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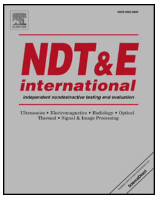

Monitoring water transfers in limestone building materials with water retention curve and Ground Penetrating Radar: A comparative study

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ABSTRACT

The rehabilitation of older buildings is necessary to achieve both a reduction in energy consumption and the preservation of cultural heritage. To ensure a successful building rehabilitation project, an efficient diagnosis makes it possible to determine the various existing pathologies and their causes. In this study, we focus on the "Tuffeau", which is a kind of limestone widely found in older buildings of the Loire Valley region in France. The durability is strongly affected by the water content for such kind of material. However, very few studies can be found in this field. Moisture condition measurements are currently carried out using punctual sensors placed into the walls. These sensors record highly localized measurements through structural alteration (coring). This paper proposes two non-destructive testing (NDT) methods with the application of Ground Penetrating Radar (GPR) in order to compare the ability of the two methods to analyze the water transfer in limestone blocks. A modified water retention curve model is proposed here to characterize the water gradients in limestone blocks: the limestone - water characteristic (LWC) model. The analysis of the results shows good agreement between the two GPR methods, which shows good capability of monitoring water ingress linking to the results of LWC model.

1. Introduction

Current energy and environmental requirements make it necessary to improve the energy performance and environmental quality of buildings, especially given that the construction sector accounts for roughly 40% of the world's energy consumption [1].

Unlike new buildings, older structures are not waterproof, and all indoor ambient moisture is greatly dependent on both outdoor moisture and the hydric state of walls [2]. The presence of moisture can therefore complicate retrofitting solutions. Moreover, to avoid humidity-related damage and propose efficient refurbishment solutions, it is essential to know the thermal conductivity of walls, which once again strongly depends on their hydric state. The thermal conductivity of water is in fact 21 times higher than that of air ($\lambda_{water} = 0.5$ W/m.K, whereas $\lambda_{air} = 0.024$ W/m.K). Tuffeau is a yellowish-white sedimentary limestone that is easy to cut and sculpt and is widely found in older Loire Valley buildings. This material exhibits a broad range of porosity values, from 30% to 50%, and is very susceptible to water penetration, hence the critical importance of assessing the water content of limestone [3,4].

Ground Penetrating Radar (GPR) was applied on priceless heritage masonry structures to help study of the interface between the old and the modern parts of structures constructed at different periods of time [5–8], and to identify older constructions embedded inside walls or buried under the building structures [6,9]. GPR has also been used to assess the efficacy of cement grouting in historical building [10], as well as in-fill of cracks/voids [11]. Beck K et al. [3] described the relationship between the water transfer and deterioration of the limestone. However, there still lacks of study on non-destructive method to quantitatively evaluate the water content in limestone.

The literature presents extensive findings regarding the sensitivity of electromagnetic techniques, such as GPR, to the water content of porous media like concrete or masonry [12–17]. In most instances, the medium is considered as homogeneous and GPR processing is defined by travel time picking, which leads to a correlation between radar wave group velocity and water content.

Nevertheless, the dispersion of concrete has been demonstrated by showing that relative permittivity is frequency dependent [13,18],

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while many authors continue to support the hypothesis that permittivity is constant at high frequency bands while conductivity is frequency-dependent [19,20]. The objective of this study is to quantify the hydric properties of healthy limestone blocks using non-destructive electromagnetic (ND EM) techniques in order to obtain information on water ingress fronts vs permittivity. For this purpose, we combined two newly developed models to accurately describe EM wave propagation in two-layer dielectric media: the WaveGuide Model (WGM) and the Full-Waveform Model (FWM). The WGM was used to invert dispersion curves derived from multi-offset Ground Penetrating Radar (GPR) measurements [21], while the FWM was used for near-field stepped-frequency radar (SFR) measurements [22,23].

The limestone-water characteristic (LWC) model is proposed to fit the results of the semi-destructive radiation method (gammadensimetry), which is considered as a reference in the field [24], with GPR measurements.

The remainder of this paper is organized as follows. Section II discusses in detail the general principle behind use of the WGM to extract the geometric dispersion of GPR waves. Section III discusses the general principle of the closed-form forward electromagnetic model describing the near-field radar data for two-layer media. Section IV defines the experiment program and methods to validate the GPR inversion procedures in determining the water imbibition front depth in limestone blocks. Section V introduces the LWC model and its characterizing performance on the water gradients of limestone. This model can be applied to the gammadensimetry results to extract the reference penetration depth. Section VI provides results and discussions, while Section VII closes by drawing a number of conclusions.

2. Extraction of EM wave geometric dispersion: WaveGuide model

An innovative two-layer waveguide model [21,25] is applied to the CMP (Common Mid-Point) measurements of the GPR to monitor the water transfer in limestone block for the imbibition experiment in the laboratory. To simplify the study, the limestone block is approximated as a two-layer waveguide medium, formed by the dry layer and the saturated layer.

2.1. Direct estimation of dispersion curves

Of all the techniques discussed in the literature, this paper focuses on examining an efficient wave-field transform based on the f - β transform [18], where f denotes the frequency and β is the propagation constant. This tool makes use of a modified form of the two-dimensional Fourier transform to describe the frequency-dependent phase velocity v_ϕ at each frequency point f_n:

$$v_\phi(f_n) = \max\left[\sum_x \frac{U(f_n, x)}{|(f_n, x)|}\exp(j\beta x)\right] \tag{1}$$

where $j = \sqrt{-1}$, U represents the radar signal spectrum and x is the propagation distance.

Figs. 1 and 2 provide an example for the limestone block during imbibition in the B-scan (Fig. 1) at specific frequencies and phase velocities inducing a maximum modulus of the complex quantity in the plane (Fig. 2). The first reflected wave is the reflection at the interface between the dry and wet layer, while the second reflected wave is the reflection at the interface between the limestone and the water. The raw data (Fig. 1(a)) and the filtered wave-field (Fig. 1(b)) were calculated respectively to get the dispersion curves of phase velocities in Fig. 2(a) and Fig. 2(b). The filtering window was a rectangular window that the wave-field after the second reflection was set to be 0. In Fig. 2, it is represented the phase velocity vs. frequency of the various transverse electric (TE) modes which propagate in the guide defined by the dry limestone layer. From Fig. 2, we find that some information at TE0 was lost after filtering. However, the velocities at TE3 and TE4 show a better variation trend, which is preferable to obtain better inversion results [21]. Moreover, the reflection after the second reflected wave is probably from the interface between the water and the ground. To obtain more accurate data, the filtered data will be used in the following study.

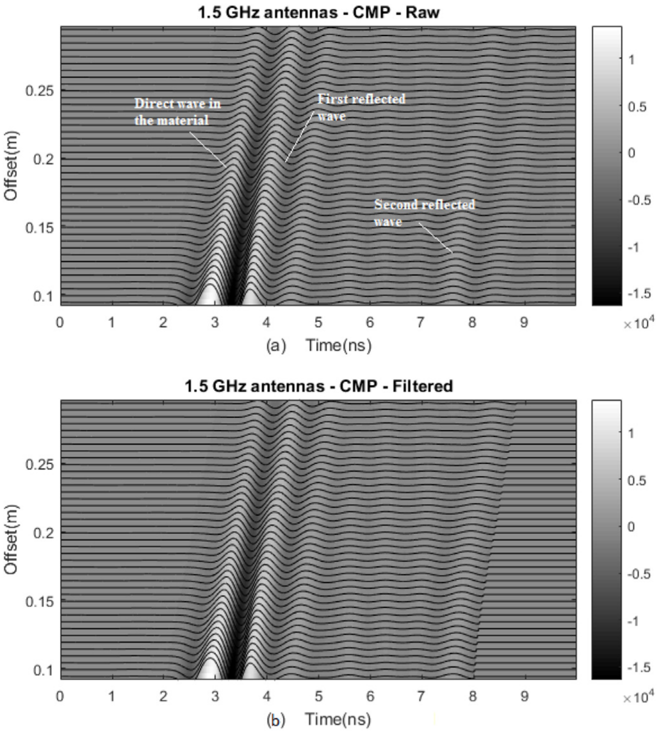

Fig. 1. B-Scan obtained using GPR measurements in CMP configuration on a limestone block during water imbibition at the time T4 (2 h): (a) raw data; (b) filtered data.

2.2. EM waveguide inversion (WGI)

For this study, we have developed and analyzed the modal propagation of GPR pulses through test media based on the fundamental equation of modal theory:

$$1 - R_{e3}^{TE}(\theta)R_{0e}^{TE}(\theta)\exp[-2j\sqrt{\varepsilon_e'}\,\omega/c_0 h\,\cos(\theta)] = 0 \tag{2}$$

where $c_0 = 3 \times 10^8$m/s, ω is the angular frequency, h is the total height of the material, ε_e' is the real part of limestone's relative permittivity, R_{0e}^{TE} and R_{e3}^{TE} are the reflection coefficients at the upper and lower boundaries of the waveguide corresponding to the angle of incidence θ (Fig. 3) [25,26]. Moreover, this study assumes that each medium generates a guided propagation of EM waves as a horizontal planar layer and that EM field components polarize perpendicularly to the incident wave plane. Assuming that the limestone block is composed of the dry layer ε_1' and the wet layer ε_2', the two-layer medium forms a leaky waveguide with the equivalent permittivity ε_e', which is given by Ref. [21]:

$$\varepsilon_e' = (\varepsilon_1' h_1 + \varepsilon_2' h_2)/h \tag{3}$$

The first step in EM waveguide model (WGM) parameterization is devoted to determining the variable θ by numerically minimizing the cost function with the algorithm *lsqnonlin* (from Matlab®):

$$residue(\theta) = \frac{1}{M}\sum_{i=1}^{M}\left|\tan^{-1}\frac{\Im[R_{e0}(f_i)]}{\Re[R_{e0}(f_i)]} + \tan^{-1}\frac{\Im[R_{e3}(f_i)]}{\Re[R_{e3}(f_i)]} - \frac{4\pi f_i\sqrt{\varepsilon_e'(f_i)}\,h\,\cos[\theta(f_i)]}{c_0} + m\pi\right|^2 \tag{4}$$

where $\Re$ and $\Im$ represent the real and imaginary part of the variable, respectively, M is the number of the frequency samples, and m corresponds to the multiple propagation modes. The water is regarded as a strong reflector, thus $R_{e3} = -1$.