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Ground Penetrating Radar: an Application to Estimate Volumetric Water Content and Reinforced Bar Diameter in Concrete Structures

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Abstract

Non-destructive evaluation of reinforced concrete structures is an increasingly important field in the construction and civil engineering community. A large number of pathologies affecting both the concrete and the reinforced bar inside the concrete are related to the presence of water and its spatial development. In this context, the quantification of both water content and bar diameter is an important part of the diagnosis of concrete.

The aim of this paper is to present the results of two important studies undertaken in order to estimate the volumetric water content and bar diameter in concrete structures.

The dielectric properties of concrete were studied as a function of volumetric water content. Experimental tests were carried out using an HP impedance analyzer. More than 800 samples of concrete were analyzed and a new relationship between the relative dielectric constant and volumetric water content was obtained. Further experimental tests were carried out by using GPR travel time tomography to study the effectiveness of the new relationship between the relative dielectric constant and volumetric water content.

The study was subsequently focused on rebar sizes estimation inside concrete structures. Models were reproduced in the laboratory using a range of rebar sizes from 8 to 22 mm. These models, which represent rebars in a concrete medium, were used to detect rebar's position and study the rebar sizes as a function of the ratio of the cross polarized to normal polarized electromagnetic wave amplitudes. GPR measurements, using the 1 GHz center frequency antenna, were performed on the model reproduced in the laboratory. The results of the GPR measurements were compared with the results of a simulation forward model, proposing an empirical relationship between rebar sizes and the ratio of the cross polarized to normal polarized electromagnetic wave amplitudes. Furthermore, several experimental tests were carried out by using a GPR to study the effectiveness of the proposed relationship.

1. Introduction

Geophysical methods used as monitoring systems are becoming more and more important in the concrete industry. The non-destructive aspect of most geophysical methods allows determination of the integrity of existing structures and monitoring of quality during construction (Alongi *et al.* 1982; Clemena 1983). The degradations of concrete structures are often due to external causes. The degree of elements degradation such as the reinforcement, the cover concrete protects, the structural elements that compose the concrete past are a good indicator of the structural quality. The corrosion can follow carbonation or chloride ingress. The corrosion can be caused by internal reaction such as alkali-silica or sulfatic reaction. The presence of water is a necessary condition to produce a chemical attack. Therefore quantification of volumetric water content is an important part of the diagnosis.

A geophysical method that has frequently been applied to structural concrete is ground-penetrating radar (GPR) (He *et al.* 2009). The number of applications of

GPR to structures began increasing in the 1980s (Forde 2004). Initial civil engineering applications included condition assessment of highway pavement and its foundation, with applications to structural concrete focusing on the inspection of bridge decks. Cantor *et al.* (1984) reviewed early developments in these areas in 1984, and Clemena reviewed radar testing of concrete in 1991. Bungey (2004) reviewed the recent developments in equipment, materials characteristics, signal processing, numerical modeling and practical aspects of applications and interpretation in a concrete survey.

Potential applications are i) determination of location of reinforcing bars; ii) estimation of the concrete cover depth; iii) estimation of moisture variations; iv) estimation of bar size (Bungey 2004; Barrile and Pucinotti 2005; Bungey *et al.* 1993).

In 1997, the Concrete Society published the standard specification for the radar methodology, and in 2003, the Federation of Construction Material Industries of Japan proposed two drafts for test standards (Method for locating of rebars in reinforced concrete by radar, and Method for locating of rebars and determining the diameters of rebars in reinforced concrete by electromagnetic induction).

Detection of reinforcing bars in concrete is one of the most widespread applications of GPR in civil engineering (Ulriksen 1983; Pucinotti and De Lorenzo 1994;

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Pucinotti and Barrile 2002; Barnes *et al.* 2008; Diamanti *et al.* 2008). Bar sizing is more difficult and there is little evidence of industrial usage.

The potentially enhanced value of test combinations is widely recognized, for example the combination of radar with infra-red thermography (Maierhofer *et al.* 2001) or impact echo (Colla *et al.* 2002), and the combination of impact echo and radiography (Dérobert *et al.* 2002).

The estimation of moisture variations is another widespread application of GPR. Several authors have demonstrated the effectiveness of GPR for the quantification of volumetric water content in subsoil materials (Du and Rummel 1994; Graves *et al.* 1996; Leucci *et al.* 2002).

However, the literature reports only few applications for the quantification of moisture surface gradient in concrete (Klysz and Balayssac 2007).

This paper describes the results of simulations, controlled tests and measurements to quantify both the volumetric water content gradients and the bar diameters in concrete.

First, 800 concrete samples, collected from several building yards with different characteristic (porosity and aggregate sizes) were analyzed at different homogeneous saturation degrees to study the effects of moisture on electromagnetic waves.

Next, the bar diameter in concrete was studied as a function of electromagnetic wave amplitude.

The results show an empirical relationship between rebar sizes and electromagnetic wave amplitude, and between the electromagnetic parameter and volumetric water content in concrete.

2. Relationship between volumetric water content and electromagnetic wave parameters

The changes in the dielectric properties of concrete are a result of changes in the water content.

To identify the dielectric changes in concrete as a function of volumetric water content, 800 samples collected from several building yards were examined with an impedance analyzer in the frequency range of 1 to 1000 MHz, and a relationship between relative dielectric constant and volumetric water content was found.

The main mixture characteristics of the 800 examined samples are summarized in **Table 1**.

Subsequently a laboratory controlled test was per-

formed using the GPR SIR-3000 and 1000 MHz and 1500 MHz center frequency antennae.

2.1 Experimental set-up and results

A HP impedance analyzer model 4191A was used to measure the dielectric properties as a function of volumetric water content of concrete at high frequencies. This analyzer generates an electrical field in the frequency range of 1 to 1000 MHz and registers the electrical capacitance and conductivity of the material. The 4191A measure 14 parameters with a maximum resolution of 4.5 digits. The concrete was cast in plastic containers where it remained during the test in order to prevent moisture exchange.

Relative dielectric constant (k) is related to the measured capacity (C) by the following relationship (Beek *et al.*, 1998):

$$k = s_{\text{cel}} (C/k_0) \quad (1)$$

where s is the “cell constant” (m^{-1}), defined as: $s_{\text{cel}} = s R$, where R is the measured resistance of the cell, s is the conductivity, formerly called the specific conductance (PAC, 1974), and k_0 is the dielectric constant of the vacuum.

The medium was watered through a discontinuous process. The concrete samples were immersed in a water tub for several hours. Afterward, the samples were weighed at each moisture level with a high-precision electronic balance (model HP 6200 C, with an uncertainty of 0.01 g).

The relative dielectric constant (k) was correlated with the volumetric water content (w) for each concrete sample.

Measurements were performed over a period of one year with repeated cycles of drying and humidification. The time of immersion in water was the same for all samples and measurement were performed every four hours.

The results were analyzed using the method of least squares. The equation of the best fit line, the 95% confidence limits, and the correlation coefficients (R^2) were determined.

The relation between the relative dielectric constant and volumetric water content is illustrated and discussed below. **Figure 1** shows the plot of k as a function of the w values.

It can be seen that, as expected, the relative dielectric constant k increases with increasing volumetric water content. The obtained values show a good correlation

Table 1 Mix proportions and strength of concretes.

Mixture Class	Proportion	Cement in Bag		Sand	Gravel	w/c ratio	Strength of Mixture (PSI)
		40 kg	50 kg				
Class AA	1:1 1/2:3	12	9.5	0.5	1.0	0.44	4000
Class A	1:2: 4	9.0	7.0	0.5	1.0	0.44	3500
Class B	1:2 1/2: 5	7.5	6.0	0.5	1.0	0.44	3000
Class C	1:3: 6	6.0	5.0	0.5	1.0	0.44	2500

Fig. 1 Volumetric water content (w) as a function of relative dielectric constant (k).

between the two parameters studied. Thus the relative dielectric constant varies from 2.5 for a dry concrete ($w = 4\%$) to 10 for a saturated concrete ($w = 16\%$). Observing the plot (**Fig. 1**), it can be seen that there are polynomial relationships between the relative dielectric constant and the volumetric water content. The regression equation is given by:

$$w = 0.001k^3 + 0.1232k^2 - 0.043k + 3.3035 \quad (2)$$

The regression equation with the correlation coefficient is high, suggesting a strong relationship between k and w . A combination of w and k could provide concise information for uniquely characterizing concrete quality.

2.2 Test measurement of water content in concrete

The test measurement was performed on a concrete cubic sample measuring 0.3 on each side (**Fig. 2**). Measurements were performed at two known volumetric water content ($w = 4.90\%$ and $w = 5.98\%$) using the GPR geophysical method.

A SIR-3000 unit was used for both two-dimensional travel time tomography (TT) and the reflection mode.

Two-dimensional GPR TT aims to obtain information on the distribution of the dielectric constant on a section of the investigated medium from the direct arrival traveltimes picked between the sources and receivers. Hence, a TT survey was performed using 1500 MHz and 1000 MHz antennae having partially overlapping frequency bands (Herman 1980). GPR data were collected using multi-offset gathers with the 1500 MHz antenna as the transmitter and the 1000 MHz antenna as the receiver (**Fig. 3**).

Data were acquired by positioning the transmitting antenna on one side of the sample and collecting data at several receiver positions on the opposite side of the sample (**Fig. 3**). The transmitter was moved in 0.025 m steps across a distance range of 0.05 to 0.2 m along the selected side. In contrast, the receiver was moved in 0.025 m steps along the whole length of the opposite side, collecting a total of 81 radar common-source gathers. The following acquisition parameters were set for each survey: (i) Recording time window: 20ns; (ii)

Samples:1024; (iii) Gain: manual. To track any fluctuations in the GPR transmitter output during data collection, a time zero calibration was conducted at every transmitter position. The inversion of tomographic data is a complex problem, and the results strongly depend on various factors, including acquisition geometry, inversion and regularization algorithm, and size of the tomographic grid. To solve the inverse problem (Nolet 1987; Holliger *et al.* 2001), the Reflexw 5.0 software (Sandmeier 2008) deploys a simultaneous iterative reconstruction technique (SIRT), which is actually suitable for slightly non-linear inverse problems, i.e. for weak velocity contrasts. More efficient algorithms exist for GPR tomography (such as LSQR, conjugate gradient, stochastic tomography), and numerous papers (Tronicke *et al.* 2001; Zhou *et al.* 2001; Cohen 1991) proved that other techniques are more suitable than SIRT for GPR data tomography. Nevertheless, the choice of SIRT is motivated by the fact that a lot of commercial software uses this algorithm.

The inversion results for the data set (**Fig. 4**) show low variations of k . Applying then the empirical formula (Equation (2)), an estimation of the average volumetric water content for the data acquired on the concrete sample was obtained (**Fig. 4**). The distribution models of w show relatively little variation of the same w . It varies from about 5.8% to about 6.4% (with error $\Delta w =$

Fig. 2 Cubic concrete sample used for test measurement.

Fig. 3 GPR traveltime tomography scheme.

Fig. 4 GPR traveltome tomography relative dielectric constant (k) and volumetric water content (w) distribution models.

$\pm 0.3\%$) in the sample with known volumetric water content of $w=5.98\%$ and from about 4.3% to about 5.1% (with error $\Delta w = \pm 0.3\%$) in the sample with known volumetric water content of $w = 4.9\%$.

In the reflection mode, the test was carried out in continuous mode using an antenna with central frequency of 1000 MHz.

Data were collected from the same concrete block used for TT tomography. The acquisition parameters were (i) time range = 8 nanoseconds; (ii) samples number = 512; (iii) gain point = 4; (iv) gain values = [7, 11, 20, 26] dB.

The resulting radar section is shown in Fig. 5.

Figure 5 shows the reflections derived from the upper and lower surface of the concrete block. In Fig. 5a, the radar section is related to the blocks that have a known volumetric water content of about 5.98% , while in Fig. 5b, the radar section is related to the blocks that have a known volumetric water content of about 4.9% .

The two-way travel time of the reflections of the concrete block top and bottom are 4.4ns (Fig. 5a) and 3.9ns (Fig. 5b), respectively. Once known the thickness of the block was known, the electromagnetic wave velocity was calculated directly using the following relationship:

$$v = (2z / \Delta t)$$

where $2z = 0.6\text{ m}$ and $\Delta t = 4.4\text{ ns}$ and 3.9 ns

Fig. 5 Reflection radar section acquired with 1000 MHz central frequency antenna on concrete block: a) known $w = 5.98\%$; b) known $w = 4.9\%$.

The calculated velocities were 0.136 m/ns and 0.154 m/ns . These values allow the calculation of the relative dielectric constant, which is 4.9 and 3.8 , respectively. Using Equation (2), it is possible to obtain the volumetric water content of about 6.17% ($\pm 0.4\%$) for the blocks that have a known volumetric water content of about 5.98% and 4.97% ($\pm 0.4\%$) for the blocks that have a known volumetric water content of about 4.9% .

The ranges of variation demonstrate the effectiveness of Equation (2).

3. Relationship between reinforced bar diameter and amplitude of electromagnetic wave

This paragraph describes the results obtained by both the controlled test survey and the forward modeling in order to obtain a relationship between reinforced bar diameter in concrete and electromagnetic wave amplitude.

3.1 Polarization in rebar detection

Polarization, the direction and magnitude of the electromagnetic field as a function of time and space, can have a significant impact related to the GPR response (Reynolds 1998). Polarization of the transmitted signal impacts how waves are scattered (reflected and diffracted) from heterogeneities in the subsurface, and the subsequent orientation of the received scattered waves. Receiving antennae are sensitive to the polarization of scattered electromagnetic waves. The target symmetry (shape and orientation) also has an impact on the polarization of a scattered wave, as do the incident angle of the wave, antenna separation, and the impedance contrast of the materials. A scattered wave can have the same polarization as the incident wave, or it can be polarized differently, in which case it is said to be “depolarized” (Beckman 1968; Roberts *et al.* 1992; Roberts 1994; Roberts and Daniels 1996).

Dipole antennae, which are typically used for GPR

field surveys, radiate electromagnetic waves with the electric field vector components predominantly oriented parallel to the long axis of the antenna. These waves are considered to be linearly polarized, as the direction of the electric and magnetic fields remain fixed during propagation (Kraus 1984). The most common antenna arrangement used for GPR field studies is a co-pole configuration (Fig. 6), where the transmit and receive antennae (and thus the electric and magnetic fields) are aligned parallel with each other. A co-pole antenna configuration receives reflected and scattered energy that has the same polarization as the incident energy. A configuration is 'co-polarized' when both the transmit and receive antennae are oriented in the same direction (Fig. 6a), whereas it is 'cross-polarized' when the transmit and receive antennae are perpendicular to each other (Fig. 6b). Co-pole field data are most commonly acquired with the transmit and receive antennae oriented perpendicular to the traverse direction (Fig. 6a).

The scattering properties of rebar are strongly polarization dependent (Guy *et al.* 1999; He *et al.* 2009). The backscattered fields from rebar may be strongly depolarized depending on the orientation of the rebar relative to the antennas, and the radius of the rebar compared to the incident wavelength (Radzevicius and Daniels 2000). These polarization dependent scattering properties have important implications for rebar detection, survey de-

sign, and data interpretation. The radiation from rebar is linearly polarized, thus the reflections can be maximized by varying the antenna orientation (Bungey 2004).

Rebar yield strong reflections when oriented parallel to the long axis of a dipole transmit antenna in a co-pole antenna configuration (Fig. 7a), but yield weak reflections when oriented orthogonal to the transmit antenna (Fig. 7b).

3.2 Measurements of rebar diameter

Several authors have demonstrated that GPR can be used to provide an indicative measurement of the size of reinforcement bars despite this being difficult and of low potential for industrial application (Bungey 2003; Stolte and Nick 1994; Olhoeft 2000; Al-Nuaimy *et al.* 2000; Utsi and Utsi 2004; Shihab and Al-Nuaimy 2005).

Rebar could be considered a cylindrical target. The reflection signal present in radargram is a hyperbola (Fig. 8), so it is possible to establish some relation between the radius of rebar and the geometry of the hyperbola.

A more interesting equation was developed by Shihab and Al-Nuaimy (2005), who state that it allows cylinders of arbitrary radii to be detected and characterized uniquely from a single radargram. The following relationships were produced between R and the general hyperbola centered around (x_0, y_0) (Fig. 8).

Fig. 6 Co-pole configuration: a) co-polarized; b) cross-polarized.

Fig. 7 Reinforced bar orientation: a) parallel to long axis of dipole transmit antenna b) orthogonal to transmit antenna.

Fig. 8 Resulting hyperbola from cylindrical object with its asymptotes and related parameters indicated in Equation (3).

$$\begin{aligned} a &= t_0 + \frac{2R}{v} \\ b &= \frac{v}{2} \left(t_0 + \frac{2R}{v} \right) \end{aligned} \quad (3)$$

Shihab and Al-Nuaimy (2005) developed a fitter based on the direct least-square method, which was specifically adopted for a hyperbolic conic sections. Both a , b and t_0 are obtained as a result of the fitting process and v and R can be calculated from a and b . The authors affirm that the fitting technique is fully capable of successfully estimating the depth and radius to within 10%.

Relationships (3) were used in order to estimate the bar diameter in controlled tests using both a synthetic data and real data.

The data are simulated in a simplified two-dimensional slab (concrete material-air) geometry. In particular, the synthetic model (Fig. 9a) is made up of an investigation domain with low relative dielectric permittivity ($\epsilon_r = 5$) and sized $1 \times 0.5 \text{ m}^2$. A metal bar of 10 mm diameter is located inside it.

The temporal and spatial sampling intervals exploited in the FDTD analysis are $t = 0.03 \text{ ns}$ and $x = 0.001 \text{ m}$, respectively. The central frequency of the antenna is 1000 MHz. To simulate GPR data, the Reflexw software was used (Sandmeier 2008). The software exploits an iterative modeling procedure based on the exploding-reflector concept (Carcione *et al.* 2002). To make use of the exploding reflector model means that starting at time $t = 0$, all points stemming from a reflector are the starting point of a Huygen's elementary wave with an amplitude proportional to the reflection coefficient for the normal incidence case. For practical purposes, using the exploding-reflector concept to simulate a zero-offset section is advantageous when performing a computer simulation of field data (Carcione *et al.* 2002).

Figure 8b shows the synthetic radar time section obtained from the corresponding model (Fig. 9a). The diameter of the bar was calculated using the relationships (3). The result was 7.9 mm.

Real data were acquired using the SIR-3000 radar and the 1000 MHz center frequency antenna. The bar diameter was 20 mm. The results are shown in Fig. 10.

Also in this case, the bar's diameter was calculated using the relationships (3). The result was 20.9 mm.

Other experiments were performed on cylindrical objects of various dimensions and the results show that the accuracy increased with increases in the diameter of the cylindrical objects.

Utsi and Utsi (2004) had used GPR to estimate bar diameter based on the A_c/A_n amplitude ratios (the amplitudes ratios of the bar signals along and across the

Fig. 9 a) synthetic model with a metal bar of 10 mm diameter; b) synthetic radar time section.

Fig. 10 Real GPR data acquired on a bar with diameter of 20 mm.

EM field) and the rebar sizing accuracy was about 20%.

In order to estimate the bar diameter, a series of experiments were undertaken. The experiments were inspired by Utsi's results (2004) and therefore considered the A_c/A_n amplitude ratio. In the case study presented here, a new relationship between the bar diameter and the A_c/A_n amplitude ratio that is different from the one presented by Utsi (2004) was found.

Fig. 11 Synthetic model with metal bars of 8 to 10 mm diameter.

A series of controlled tests using both synthetic data and real data were performed.

The data were simulated in a simplified two-dimensional slab (concrete material-air) geometry. In particular, the synthetic model (Fig. 11) was made up of an investigation domain with low relative dielectric permittivity ($\epsilon_r = 5$) and sized $1 \times 1 \text{ m}^2$. Within it were located a series of metal bars with different diameters ranging from 8 mm to 20 mm.

The Reflexw software was exploited (Sandmeier 2008) to simulate the GPR acquisition with a 1000 MHz antenna. The radar signal acquisition was simulated with the bar position along and across the EM field.

Figure 12 shows the synthetic radar time sections, the bar's diameter of 10 mm, related to the bar signals along (Fig. 12a) and across (Fig. 12b) the EM field.

As expected, the rebar yield strong reflections when oriented parallel to the long axis of a dipole transmit antenna in a co-pole antenna configuration, but they yield weak reflections when oriented orthogonal to the transmit antenna.

Fig. 12 Synthetic radar time sections zoomed on 10 mm bar diameter: a) bar signals along EM field; b) bar signals across EM field.

Fig. 13 Synthetic radar time section processed.

Synthetic data were processed using the Reflexw software as follows: (i) background removal filter; (ii) migration; (iii) trace envelope. The results are shown in Fig. 13.

For real data the SIR-3000 radar and the 1000 MHz center frequency antenna were used to measure the signal amplitude reflections from a series of different known size bars placed at known distances in the concrete structure (Fig. 14). Each rebar was surveyed both in normal polarization and parallel polarization. The GPR data were processed using the Reflexw software as follows: (i) background removal filter; (ii) migration; (iii) trace envelope. The results are shown in Fig. 15.

Fig. 14 Controlled test scheme.

Fig. 15 GPR processed data: a) normal polarization; b) parallel polarization.

Fig. 16 Bar diameters versus A_c/A_n ratio obtained using both forward modeling data and real acquired data.

Fig. 17 Test data on known bar diameters of 20 mm: a) normal polarization; b) parallel polarization.

Both forward modeling and acquired GPR data were analyzed in terms of the amplitude of the reflected radar signal.

The ratio of the cross polarized to normal polarized ($A_r = A_c / A_n$) was plotted against the bar diameters (Fig. 16).

Figure 16 shows that A_r is approximately proportional to bar diameter.

The results were analyzed using the method of least squares. The equation of the best fit line, the 95% confidence limits, and the correlation coefficients (R^2) were determined. The regression equation is given below:

$$d = 4.482 A_r^{4.7241} \quad R^2 = 0.8873 \quad (4)$$

The regression equation with the correlation coefficient is high, suggesting a strong relationship between A_r and d .

In order to evaluate the capability of Equation (4) measurements were performed in several building yard. In these cases the bar's diameter was known (Figs. 17 and 18). The bar's diameter was calculated with a 6% accuracy.

It is important to underline that, as demonstrated by Gagliardi *et al.* (2005), the ratio of the cross polarized to normal polarized electromagnetic wave amplitudes is

strongly dependent on the frequency of the used antenna and from the depth of the bars. Therefore the validity of Equation (4) is related to the use of a 1000 MHz center frequency antenna.

4. Conclusions

This paper presents results for the concrete characterization from the viewpoint of the evaluation of volumetric water content and reinforcing bar size. The developed methods allow both reinforcing steel of radii and volumetric water content to be quantitatively detected through GPR radargram, resulting in a more accurate estimation of both the amplitude of reflected signal and dielectric constant.

The experimental results obtained on concrete samples with controlled water content pointed out that relative dielectric constant (k) and its variations are polynomials linked to the volumetric water content (w). The application of the GPR method to real structures with known volumetric water content make it possible to verify the validity of the estimated relationship (Equation 2). The results indicate that this method is capable of estimating the volumetric water content within 0.4% of the actual volumetric water content value.

Since both experimental and modeling results pointed

Fig. 18 Test data on known bar diameters of 6 mm: a) normal polarization; b) parallel polarization.

out a relationship (Equation 4) that could be used to estimate the bar size in concrete if a 1000 MHz antenna is used.

The use of the ratio of the cross polarized to normal polarized (A_r) amplitude produces interesting results. In fact, A_r is totally independent from the variation of radar energy absorption due to the electromagnetic characteristics of the various concrete materials.

The results indicate that this method is capable of estimating the radius of rebar to within 6% of the actual size, which validates the method. Finally, the controlled test specimens from this study will provide excellent material for preliminary tests prior to their use in field trials.

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