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Using microwave near-field reflection measurements as a non-destructive test to determine water penetration depth of concrete

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ABSTRACT

A non-destructive version of a standard test for concrete permeability has been demonstrated. The method is based on water penetration depth estimation from near-field microwave measurements using an open-ended rectangular waveguide. In particular, water penetration is determined from the differential measurement of reflection coefficient in the S-band before and after injection of water under pressure. Experimental results show a good correlation between the standard destructive test and the new method. Microwave measurements simplify the standard test avoiding the need of drilling out a sample from the structure and thus reducing both the cost and time needed in the analysis.

1. Introduction

Concrete is one of the main materials used worldwide in construction and civil engineering due to its potential long lifetime, low cost, capability to be molded, being non-combustible, etc. However, concrete structures might suffer premature deterioration caused by degradation processes (physical, chemical or biological). Many of these processes are caused by the transport of aggressive substances through the concrete mass that modify its strength, stiffness and appearance, or in a similar fashion, these processes affect the security, functionality and appearance of the buildings. Thus, concrete durability depends on the porous structure [1], and consequently, on its permeability, since both parameters are directly related [2–4]. According to Darcy's Law, the flow of a fluid through a porous medium is proportional to the cross-sectional area to flow, the hydraulic pressure gradient and the intrinsic permeability of the medium. This permeability coefficient depends on the characteristics of the medium and the fluid. According to Beltrán et al. [5] this coefficient is directly proportional to the solid porosity and to the square of the mean pore radius and inversely proportional to the square of the tortuosity of the porous structure. In particular, concrete permeability is mainly given by the size, kind and distribution of the pores rather than the whole pore volume [6]: a material can have low permeability if its pores, although numerous, are not connected among them. The best approach to reduce attacks in concrete is reducing pore size and interconnections in the capillary network. Due to the lack of a standardized method to monitor these parameters, indirect tests are needed, such as water permeability.

A way to evaluate whether the porous structure of a particular concrete is impermeable enough for a given environment is through the test based on penetration depth of water under pressure, defined in the European Standard EN 12390-8:2009 [7]. The procedure described in this norm coincides with ISO 7031 [8] and Recommendation RILEM CPC 13.1 [9]. This test has been used for the evaluation of the performance of concrete [10–12]. Moreover, there are some research works where the penetration depth can be related not only with the porous structure of concrete [13–15] but also with other indicators of durability such as carbonatation depth, chloride penetration [16] or electrical resistivity [17].

Some European codes, such as Eurocode EC-2, EN-206 or Model-Code CEB-FIP 93, as well as the regulations on reinforced concrete of several countries (e.g. [18–20]) resort to this test to assess in aggressive environments whether a given concrete is suitable from a durability point of view. From the penetration depth reached by water after the assay, it is established whether the concrete under test is suitable for a given environment. Thus, permeability measurements are mandatory in multiple countries

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when reinforced concrete constructions are built in areas of high environmental aggressiveness (seafront, chemical aggressive areas, regions prone to frost, etc.). Additionally, as pointed out by the Concrete Society [21], many projects built in extreme environments or that require very long lives include specific criteria on permeability to be verified by testing the supplied concrete or precast concrete elements.

The water penetration depth standard (ISO 7031) is based on drilling out a cylindrical core from the structure under test, and, in a laboratory, injecting water at a given pressure, breaking the specimen into halves and measuring the penetration depth of the water front. The main issue of this test is the destructive nature of the method since currently it is the only way to detect the water front, that results in a deterioration of the element under test.

Microwave near-field sensing offers a good alternative to concrete characterization. Being a dielectric medium, electromagnetic radiation can permeate concrete and, in general, interact with a certain volume of the sample not just the surface. Therefore, microwaves have been used for the inspection of dielectric materials since they allow non-destructive, cost-effective and simple to deploy test procedures. In particular, for concrete and cement-based structures, microwaves have been used to monitor the curing state [22], to determine the strength from the estimation of the water/cement content [23–25], to monitor moisture content [26] and distribution [27], to obtain their dielectric properties [28–30], to characterize the effect of aggressive compounds such as chloride [31–33], to identify reinforcement bars [34] and crack detection [35].

Since several international codes as well as national regulations resort to the water penetration test to assess the suitability of a concrete structure in an aggressive environment, in this paper, a non-destructive method to determine water penetration depth in concrete is developed and compared to the standard test. The proposed method is based on near-field microwave measurements using an open-ended rectangular waveguide and a microwave network analyzer. In particular, the procedure relies on the analysis of the magnitude of the reflection coefficient of concrete before and after injection of pressured water. Unlike previous works, this study focuses on relating microwave measurements with a standard test for concrete permeability. The results show that the standard procedure of sample drilling can be replaced by a non-destructive microwave measurement.

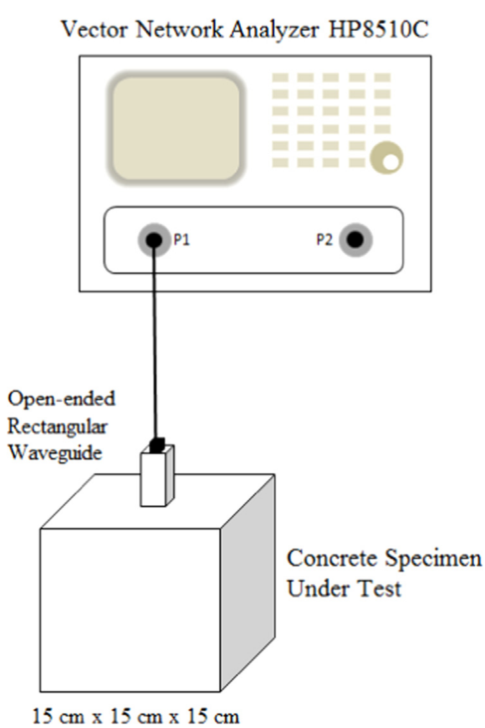

Fig. 1. Schematic of experimental setup.

2. Experimental plan

2.1. Microwave penetration depth test procedure

The proposed method is based on comparing the magnitude of the microwave reflection coefficient of a concrete specimen before and after water injection. The effective relative dielectric properties (ε_{reff}) of the concrete specimens can be calculated as [27]:

$$\varepsilon_{reff} = \varepsilon_{rw} f_w + \epsilon_{rc} f_c + f_a \quad (1)$$

where ε_{rw} and ε_{rc} are the complex relative dielectric properties of water and concrete, respectively, and f_w, f_c and f_a are the volume fractions of water, concrete and air respectively. Since the reflection coefficient is related to the dielectric properties of a dielectric material, the increment on the magnitude of the reflection coefficient offers an indirect estimation of the water content, and therefore of the water intake which is related to concrete porosity. In other words, from the difference in the magnitude of the reflection coefficient given by the strong different relative permittivities in the S-band between cured concrete and free water filling the structure pores, which largely affects microwave signals [36], it is possible to derive the water penetration depth. The differential method circumvents the inherent difficulties in characterizing very heterogeneous materials as concrete. Additionally, it eases system calibration.

Therefore the standard destructive depth penetration test (ISO 7031) can be implemented in a non-destructive approach. This reduces the cost and complexity of the assay and avoids damaging the structure.

Specifically, the magnitude of the reflection coefficient, $I\Gamma I$ or $|S_{11}|$, is measured along an axis on one side of each specimen using an open-ended rectangular waveguide to get a profile of water penetration in concrete. This measurement can be done using a microwave network analyzer, as shown in Fig. 1. It is also possible to make the measurements on a grid over the concrete surface instead of just along a line to draw a 3D image of water penetration. However, for the sake of validation with the standard procedure, only the 2D profile has been obtained in this work.

The technique assumes that measurement conditions only change due to water content. During the measurement care has to be taken to keep the rectangular guide in contact with the concrete surface and avoid the presence of air-gaps that might change the permittivity measurement [37–39]. To minimize these errors, the concrete surface should have low roughness and therefore a flat section of the structure under test is recommended to apply this method. Considering Rayleigh or Fraunhofer criteria the standard deviation of surface roughness should be smaller than 10 and 2.7 mm, respectively, for 3.5 GHz. It is quite common to have concrete surfaces with roughness well below these thresholds. In our experiments, the measurement was done over the sides of the samples that were in contact with the mould. According to the fabrication tolerance of these molds, surface irregularities are smaller than 0.15 mm.

2.2. Sample preparation

To validate the measurement method in concretes of different permeabilities, a set of concrete specimens with different mix proportions was made. To achieve proper durability in concrete structures, the usual range of w/c ratios used in building