Moisture Measurement in Walls using Microwaves

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Abstract

A novel measurement procedure and set-up is presented, which is suitable for moisture measurements in brick- and stone walls at places, where the wall is accessible only from one side. Local dielectric constant and hence spatial moisture content profile are determined by tracing the complex electric field using an electrically small field probe, which intrudes and is moved in a small bore-hole. Only one hole with a diameter of 8-15mm is needed. A prototype set-up and measurements are presented in order to demonstrate the practicability of the method.

1 Introduction

In civil engineering monitoring of the moisture content of parts of a building made of concrete, brickwork, or other kinds of stone material is an important task. A moisture content too high over a longer period can lead to severe deterioration of the room-climate. It may even cause damage of the building under certain circumstances, especially in combination with dissolved salts. In Europe, many historic buildings are threatened by extensive moisture in the walls.

The causes for such defects are manifold: Besides wrong construction, there may exist damage of the roof or the foundation walls. Often the reason for the high moisture content is not obvious and the moist wall has to be monitored over a longer period of time. Also the spatial profile of the moisture defect across the wall is of interest and may help to find its cause. Having suitable equipment and measurement procedures at hand in order to fulfill the described task is of considerable economic interest.

At present, the method applied most often is taking samples with a diameter of several centimeters (typically 10cm) using a drilling machine. The moisture content

$$\psi = \frac{m_w}{m_w + m_d} \cdot 100\% \quad , \qquad (1)$$

is then determined by applying the dry-weighing method, where the sample is weighed, dried and weighed again (m_w, m_d are the masses of water and dry material, respectively). Such an approach leads to unwanted damage of the wall and is extremely time-consuming. Also, the drilling process may alter the moisture content by heating the material.

In this context, it has to be kept in mind, that in most cases a wall to be measured is only accessible from one side (Imagine for instance a situation in the basement of a building).

Nondestructive measurement procedures are also frequently applied [1]. Such methods comprise capacitance and conductance measurements, using electrodes which are brought into contact with the wall. The result of these surface moisture measurements depends on the roughness of the surface, on the pressure applied to the electrodes and on several other effects. Obviously these measurement procedures can only deliver a limited accuracy and do only reflect the condition of the surface, which strongly depends on the room climate.

In order to access deeper regions of the wall, electromagnetic waves have been used also. Impulse-radars, emitting ns-pulses, have been tried [2], however, with limited success. The response of the moist wall on the impulse depends on the moisture content, but the interpretation of the reflection pattern is very difficult. It is nearly impossible to obtain quantitative measurements. At most a decission can be made about relative changes within several percents of moisture.

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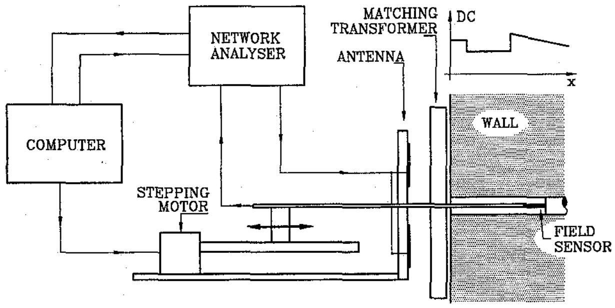

Figure 1: Schematic measurement set-up

A microwave-method has been proposed also [3]. It uses two holes of small diameter (10-15mm) drilled into the wall. Two coaxial lines are introduced into the holes, where the ends act as monopole antennas, and the attenuation between the sensors is measured. A disadvantage of this method is the extremely high effort, which is required for drilling two holes in parallel with the demanded accuracy. The deviation has to be less then 1mm at 1m depth. This method is of limited practical value due to this reason.

In this paper, we describe a novel microwave method for collecting data and measuring spatial moisture profiles within walls of bricks or stone, which overcomes the described problems and is highly practical. A prototype measurement sensor has been built up and tested at various building materials and wall structures.

2 Measurement-procedure and set-up

The proposed measurement set-up is sketched in Fig. 1. A photograph is shown in Fig. 2. The measurement-principle is to trace the complex field amplitude of the electric field in the wall. A small hole (diameter 8-15mm) has to be drilled into the wall. Such a hole does not represent a severe destruction, but is tolerated and can be closed very easily. A small electric field probe is introduced into the hole and can be moved mechanically. It is agitated by a stepping motor in longitudinal direction under computer control. The spatial increment of the movement is less then 1mm. A microwave field is radiated into the wall from outside by a flat plate antenna. An integrated antenna with four patches is used in order to arrive at a compact design. At the center of the patch antenna, the coaxial field probe crosses at right angles and is thus decoupled from the electric field.

The electric field is polarized in parallel to the surface of the wall and penetrates the region around the field

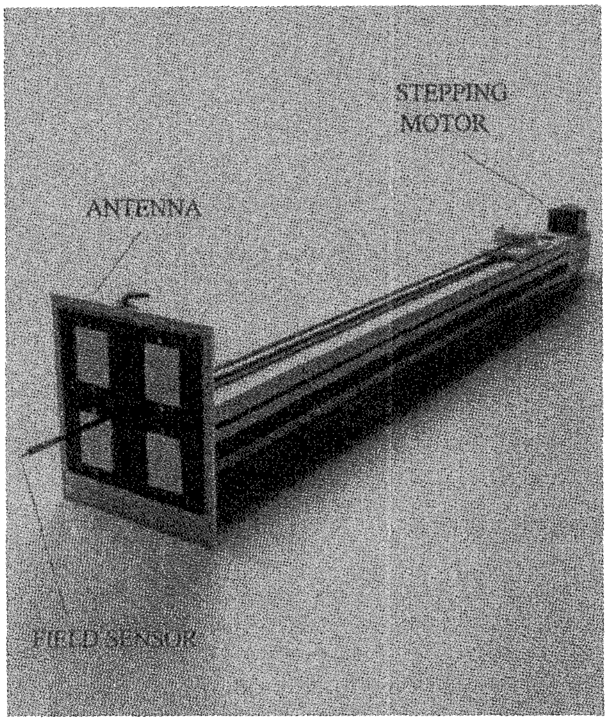

Figure 2: Photo of the measurement set-up

probe, where it can approximately be described as a plane wave. This plane wave suffers attenuation and phase-shift depending on the water-content within the wall.

Hence, when performing complex amplitude measurements using a network-analyser, the complex dielectric constant (DC) and thus the moisture content can be derived. Due to the spatial motion of the field-probe within the wall, relative changes of the field across the depth are recorded. Knowledge of the irradiation efficiency at the interface between the antenna and the wall is not required. However, in order to optimize dynamic range, a matching transformer made of a plastic plate is placed in front of the antenna. Since tracing of the field delivers highly redundant information about the DC, its spatial distribution and thus the spatial profile of the moisture content can be derived with good resolution.

The applied frequency represents a compromise between penetration depth into the moist dielectric, spatial resolution, and sensitivity against scattering due to inhomogeneties. Presently we are using the ISM-frequency of 2.45GHz (12.2cm wavelength in air). Another advantage of this frequency range is the possibility of building very low cost microwave circuits using SMD-techniques. Hence the required network analyser and the microwave source can be integrated together with the antenna and the field probe to form a low-cost and easy to use measurement set-up, which runs under computer control and can be used even by unskilled personnel.

If only reflections at the endface of the wall and at interfaces between different layers of materials dominate, propagation can be described by the one dimensional wave equation

$$\frac{\partial^2 E(x)}{\partial x^2} - \gamma(x)^2 E(x) = 0 \quad . \tag{2}$$

The propagation constant γ is supposed to depend only weakly on the spatial coordinate x. The common solution to (2) is given by forward (+) and reverse (-) travelling waves

$$E = E^- e^{\gamma x} + E^+ e^{-\gamma x} \quad .$$

Since the distribution of $E(x)$ is measured with respect to some reference value E_0 at $x = 0$, the propagation constant γ can be derived from the second derivative in (2) as

$$\gamma^2 = \frac{1}{E}\frac{\partial^2 E}{\partial x^2} \quad . \tag{3}$$

In the partial differentiation the spatial dependence of γ is neglected. The complex effective DC

$$\epsilon_r = \epsilon' - j\epsilon'' \tag{4}$$

can be derived from the relation

$$\gamma = j\frac{\omega}{c}\sqrt{\epsilon_r} \tag{5}$$

where c means the velocity of light.

Once the DC (4) is known, the moisture content can be determined from a dielectric mixing formula. To this end the complex refractive index model [4] proves to yield accurate results. The moist wall is composed of stone (s), air (a) and water (w). If volume fractions are denoted by v, the effective DC is then described by

$$\sqrt{\epsilon_{r,e}} = v_s\sqrt{\epsilon_{r,s}} + v_w\left(\sqrt{\epsilon_{r,w}} - 1\right) + v_a \quad , \tag{6}$$

where v_a means the volume fraction of air in dry stone (porosity) and $\epsilon_{r,s}$ is the true DC of the stone material. With the known true density ρ_s of stone and the relation between density and mass

$$m_s = \rho_s v_s \quad , \tag{7}$$

the moisture content follows as

$$\psi = \frac{v_w}{v_w + \frac{\rho_s}{\rho_w}v_s} \cdot 100\% \quad . \tag{8}$$

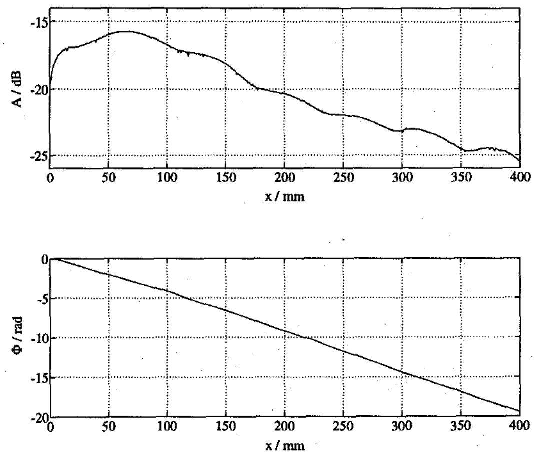

Figure 3: Measured a) amplitude- and b) phase-shift in air

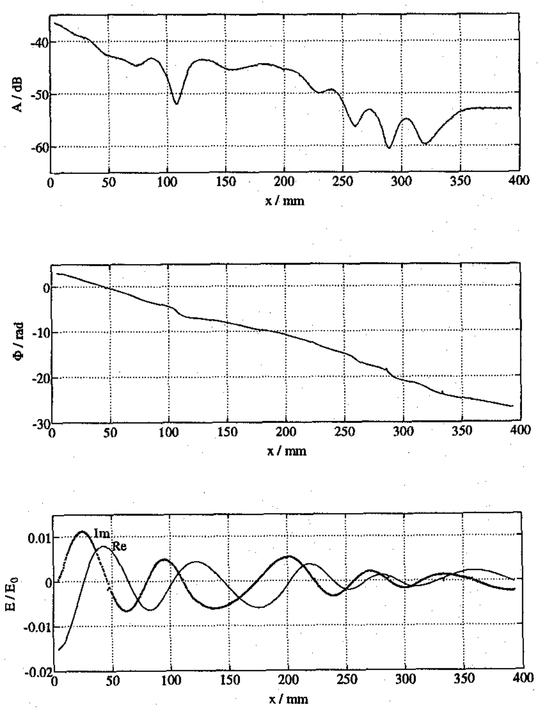

Figure 4: Measured a) amplitude- , b) phase-shift and c) complex electric field for sand

3 Measurement Results

In order to demonstrate the proper operation of the measurement setup, the decay of field amplitude in air and the associated phase shift as picked up by the field probe was recorded and is shown in Fig. 3.

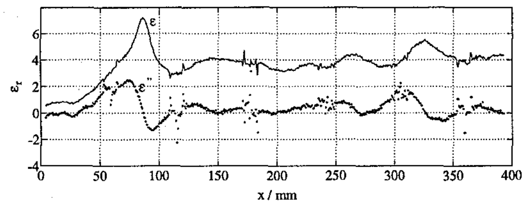

Figure 5: Measured DC of sand

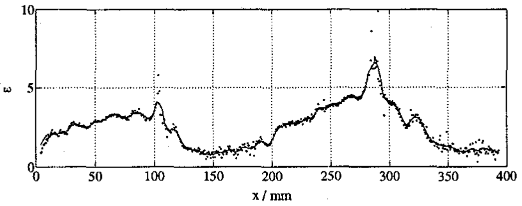

Figure 6: Measured DC of a multilayer-wall

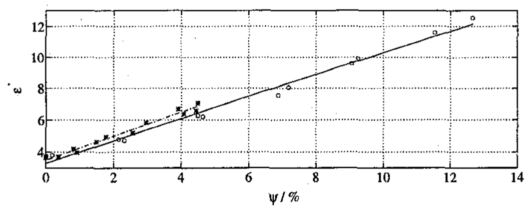

Figure 7: DC of two stone materials versus moisture as determined in a waveguide (o = sandy limestone; * = sandstone)

Fig. 4 depicts the result of a test measurement, where the medium was sand. The interface between air and sand can clearly be detected. Fig. 4a shows attenuation and 4b associated phase shift. In Fig. 4c the reconstructed real- and imaginary parts of the electric field are visualized. Finally Fig. 5 presents the calculated DC, which still has to be correlated with the moisture content. As a final measurement, the local distribution of the dielectric constant (only real part ϵ' given) in a multilayer-wall is presented in Fig. 6. The wall consists of a brick layer (0...~120mm), an air gap in between for temperature isolation purposes, and a second layer of sandy limestone (200...320mm), followed by air again. Comparison of Fig. 6 with Fig. 7, which shows the DC of stone-materials as a function of the moisture content determined in a waveguide set-up, delivers the moisture content of the multilayer-wall according to (6) and (8).

A problem with the DC-measurements are overshots of the measurement result at dielectric interfaces, possibly caused by distortions of the electric field in the presence of the probe. Also, it has to be remembered, that the field-probe, although electrically small, exhibits certain reception-characteristics, which are convoluted with the local electric field. Finally, it has to be remembered, that eq. (3) is not valid at an interface, because γ changes strongly with the spatial coordinate.

4 Conclusion

The results given show the feasability of the new approach. Accuracy of the moisture measurement seems to be in the order of 1% and local resolution is better then 2-3cm. For the actual measurements, specimen with known moisture content were used. A calibration procedure in order to perform absolute measurements is in progress.

5 Acknowledgment

This work is a part of the project *Kontinuierliche und zerstörungsfreie Feuchtemeverfahren mit Mikrowellen.* Financial support by the *Volkswagen-Stiftung* under contract I/67 193 is gratefully acknowledged. The authors would like to thank O. Vogt for technical support and measurements.

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