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Influence of corrosion-induced damage in reinforced concrete on GPR signal parameters

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Abstract

Ground penetrating radar (GPR) is a non-destructive technique (NDT) that is mainly used to locate reinforcement in structures. Even though several studies have shown promising results in characterizing corrosion with GPR, more research should be conducted on the effects of corrosion on GPR signal parameters. This paper presents experimental work aimed at observing the effects of water, water contaminated with chlorides, and corrosion-induced cracks in reinforced concrete, on the ground penetrating radar signal strength. Two reinforced concrete specimens with two reinforcing bars were cast; one to observe the influence of water and the other to observe the influence of water contaminated with chlorides and ccorrosion-induced cracks on GPR signal. The results show that, with the presented experimental setup, the changes due to these effects are small. Immersion in water for 11 days caused a decrease in amplitude of 3.7 %, 11.2 % for immersion in water contaminated with chlorides, and 12.69 % for a 0.8 mm crack.

Key words: ground penetrating radar (GPR), corrosion, concrete, chlorides, moisture

Utjecaj oštećenja izazvanih korozijom u armiranom betonu na parametre GPR signala

Sažetak

Georadar je nerazorna metoda koja se kod ispitivanja konstrukcija uglavnom koristi za određivanje lokacije armature. Iako postoje određene studije u kojima je korozija karakterizirana georadarom, potrebno je provesti više istraživanja o učincima korozije na signal georadara. Ovaj rad predstavlja eksperimentalni rad na promatranju utjecaja vode, vode i klorida te pukotina izazvanih korozijom u armiranom betonu na signal georadara. Dva armiranobetonska uzorka s dvije armaturne šipke su izrađena; jedan za promatranje utjecaja vode, a drugi za promatranje vode i klorida, i pukotina izazvanih korozijom na signal georadara. Rezultati su pokazali da su s prikazanom eksperimentalnom postavkom promjene zbog ovih učinaka bile male. Potapanje uzorka u vodu tijekom 11 dana uzrokovalo je smanjenje amplitude od 3,7 %, 11,2 % potapanje u vodu i kloride, te 12.69 % za pukotinu od 0,8 mm.

Ključne riječi: georadar, korozija, beton, kloridi, vlaga

1 Introduction

Corrosion is the main problem that threatens service life of reinforced concrete structures [1]. Chloride-induced corrosion emanating from the marine environment and deicing salts is of great concern to global infrastructure. While some strategies aim to propose design-level solutions, the world yearns for strategies that can mitigate the effect of corrosion on existing structures. The extensive and rational use of non-destructive techniques (NDT), applied periodically, could lead to early detection of corrosion. The results of this type of inspection, integrated with management systems, could improve global performance of infrastructure facilities, leading to lower maintenance costs. In particular, this can also be improved by an optimum combination of NDT inspections.

Ground penetrating radar is one of the most promising non-destructive techniques [2] mainly because of the nature of the inspection. The technique involves acquisition of couple line scans to cover an area with a wheeled instrument. Depending on the area, the inspection can be completed in a few minutes. This method is electromagnetic based [3], and is mainly used to locate reinforcement in structures. However, proper and comprehensive analysis of the results can also be used for corrosion characterization [4–7]. The analysis is based on observing changes in signal strength during the corrosion process. This is still a new approach and there is no clear link between laboratory studies and field practice [8].

Laboratory research is based on the isolation of a single corrosion-related effect (e.g., chlorides and water that provoke it, and rust as its consequence) [9, 10, 11, 12]. The aim of these laboratory studies is to analyse in detail how this single effect influences the strength of the GPR signal. Field practice is based on simple localization of areas with disturbed signal as a sign of corrosion originating from synergistic corrosion effects [7, 13].

However, there is still much confusion in the research community as to what is the predominant cause of a disturbed signal strength. The effects of water, water contaminated with chlorides, and corrosion-induced cracks, on GPR signal are compared in this study.

2 Ground penetrating radar signal parameters

Ground Penetrating Radar (GPR) is an electromagnetic-based, non-destructive method used primarily to locate objects situated under the ground surface. The device has antennas that emit electromagnetic waves into the material and register the waves reflected from the object. GPR records the time it takes for the reflected wave to reach the object and return to the receiving antenna, as well as the strength of the reflected wave. These parameters can be seen on the A-scan or trace, which is the starting point for analysing the results collected by GPR, Figure 1.

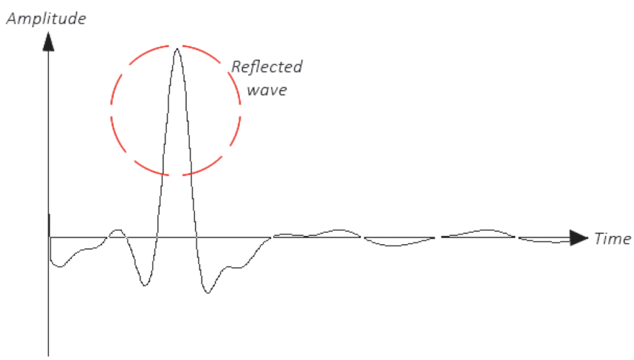

Figure 1. The A-scan

As mentioned before, the position and depth of the object is desired for most practical uses. For that purpose, the time *t* is converted into the depth *d* according to equation (1),

$$\mathbf{d} = \mathbf{V} \cdot \frac{\mathbf{t}}{\mathbf{2}} \tag{1}$$

where *V* is the velocity of electromagnetic waves. The velocity is calculated from equation (2),

$$\mathbf{V} = \frac{\mathbf{C_{air}}}{\sqrt{\varepsilon_{\mathbf{r}}}} \tag{2}$$

In this equation, C_{air} is the velocity of wave in the air (300 mm/ns), while ε_r is the dielectric constant of material [14].

The basis of propagation of electromagnetic waves through a material is described by Maxwell's equation [15] which depends on the material properties, namely electrical conductivity σ, dielectric permittivity ε, and magnetic permeability μ. In the case of concrete, which is considered to be devoid of magnetic properties, the magnetic permeability is equal to the permeability of free space [16]. On the other hand, the electrical conductivity and the dielectric permittivity are strongly dependent on the condition of concrete. The electrical conductivity is determined by the presence of free charges in the pores of concrete. If concrete pores are contaminated with free charges, e.g., chlorides, the propagation of electromagnetic waves will result in the movement of charges leading to a loss of electromagnetic energy. Similarly, the dielectric permittivity depends on the ability of polar molecules in the material to resist rotation in the presence of an electromagnetic field. As a result, variations in material properties are to be expected in the presence of moisture and/or chlorides in concrete. The presence of water molecules and chlorides in pores results in an overall loss of energy and signal, as manifested in a reduced amplitude of the reflected wave in the A-scan.

3 Methods

Concrete specimens were produced using cement CEM I 42.5 R, river aggregate classified into three fractions (0/4mm, 4/8mm, 8/16mm), potable water, superplasticizer, and air-entraining admixture. The design of mixture is shown in Table 1.

Table 1. Concrete mix design

Cement [kg/m³]	Water [kg/m³]	River Aggregate			Superplasticizer [kg/m³]	Air-entraining admixture [kg/m³]
		(0/4mm)	(4/8mm)	(8/16mm)		
401	121	843	501	579	2	1,6

Two samples each measuring 70 cm in length, 30 cm in width, and 25 cm in height, were cast. Two rebars 20 mm in diameter were embedded 5 cm below the concrete surface, Figure 2a. Copper wires enabling electrical connection for the accelerated corrosion test were connected to the rebar. The connection was protected by an impermeable mastic. The sides of the specimens were coated with epoxy.

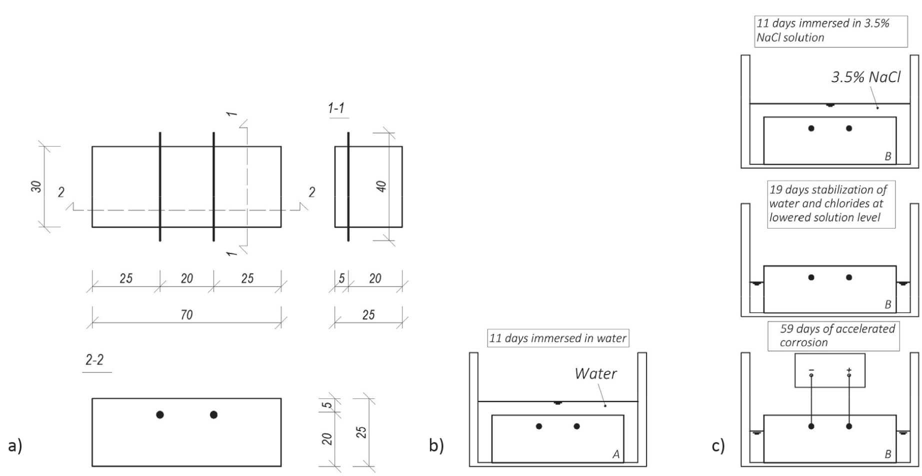

Figure 2. a) Sample design, b) Experimental setup for sample A, c) Experimental setup for sample B

The first sample (A) was used only to observe the effect of water on the GPR signal, while the second one (B) was used to observe the effect of water contaminated with chlorides, and corrosion-induced cracks. Sample A was immersed in water (Figure 2b), while sample B was immersed in a 3.5 % sodium chloride (NaCl) solution for 11 days (Figure 2c). Relative humidity of specimens was checked after immersion of samples using the Concrete Moisture Meter PosiTector CMM IS. This value was determined at the sample depth of 5 cm.

After immersion, the level of the solution was lowered 90 mm below the surface for sample B. The sample was then left for 19 days to stabilize the water and chloride content. The corrosion was then accelerated using the impressed current method. The working electrode is a rebar connected to the positive terminal of the current source, while the second electrode is connected to the negative terminal, Figure 2c. The current source was set to the constant current mode (CC), which means that the current intensity was not changed during the process. A total current of 0.038 A was applied, corresponding to a current density of 200 $\mu A/cm^2$. The sample was exposed to the accelerated corrosion process for 59 days, which is equivalent to a mass loss of 7,5 % according to Faraday's law.

Data were acquired using a 2.7 GHz GPR device with the scanning rate of 8 scans/cm. GPRA-scans were acquired over one rebar for sample A and over the working electrode for sample B. Measurements were acquired before and after immersion in water and sodium chloride for specimens A and B, and periodically during crack propagation induced by corrosion process for specimen B. GPR parameters were derived using Radan 7 software for the analysis of GPR data. The crack width was measured with a crack width ruler as a mean value of three measurements above the anode bar.

4 Results

4.1 Influence of water on GPR signal parameters

Relative humidity of sample A after immersion in water was 100 %. The results indicated that immersion in water influenced the overall decrease in signal amplitude and caused a delay in reflection, as can be seen in Figure 3. The presence of water molecules in concrete pores influenced the increase in dielectric permittivity and electrical conductivity, and this effect increased attenuation of waves.

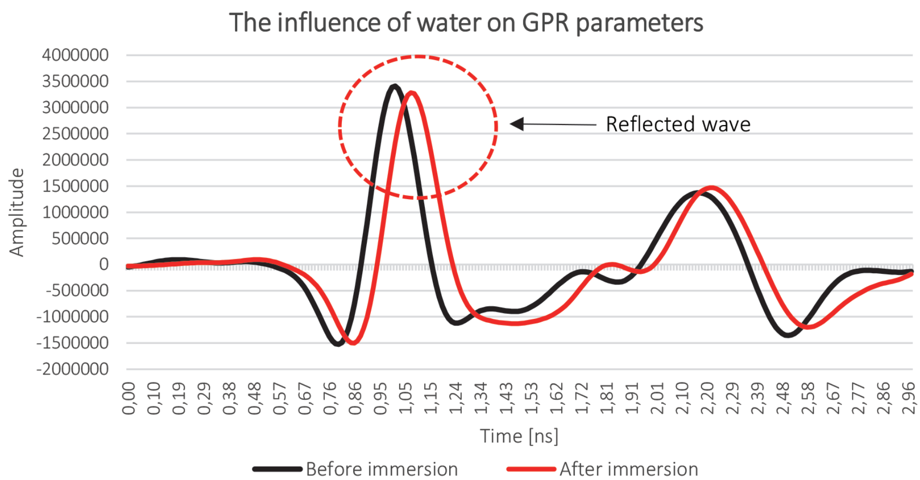

Figure 3. A-scans of sample A before and after immersion in water

4.2 Influence of water contaminated with chlorides on GPR signal parameters

Relative humidity of sample B after immersion in sodium chloride solution was 100 %. The change in signal strength was more pronounced when specimen was immersed in sodium chloride solution than in the case of pure water. This is expected since chlorides additionally have strong influence on material properties. Namely, chlorides in large degree influence electrical conductivity which enforces attenuation of signal.

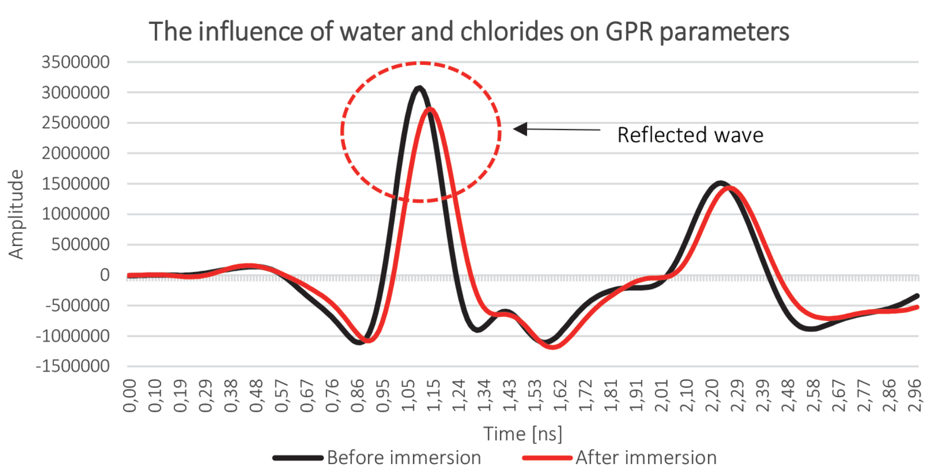

Figure 4. A-scans of sample B before and after immersion in sodium chloride

4.3 Influence of cracks on GPR signal parameters

The trend of change of signal amplitude during crack propagation is shown in Figure 5. Amplitudes of reflected waves are given for various crack widths. In general, the decrease in amplitude was observed with an increase in crack width. The exception was for crack widths 0.4, 0.5 and 0.7 mm, where the amplitudes were very similar, and it could not be argued that there was a clear influence from crack widening. The loss of signal could be explained by irregular crack boundaries affecting dispersion of the signal and general decrease in wave amplitude.

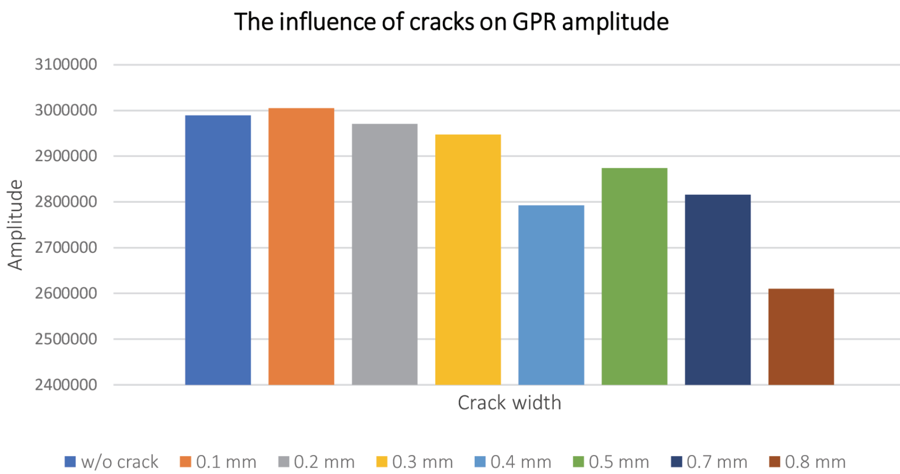

Figure 5. Signal amplitudes of sample B during crack propagation

4.4 Discussion

To compare the influence of water, water contaminated with chlorides and cracks, on GPR amplitude, the comparison before and after these influences is shown in Table 2.

Table 2. Comparison between various effects on GPR amplitude

	Event	Amplitude	Change relative to amplitude before immersion [%]	Change relative to amplitude w/o crack [%]
Water	Before immersion in water	3413082	/	/
	After immersion in water	3287298	3.69	
Water contaminated with chlorides	Before immersion in sodium chloride	3075655	/	
	After immersion in sodium chloride	2730460	11.22	
Cracks	w/o crack	2989515	/	/
	0.1 mm	3004932		-0.52
	0.2 mm	2970671		0.63
	0.3 mm	2947078		1.42
	0.4 mm	2792562		6.59
	0.5 mm	2873972		3.86
	0.7 mm	2815890		5.81
	0.8 mm	2610181		12.69

Based on results, It was concluded that the most severe amplitude decrease was caused by a 0.8 mm crack. However, the authors are aware that all signal strength changes listed in this paper are very subtle. The amplitude changes are consistent with the theory, but they should be more obvious to claim that some effect influences the change in amplitude. The cause of the subtle changes due to water and chlorides could be a very dense concrete with high durability properties, and so the exposure of the specimens to this condition is not realistic.

5 Conclusion

Preliminary experimental work on the influence of corrosion-related effects on the parameters of the ground penetrating radar signal is presented in this paper. The influence of water and chlorides, and corrosion-induced cracks, was observed.
It was found that a 0.8 mm crack caused a more significant change than immersion in water and sodium chloride for 11 days. However, the changes in amplitude were small for all three effects. Further research will focus on observing the effect of different material properties and exposure conditions on the signal strength. Furthermore, extensive research will aim to confirm the subtle change in amplitude

originating from cracks. In addition, crack widths will be extended to determine which crack width causes a significant change in signal.

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