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Determining the permittivity profile inside reinforced concrete using capacitive probes

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ABSTRACT

Non-destructive techniques are the future of structure health assessment and monitoring. The dielectric permittivity is sensitive to the water and ionic content of concrete and it can be measured by capacitive probes. In this paper, an inversion method to obtain the permittivity profile inside reinforced concrete from surface capacitive measurements is presented. The inversion process is applied to synthetic models using two forms of parametrizations (discrete and continuous). In addition, the effect of data noise on the inversion is studied. At last, water saturation profiles inside a concrete slab are obtained by means of inversion of experimental capacitive data.

1. Introduction

The development of infrastructures has played an important role in economic growth and the quality of life. The consequences of lack of maintenance of infrastructures can be dangerous to the economy, the environment and most importantly to human lives. Therefore, regular inspections and performance control are essential to ensure the safety and the durability of infrastructures.

For these reasons, many research programs have been conducted to optimize inspection and maintenance management [1–6]. Early inspection and repair of the structures can limit the damage and lower the costs. Several inspection methods can be applied depending on the purpose of the inspection, the accuracy and the cost of the methods [2]. In preliminary assessment, visual inspection is the most simple and used technique [3]. However, visual inspection can fail to detect critical damage inside the structure and therefore the use of more developed non-destructive techniques (NDT) can improve the reliability of the assessment.

Various NDT applied to civil engineering have been developed, they are sensitive to different properties of the material and they vary with their investigation depth. For strength assessment and defect detection for example, ultrasonic methods can be applied for they are sensitive to the elastic modulus and the density of the material as well as to the presence of voids and cracks [7–11]. Furthermore, electromagnetic methods measuring the dielectric permittivity have been proven sensitive to the water and ionic content [12–15].

This article deals with NDT based on capacitive probes that measure the real part of the complex dielectric permittivity in concrete [13,16]. The dielectric permittivity of concrete is sensitive to the three phases constituting the material (gaseous, dry and liquid phases) [14]. Therefore, variation in permittivity can indicate a variation of water and ionic contents. Assessment of these parameters is very important to monitor the health of the concrete. Chloride penetration for example can induce corrosion of reinforcement bars hence damaging the structure. Furthermore, water content affects the rate of chloride penetration [17–19] and other damage mechanisms [20] such as alkali–silica reaction [21,22] and freeze/thaw attack [23]. For these reasons, this article focuses on determining the water content profile using capacitive techniques.

The capacitive system offers three probes of different sizes and thus allows a range of investigation depths. The capacitance can be expressed in terms of permittivity of the material. The permittivity obtained is referred to as “apparent”: it is the permittivity of a homogeneous medium whose capacitance measurement is the same as that of the medium being tested [24]. Our aim in this study is the development of an inversion process to obtain the permittivity profile versus the depth in a concrete slab which can

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be converted to a water saturation degree profile using curves relating permittivity to saturation degree.

We first describe the used capacitive probes as well as the calibration process of the technique. Secondly, we present the inversion theory used and the governing equations. Thirdly, we discuss the numerical inversions obtained as well as the impact of data noise on the results. At last, we compare water content profiles obtained by capacitive measurements to those obtained by embedded relative humidity sensors.

2. Capacitive techniques

Capacitive techniques are used in various fields for motion detection, thickness measurement, humidity and moisture evaluation and other applications [25]. Furthermore, capacitive probes can be used to measure water content in soil [26,27] and it has also been applied for concrete assessment [28] and for post-tensioned structures assessment [29]. At IFSTTAR laboratory, it has been studied since 1970 for measuring water content in soil [30]. Recently it has been applied to reinforced concrete with different water contents [13] and chloride contents [16]. A brief definition of permittivity as well as the dielectric behavior of concrete is presented in the following paragraph. Subsequently, the capacitive technique and its calibration procedure are developed.

2.1. Dielectric permittivity of concrete

An electric field applied to a medium will provoke the movement of “free” charges and a local redistribution of “fixed” charges [31]. The mechanism related to the movement of free charges is the conduction, measured by electric conductivity σ and that of fixed charges is polarization, measured by dielectric permittivity ε. Concrete is an imperfect dielectric material and therefore its permittivity and conductivity are complex properties that vary with frequency. In practice, most electromagnetic techniques cannot distinguish the effects of permittivity from conductivity and therefore an effective permittivity is defined that takes both effects into account [13,14,32]:

$$\varepsilon_{\text{eff}} = \varepsilon + \frac{\sigma}{j\omega} = (\varepsilon' - j\varepsilon') + \frac{(\sigma' + j\sigma')}{j\omega} = \left(\varepsilon' + \frac{\sigma'}{\omega}\right) - j\left(\varepsilon' + \frac{\sigma'}{\omega}\right) = \varepsilon'_{\text{eff}} - j\varepsilon'_{\text{eff}} \quad (1)$$

where ω is the angular frequency (rad/s).

The real part of the effective permittivity ε'_{eff} measures the capacity of the material to store electromagnetic energy, and the imaginary part ε''_{eff} measures the loss of energy. The permittivity is usually divided by the permittivity of the vacuum ($\varepsilon_0 = 8.854.10^{-12}$ F/m) and is known therefore as a relative permittivity ε_r:

$$\varepsilon_r = \varepsilon'_r - j\varepsilon''_r \quad (2)$$

The permittivity of the solid phase or of a dry concrete (no liquid phase) is a real number and lies between 3 and 5, depending on the EM nature of the aggregates, and the permittivity of a wet concrete is a complex number that varies with the frequency. The presence of water and ions in concrete induces polarizations that decrease as the frequency of the electric field increases. Since the real part of the permittivity increases with polarization, the effect of the water on permittivity is greater at low frequencies. In Fig. 1, the variation of permittivity with different water content is presented at two frequencies: 33 MHz for the capacitive techniques and 1 GHz for the radar technique [33]. The variation range scale is greater at 33 MHz for the same concrete and this is one of the advantages of the capacitive technique.

Capacitance is the ability of the material to store electric energy. It depends on the real part of the complex permittivity ε'_r and therefore, to simplify, the term permittivity henceforth will refer to ε'_r.

2.2. Capacitive probes measurement system

The capacitive probes used in this study are each connected to a resonant circuit with an oscillator operating at 33 MHz (Fig. 2). The measurements are carried out by applying the electrodes to the surface of the concrete structure forming a coplanar capacitor. We dispose of three different types of probes, each one is composed of metallic electrodes and a support made of Plexiglas (Fig. 3). The difference between the probes is the number of the metallic plates forming the electrode and their dimensions, consequently making their investigation depths different. The smallest electrode (PE) is composed of 5 plates (70*5 mm, 5 mm spacing), the medium electrode (ME) of 4 plates (70*10 mm, 10 mm spacing) and the largest electrode (GE) of 2 plates (70*40 mm, 40 mm spacing).

The raw measurement obtained is the resonance frequency f_{osc} (Hz) of the circuit which varies with the capacitance C (F) (Eq. (3)). For each probe, the capacitance C is the sum of the capacitances of the tested material C_{mat}, the measurement system C_{system} and the environment C_{env}. The last term C_{env} includes the variations due to

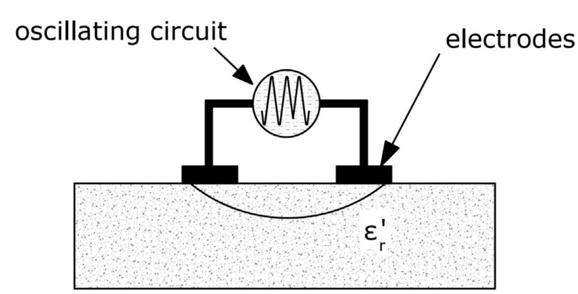

Fig. 2. Schematic diagram of the capacitive electrodes applied on the surface of the material.

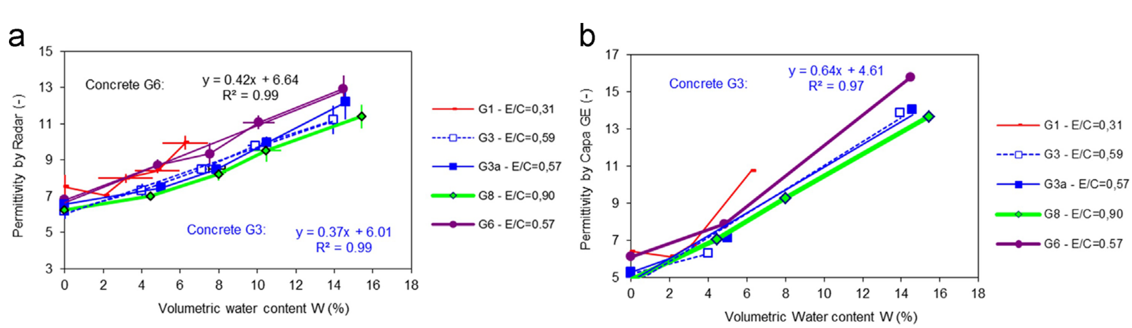

Fig. 1. Variation of permittivity with water content in concrete at 1 GHz (a) and 33 MHz (b) [33].