MICROWAVE MOISTURE MEASUREMENTS ON A TEST-BUILDING

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Abstract: The adaptive modeling of chemical attack on concrete for the prediction of durability and for the quality control of concrete structures requires the assessment of the concrete moisture content. Two sensors were designed to determine the permittivity which is related to the moisture content. These relations can be obtained from a calibration procedure. The applicability of the sensors was investigated in a field experiment on a test-building. First long-term results are reported.

Keywords: moisture, microwave, permittivity, measurement.

1 INTRODUCTION

The assessment of the moisture content is required for the adaptive modeling of the chemical attack on concrete [1]. This is essential for the prediction of the durability and for the quality control of concrete structures. Within the frame of a collaborate research project devoted to the durability of buildings two microwave sensors, a coaxial and a waveguide-sensor, were designed to determine the permittivity which is related to the moisture content. They are intended to be part of a more comprehensive in-situ measurement system for monitoring the chemical attack on buildings at strategic locations. As an essential part of these investigations the sensors have to be tested under realistic conditions. This paper reports on first such experiments where the aforementioned sensors were integrated in a test-building and exposed to the natural environment. First results of this long-time study with several prototype sensors are presented and discussed.

2 THE SENSORS

The absorption of water alters the dielectric properties of every material, described by the complex permittivity ($\varepsilon_r = \varepsilon_r' - j\,\varepsilon_r''$) [2]. This quantity can easily be measured at microwave frequencies. Two sensors were designed for this purpose. A model is required to extract the permittivity from the measured data, and a calibration to establish a relation between the surrounding moisture and the permittivity.

Both sensors rely on the measurement of the reflection coefficient S_{11}. The first one, labeled *coax sensor* in the following, simply consists of the open end of a coaxial line immersed in the material to be characterized (Fig. 1a). This configuration can be modeled by an impedance Z that relates to the permittivity of the surrounding material [3, 4].
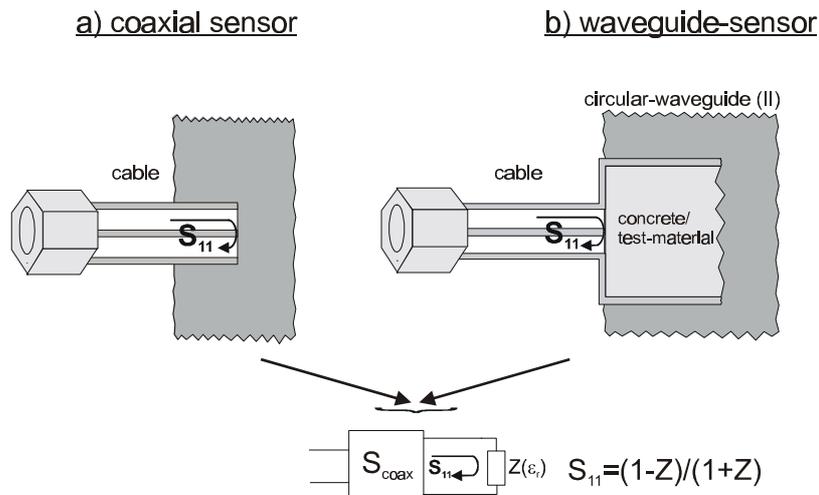

Figure 1. Structure and model of the sensors.

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The second device, labeled *waveguide-sensor* in the following, is based on a circular waveguide fed by a coax (Fig. 1b). The waveguide is filled with concrete or some other adequate test-material [5]. It is operated below its cutoff-frequency to prevent electromagnetic leakage at its open end which is necessary for moisture penetration. The discontinuity at the end of the coax can again be described by an impedance Z which now depends on the permittivity of the waveguide-filling. A full-wave analysis is needed to this end [6, 7]. For both sensors the permittivity can be extracted numerically from a comparison of the measured and the computed value of Z (or S_{11}).

3 VERIFICATION

The validity of the model, the accuracy of the extraction algorithm and the functionality of the sensors was verified by measuring known materials (e.g. air, TEFLON or 2-propanol). As a typical example the response of the latter is shown in Fig. 2 which depicts the permittivity obtained from both sensors together with the theoretical prediction of the Debye-model [2]. The agreement compares well with results published elsewhere [3, 4, 8] and thus qualifies the sensors for the assigned task, i.e. the determination of the moisture content of concrete.
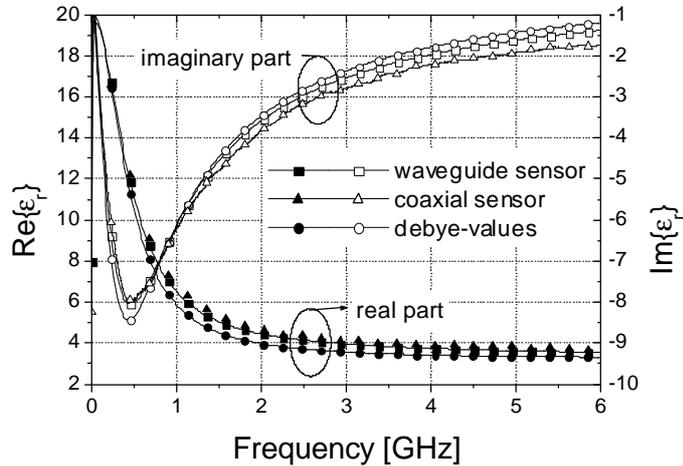

Figure 2. Measured and theoretical permittivity of 2-propanol.

4 CALIBRATION

Two types of calibration have to be performed. The first one serves the electrical characterization of the sensors, i.e. reflection and losses due to the connector and the cable and symbolized by S_{coax} in Fig. 1. This correction term is determined from the response of three known terminations, such as a short, an open and a reference liquid. The second calibration establishes the relation between the permittivity and the relative humidity level: Different saturated aqueous solutions of inorganic salts are used to define constant relative humidity levels in air tight boxes [9]. Samples are placed in these boxes until equilibrium is reached and are then characterized to obtain a calibration diagram. Fig. 3 presents the results for a cement sample (Portland CEM I 32.5 R, 0.4 w/c ratio) as measured after an exposure of three months. The calibration is temperature sensitive [5], and whether the stationary condition was fully reached at the highest relative humidity level remains somewhat uncertain, here. Further long-term experiments are currently in progress.
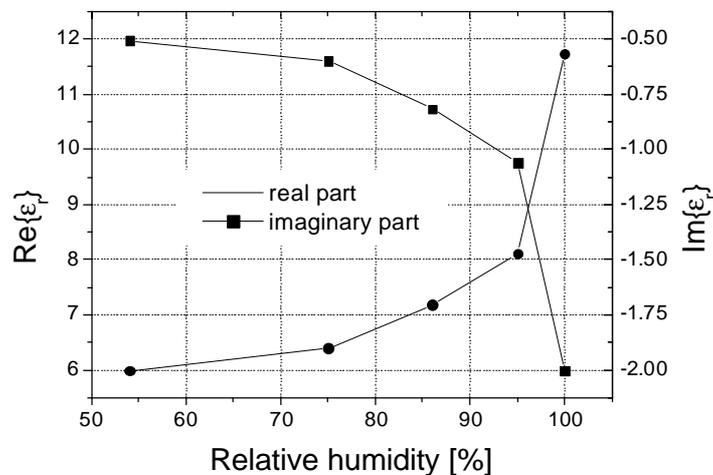

Figure 3. Calibration curve of cement (CEM I 32.5 R, 0.4 w/c ratio).

5   THE TEST-BUILDING

Figs. 4 and 5 show the test-building. In order to achieve a better moisture diffusion and for a more realistic experiment fissures were produced on the back of the building by prestressed steels. The device is exposed to the natural environment. In addition, to simulate chemical attack, the back of the building is prepared with four boxes (Figs. 4, 6). In each of them the concrete is exposed to different chemical agents: lye (I), $NaSO_4$ (II), acid (III) and aqueous solutions of NaCl (IV). Results of these tests will be reported in another context.
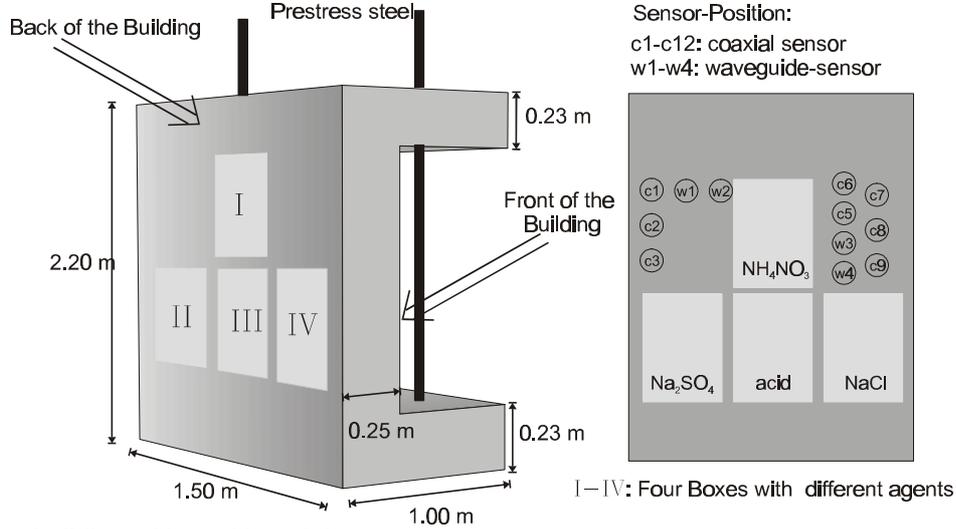

Figure 4. Test-building with position of the sensors.

Figure 5. Test-building.

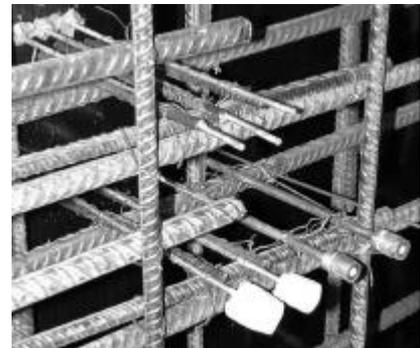**Figure 6.** Boxes for chemical attack on the back of the test-building.

Figure 7. Sensor fixation at the reinforcement.

The test-building was equipped with eight coax and four waveguide-sensors to measure the moisture content during and after the drying. The microwave excitation is performed from the front of the building (Fig. 4). The sensors were calibrated with a short, air, acetone (coax) and TEFLON (waveguide). The tips of the coax sensors c4 and c5 were cast into a cement cube before being mounted in the building. The waveguide-sensors had either ceramic or a cement filling (Table 1).

Table 1. Sensor characteristics.

Sensor	c1	c2	c3	c4	c5	c6	c7	c8	W1	w2	w3	w4
Depth [cm]	2.5	2	3	3	2	2.5	2	3	2	2	2	2
Material	C	C	C	Ce	Ce	C	C	C	C	Cer	Cer	C
Area	N	N	N	N	N	N	N	N	N	N	N	N
C: concrete; Ce: cement; Cer: ceramic; N: natural environment												

The sensors were fixed at the reinforcement of the building (Fig. 7). During the construction the shuttering was rearranged several times. The mounting depth below the surface given in Table 1 is only approximate, therefore. Thus, the comparison of the results from different sensors is only meaningful when these are closely spaced.

All measurements were performed with a vector network analyzer (HP8753D) in the frequency range from 30 kHz to 6 GHz. The results presented here show the permittivity at 4 GHz. Qualitatively, they are representative for all other frequencies. The first measurements (day 0) were performed three days after the construction of the test-building. After the 41st day the boxes were flushed with distilled water, while the actual chemical attack was initiated only on the 55th day.

6   RESULTS FOR THE COAXIAL SENSORS

Fig. 8 demonstrates the dependence of the permittivity on the depth of the sensors. As can be seen from Table 1 sensor c5 is closer to the surface of the back of the building than sensor c4. Consequently, it is also more sensitive to changes in the moisture content caused by drying and/or rainfall. During the first weeks the drying process dominates, the surface being dryer than deeper layers as can be seen from the lower permittivity measured with sensor c5. The vicinity of the boxes for chemical attack may explain the sharp rise observed at sensor c5 shortly after day 41 when flushing began. Again, sensor c4 is much less sensitive, although it essentially exhibits the same dependence.
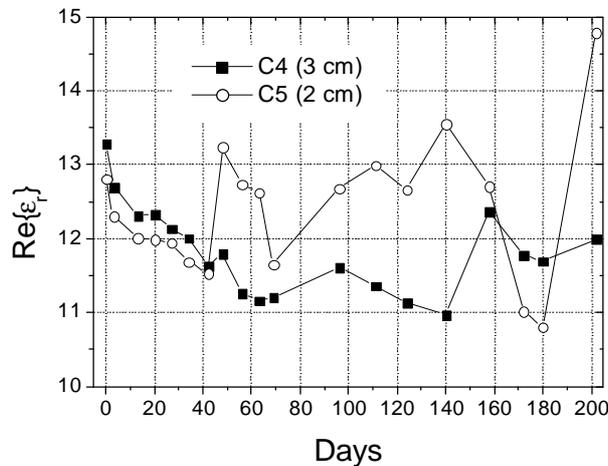
Figure 8. Real part of the permittivity measured with sensors c4 and c5.

In contrast to sensors c4 and c5, Fig. 9 shows the results of three coax sensors that were directly immersed in the concrete. Again, they are placed at different depths (Table 1). Peaks in the diagram correlate well with rainy periods shortly before. In general, the sensor closest to the surface exhibits the strongest response, confirming the previous observation. The measured permittivity value is a result from partly competing effects, namely surface moistening, diffusion and surface drying. The observed discrepancy around the 160th day, however, is most likely due to the lack of data between day 140 and 160 and the consequent crude graphical interpolation.
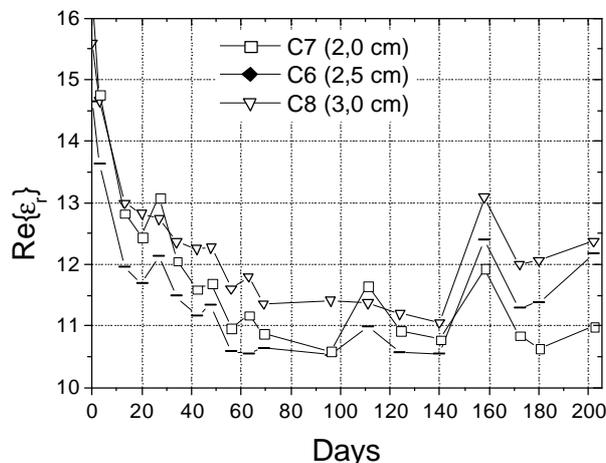
Figure 9. Real part of the permittivity measured with sensors c6, c7 and c8.

7   RESULTS FOR THE WAVEGUIDE-SENSORS

The four waveguide-sensors were mounted in different positions as depicted in Fig. 4. As was recently shown [5] a ceramic filling as used in sensors w2 and w3 is well suited for an application in environments with extremely high moisture content. This was verified with the experiments on the test-building. Shortly after the construction the building contains a high level of water. The drying process during approximately the first 100 days is illustrated in Fig. 10 by the strong decrease (increase) of the real-(imaginary-)part of the permittivity. The two sensors, although almost identical, exhibit very different responses during the drying process, sensor w2 indicating a higher moisture content than sensor w3. Beyond the drying time the results of the two sensors converge to the same level. This phenomenon cannot be explained at this time. It could however be a hint to inhomogeneities in the surrounding concrete leading to a different drying behavior.
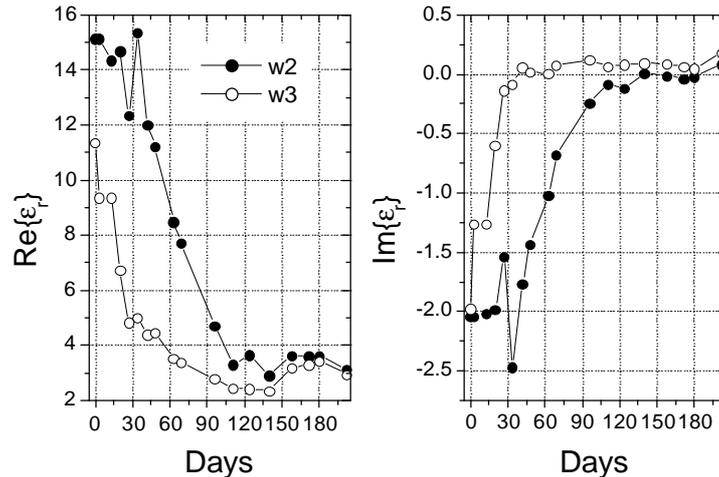

Figure 10. Permittivity measured with sensors w2 and w3.

The sensors equipped with cement behave quite differently (Fig. 11). The drying process can again be observed but no stationary conditions are reached. The sensors are more sensitive to changes in the moisture content than those with a ceramic filling. Again, the difference between the two sensors may be caused by variations of the moisture or the surrounding material itself.
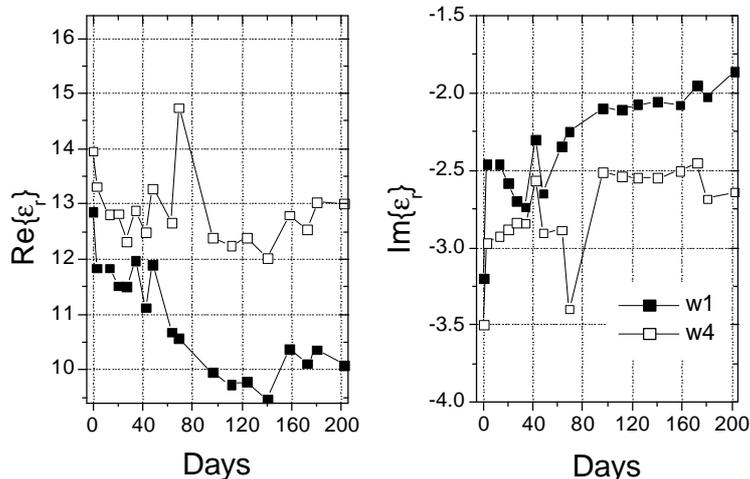

Figure 11. Permittivity measured with sensors w1 and w4.

8   CONCLUSION AND OUTLOOK

Two sensor types were investigated in a practical test-building. Although still more experimental data is needed both concepts appear to be suited for the in-situ determination of the permittivity, i.e. the moisture of concrete. This is because they combine sensitivity with a robust and cheap design. Future work will be concerned with the further optimization of the waveguide filling and the investigation of chemical attack on concrete. Temperature effects also need to be taken into account.

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