concrete samples used in the study

Analysis	Notation	Description	% of moisture content
Moisture content	SW	Saturated	10.1
	DS1	Dry sample no. 1	9.4
	DS2	Dry sample no. 2	7.1
	DS3	Dry sample no. 3	5.0
	DS4	Dry sample no.4	3.2
	DS5	Dry sample no. 5	1.7
	FD	Fully dried	0.0
Chloride content	SW	Saturated	10.1
	SC10	10 g/L chloride	9.3
	SC20	20 g/L chloride	12.1
	SC30	30 g/L chloride	9.0
	SC40	40 g/L chloride	10.2
	SC50	50 g/L chloride	10.2

The effect of immersed chloride content on radar signal was evaluated by six samples denoted as SW, SC10, SC20, SC30, SC40 and SC50. All samples except SW were oven dried until the sample weights were constant. These samples were then immersed directly in the distilled water containing different chloride concentrations of 10, 20, 30, 40 and 50 g/l for one month. After the chloride immersion period was completed, each sample was tested.

2.3 GPR Signals Measurement

The GPR signal data acquisition was carried out on the top surface of all samples using 1.6 GHz ground-couple antenna that is placed on the concrete surface and processed by SIR-3000 system. All samples were tested at a point marked at the middle of the slab. Figure 1 shows the test done on the slab with a metal plate inserted at the bottom of slab to simulate RW by the metal and Figure 2 shows test done on the slab without the metal plate, to simulate reflected wave at air-concrete interface. The signal data acquisition was taken at 100 times per sample and the average amplitude were computed. The range of signal was 6 nanoseconds for 510 signal traces. The aliasing effects on radar signal was avoided by sampling the radar signal at a sampling frequency, f_s, of 85 GHz, which is more than twice of the Nyquist frequency[12] as mentioned by Parker.[12]

The plot of average signals attributed by both situations was carried out using MATLAB software and shown in Figure 3. The arrival of the DW is easily identified from the plot as the first positive amplitude of both signals. As reported by GSSI,[13] metal plate has the capability to reverse the amplitude polarity of the signal, the arrival of the reflected waves (RW) is identified by locating the phase reversal of signal by sample with metal plate as shown in Figure 3. For both signals plotted in time domain, the peak-to-peak amplitude, denoted as A_d for DW and A_r, which corresponds to RW, were analyzed and divided with respect to the peak-to-peak amplitude of direct wave signal recorded in air according to Equation 2,

$$\mu = -20\log_{10}\left(\frac{Ac}{Aa}\right) \qquad (2)$$

where μ is the amplitude ratio (attenuation) of peak-to-peak signal in decibels, A_c is the peak-to-peak amplitude of direct or reflected waves relative to concrete (A_d or A_r) and A_a corresponds to the peak-to-peak direct wave amplitude of the air.

Figure 1 Sample with a metal plate

Figure 2 Sample without a metal plate

3.0 RESULTS AND DISCUSSION

3.1 Effects of Water Content on Peak-to-Peak GPR Amplitude

The peak-to-peak attenuation of both amplitudes, μ_{DW} and μ_{RW}, were plotted against the measured water content inside the slabs and presented in Figure 4 and Figure 5 respectively. Both plots show good linear relationship (R^2 = 0.82 and 0.96, respectively) with respect to the water saturation of the samples, and is consistent with the similar relationship obtained by other reseacher[14] and tabulated in the Table 3. Sbartai *et al*. found that the attenuation of direct and reflected wave is attenuated linearly by 7 and 11 dB respectively as the volumetric water content increases from 0 to 16 percent of its dried concrete weight.[14] In the current study, the normalized peak-to-peak of both direct and reflected waves increased by about 5.6 and 9 dB respectively while water content is increased from 0 to 10.1%.

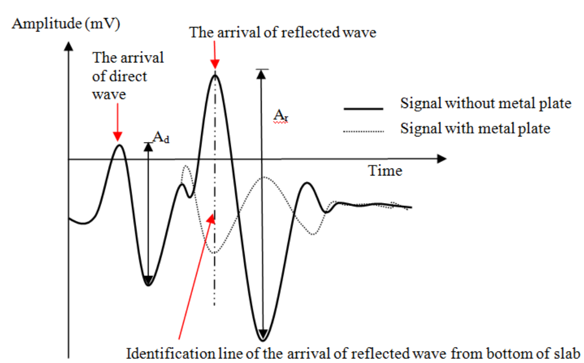


Figure 3 Typical time-domain plot of GPR waves

Table 3 Comparison of current study peak-to-peak attenuation with Sbartai *et al*. (2006)

Type of wave	Peak-to-peak attenuation (dB) Sbartai *et al*. (2006)	Peak-to-peak attenuation (dB) Current research
Direct wave	7	5.6
Reflected wave	11	9

The attenuation of the DW was found to be less sensitive than the RW. According to Harry, this increment results from an increase in the dielectric and conductive losses which affect the GPR energy absorption attenuation.[15] However, both DW and RW signals are able to characterize the water saturation level in a concrete.

3.2 Effects of Chloride Content on Peak-to-Peak GPR Amplitude

Figure 6 and 7 show the plot of peak-to-peak attenuation of DW and RW as the chloride content of saturated samples are varied from 0 to 50 g/l. Both plots present linear relationship, with a good linear coefficient of determination (R^2 = 0.97) for the RW, however, a weak relation is observed on DW signal. This weak relation may be attributed from different smooth surface condition of samples that influence the reflection and absorption of GPR energy signals.

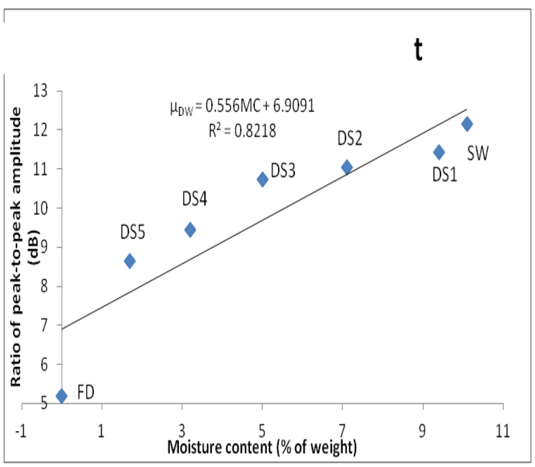


Figure 4 Peak-to-peak attenuation of direct waves, μ_{DW}, on moisture

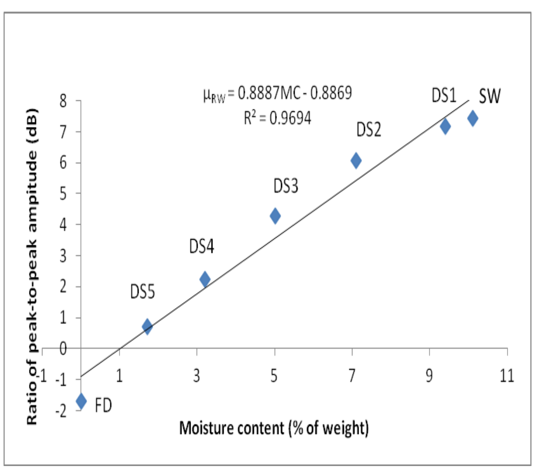


Figure 5 Peak-to-peak attenuation of reflected waves, μ_{RW}, on moisture

The normalized peak-to-peak of direct and reflected waves was increased about by 1.4 and 24 dB respectively, when the immersed chloride concentration is increased from 0 to 50 g/L. Sbartai *et al*. found that the attenuation of the DW is increased by about 3dB while the concentration of chloride increased from 0 to 60 g/L.[15] These increases can be explained by the high mobility of free chlorides in saturated concrete, which increases both ionic conduction and polarization. The attenuation of the DW is less sensitive than the RW. Based on the laboratory results, it can be inferred that both of the variation of DW and RW increass as the immersed chloride level increases. The DW attenuation of the present study is almost consistent with the findings of other researcher for the DW attenuation and shown in Table 4.

Table 4 Comparison of present peak-to-peak attenuation with Sbartai *et al*.[16]

Type of wave	Peak-to-peak attenuation (dB) Sbartai *et al*. (2007)	Peak-to-peak attenuation (dB) Current study
Direct	1.4	3
Reflected	-	24

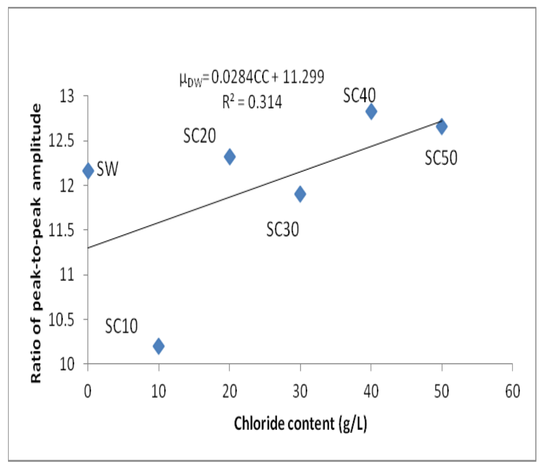


Figure 6 Peak-to-peak attenuation of direct waves, μ_{DW}, on chloride

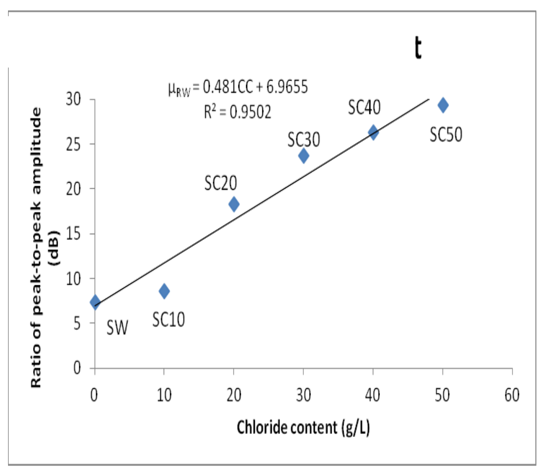


Figure 7 Peak-to-peak attenuation of reflected waves, μ_{DW}, on chloride

4.0 CONCLUSIONS

In this study, the following conclusions can be derived:

a) The peak-to-peak amplitude ratio of GPR DW is influenced by the amount of moisture in concrete and chloride content.
b) Te DW and RW amplitude ratio are linearly correlated with the moisture and chloride content increment.
c) Further effort on estimating the moisture and chloride content in concrete can be provided by developing a model relating the amplitude attenuation with both corrosive agent amounts to map the problematic zone on concrete contaminated with moisture and chloride.

Acknowledgement

The authors acknowledge Universiti Kebangsaan Malaysia for providing the financial support through projects GUP-2013-017 and DLP-2013-033.

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