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Non-invasive estimation of moisture content in tuff bricks by GPR

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HIGHLIGHTS

- A GPR system is tested to measure water content in porous building materials.
- The method is tested on a real scale wall made with yellow Neapolitan tuff bricks.
- Acquisitions by GPR are coupled with gravimetric measurements of water content.
- Full inverse modelling of the GPR signal is used to retrieve electrical properties.
- Calibration equations are found, linking tuff electric properties to water content.

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ABSTRACT

Measuring water content in buildings of historical value requires non-invasive techniques to avoid the damage that sample taking or probe insertion may cause to the investigated walls. With this aim, a stepped frequency ground penetrating radar (GPR) system was tested to assess its applicability in moisture measurements of porous masonry elements. The technique was tested on a real scale wall made with yellow Neapolitan tuff bricks, a material commonly found in historical buildings of Campania (Southern Italy). First, the antenna was calibrated to find its characteristic transfer functions. Then 64 GPR acquisitions, coupled with gravimetric measurements of the volumetric water content, were performed on the tuff wall in laboratory controlled conditions. A full inverse modelling of the GPR signal on tuff was used to retrieve dielectric permittivity and electrical conductivity of tuff at various water contents. By linking these characteristic electromagnetic parameters to the water content, the calibration relationships specific for yellow Neapolitan tuff are defined, which can be used for moisture measurements by GPR in real case studies. The experimental results lead to a robust identification of clearly defined monotonic relationships for dielectric permittivity and electrical conductivity. These are characterized by high values of the correlation coefficient, indicating that both parameters are potentially good proxies for water content of tuff. The results indicate that GPR represents a promising indirect technique for reliable measurements of water content in tuff walls and, potentially, in other porous building materials.

1. Introduction

Measuring the water content of building materials is essential to prevent the damage that moisture may cause to construction elements such as walls, but also to the plaster that protects them and even to frescoes covering it. The moisture content and its distribution in a building should be repeatedly evaluated in the easiest and least-invasive way possible. Based on such monitoring results, more effective decisions for renovation or restoration can be made.

Volcanic tuff is among the building materials that show the highest ability to absorb and retain water [1,2]. It is a natural pyroclastic stone, which is widespread in Campania (Southern Italy), where it has been used for centuries to build vertical barriers of any kind of construction, including heritage buildings. Common destructive or invasive methods cannot be used in buildings of historical value for measuring moisture content, because the walls of those structures are often covered by frescos or valuable plasters. Hence, novel approaches are needed to estimate the water content in porous building materials in a non-invasive way. Over the years, many different techniques have been tested, such as gamma ray attenuation [3,4], infrared thermography [5,6], neutron radiography [7], capacitance methods [8], non-invasive time domain reflec-

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tometry [9–11], X-ray radiography [12,13], impedance tomography [14], evanescent-field dielectrometry [15], high-frequency sensors [16], wireless inductive-capacitive sensors [17], and, recently, early stage optic fibre sensors prototypes [18]. The dependence of bulk relative dielectric permittivity (ε_r) and bulk electrical conductivity (σ) of porous media on their water content is indeed well known [19] and most of the above mentioned techniques rely on that.

Another experimental technique sensitive to electric properties of materials and used to map the shallow subsurface with high resolution is ground penetrating radar (GPR). It operates through electromagnetic radiation in the microwave band of the radio spectrum, with frequencies typically comprised between a few MHz and 5 GHz [20]. The transmitting antenna of the GPR system generates a signal, which propagates through the material with a speed related to the dielectric permittivity of the medium, assuming the magnetic permeability is that of free space. The reflected signal from the subsurface is detected by the receiving antenna [21]. Thanks to its safe, rapid, non-destructive and non-invasive features, GPR continues to find more civil engineering applications [22]. GPR is an established method to assess the presence of cracks in road and highway pavements [23], bridges [24] and tunnels, and to perform in-situ quality control of density and moisture content of fresh bituminous mixtures [25,26]. In addition, the GPR method is widely used in geological surveys to detect subsurface cavities and voids [27], map soil layers and texture [28], and to image the foundations of buildings and their surroundings [29]. Another successful application of GPR is the discovery of buried archaeological objects [30] and underground utilities such as gas and water pipes [31]. GPR can also be used to evaluate the electromagnetic properties [32,33] and moisture content of soils [34–36].

In the building industry, subsurface remote sensing is a useful tool to detect inclusions [21], voids [37,38] and damage [39–41] and to measure the water content [42–48] over a wide area of a construction in a non-invasive way. It is worth noting that this analysis enables to obtain a more complete picture of the state of health of a building than single-point tests (e.g. drilling) [49].

In this study the feasibility of using the GPR technique to measure the moisture content in yellow volcanic tuff masonry without damaging the historical heritage is evaluated. The procedure to characterize the response of the antenna and the forward model adopted for GPR data processing are described. Then, the results of GPR experiments on a real scale wall are presented, with the aim of calibrating the GPR response to water content variations. The relationships linking dielectric permittivity and electrical conductivity of volcanic tuff to its volumetric water content are identified. Finally, the quality with which the water content can be estimated from GPR reflection data is assessed. This initial calibration phase is indeed essential to carry out GPR surveys in real case studies.

2. Theory of ground-penetrating radar system

A stepped frequency continuous wave (SFCW) radar, combined with a dielectric-filled transverse electric and magnetic (TEM) linear polarized double ridged broadband horn antenna (BBHA 9120 A, Schwarzbeck – Mess-Elektronik) used off-ground in monostatic mode (i.e. a single antenna used as emitter and receiver) was used to map the dielectric permittivity and electrical conductivity of the subsurface. This radar configuration allows an effective and realistic modelling of the radar-antenna-subsurface system [50]. A SFCW radar enables the user to control an ultra-wide frequency band (UWB) that results in a finer depth resolution. Moreover, for this type of radar, the effect of the dispersive properties of the UWB antennas on the measurements can be taken into account by performing a prior calibration. Performing measurements with an SFCW radar has two more advantages over those with a pulse radar. Firstly, pulse radars are subsampled and require many emissions to build a measurement in the time window of interest, whereas at each frequency an independent measurement is taken. Secondly, at each frequency the same signal strength can be achieved, whereas for pulse radars most of the energy is concentrated around a so-called centre frequency. A ZVH8 Cable and Antenna Analyzer (ZVH8, 100 kHz to 8 Ghz, Rohde & Schwarz, München, Germany) with the K42 Vector Network Analyzer and K40 Remote Control options was used to emulate an UWB-SFCW radar system. The antenna is 195 mm long, has an aperture of 245 × 142 mm, and operates in the range of 0.8–5 GHz. It was connected to Port 1 of the VNA via an N-type 50 Ohm coaxial cable. This setup allows for a measured GPR signal consisting of the complex ratio $S_{11}(\omega)$ between the reflected signal and the emitted signal, ω being the angular frequency [51].

The VNA was calibrated at the connection between its feed point and the cable using the *Open*, *Short* and *Match* loads of a high precision standard calibration kit (85032B Type-N, 50 Ohm, Keysight Technologies). This procedure is necessary to establish a reference plane where S_{11} is measured. The radar-antenna-subsurface system was modelled using the block diagram shown in Fig. 1, as introduced by Lambot et al. [32]. The proposed model for describing the radar signal is based on two main assumptions. First, the shape of the electromagnetic field received by the antenna is independent of the target, meaning that only the phase and amplitude of the field are functions of the target. This assumption has been proven to be valid when the investigated surface is situated in the far-field region of the antenna [32,33], which can then be modelled accurately as an interactive point source and point receiver rather than as a spatially distributed source and receiver. Second, the subsurface can be described as a horizontally layered medium [51], which is a consequence of the first assumption, provided that

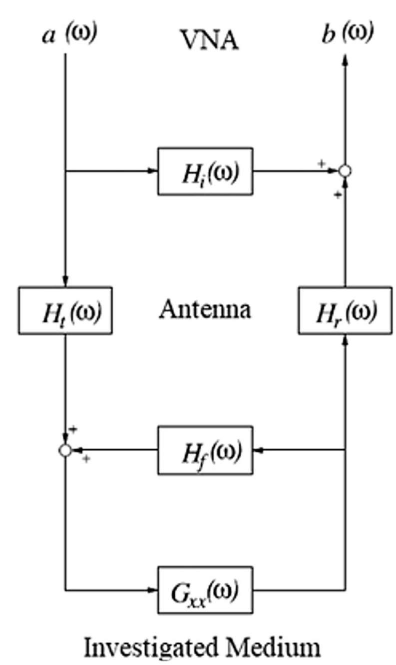

Fig. 1. Block diagram representing the radar-antenna-subsurface system, modelled as linear systems in series and parallel, where $a(\omega)$ and $b(\omega)$ are the emitted and received waves at the VNA reference plane, respectively; $H_i(\omega)$ is the return loss; $H_t(\omega)$ and $H_r(\omega)$ are the transmitting and receiving transfer functions, respectively; $H_f(\omega)$ is the feedback loss; and $G_{xx}(\omega)$ is the transfer Green's function of the air-subsurface system (redrawn after [50]).