Monitoring of Drying of Cement Screed with the Help of Ultra-Wideband Microwaves and Air-Coupled Antennas

Maryam MANAVIPOUR[1], Christoph SKLARCZYK[1], Klaus SZIELASKO[1]
[1]Fraunhofer-Institute for Nondestructive Testing, Saarbrücken, Germany

Contact e-mail: maryam.manavipour@izfp.fraunhofer.de

Abstract. The drying behaviour of freshly prepared anhydrite screed and cement screed samples was investigated non-destructively and in contact-free way using ultra-wideband microwave signals in the frequency range between about 1 GHz and 10 GHz. The measurements have been performed using a vector network analyser and air-coupled wideband horn antennas in reflection mode. Both entry echo and back wall echo at the interfaces of the samples were analysed. The amplitudes of the entry signals decreased within few weeks as the real part of the relative permittivity decreased with drying. Finally a plateau level was reached. At the beginning of the tests the back wall signal of the specimen was not recognizable since the attenuation of the microwaves resp. the imaginary part of the permittivity in the moist sample was too high. After a few weeks of drying, a back wall signal was detected. It increased with continued desiccation and thus lowered attenuation, until here again a constant level was reached. At the same time, the temporal position of the back wall signal moved to smaller times since the propagation velocity of the microwaves increased until a constant value was reached as well.

1. Introduction

Within a measurement initiative for the quantitative determination of moisture in building materials by the Robert Bosch GmbH, the drying behavior of two freshly produced screed samples was analyzed with broadband pulse echo radar in the microwave range. The investigations took place at the Federal Institute for Materials Research and Testing (BAM) in Berlin.

1.1. Theory of Microwave Testing

Like with all electromagnetic radiation, microwave propagation depends on the interaction between time-varying electric and magnetic fields. These fields oscillate in waves that are called travelling waves because energy is transported from one position to another. According to the medium through, in which the electromagnetic waves propagate, the velocity of propagation changes. Microwaves lie within a broad frequency range from 300 MHz up to 300 GHz, corresponding to wavelengths of 100 – 0.1 cm. Electromagnetic microwave radiation has been used in the determination of water content in various materials for at least four decades. One of the most important applications of microwave sensors is measurement of moisture [1,2].

The propagation of a plane electromagnetic wave along the x-axis in a lossy medium can be described by

$$\overline{E} = \overline{E}_0 \exp(-jkx) \tag{1}$$

where $\overline{E}$: Electric field strength and $\overline{E}_0$: peak value (vector) of $\overline{E}$, while

$$k = k' - jk'' \tag{2}$$

K is the complex propagation factor, where k' is the real part and k'' is the loss factor by which the propagation losses in the medium are taken into account.

Dielectric spectroscopy determines the dielectric properties of the sample as a function of frequency. The complex permittivity ε is the dielectric property that describes how the material under an electromagnetic field influences the electric field.

$$\varepsilon = \varepsilon^{'} - j\varepsilon^{''} \tag{3}$$

where ε' is the absolute permittivity or real part of permittivity and ε'' is the absolute loss factor or imaginary part of permittivity [3].

Absolute permittivity reflects a material's ability to store energy, and the loss factor is related to the absorption and dissipation of the electromagnetic energy by conversion into other kinds of energy (such as the thermal kind). The propagation factor is related to the permittivity by

$$k = 2\pi f \sqrt{\mu\varepsilon} \tag{4}$$

also

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \tag{5}$$

where μ is the magnetic permeability and c is the propagation speed.

The values for permittivity, permeability and speed of propagation in vacuum are:

$$\varepsilon_0 = 8.854 \times 10^{-12} F / m$$

$$\mu_0 = 4\pi \times 10^{-7} H / m$$

$$c_0 = 2.998 \times 10^{8} m / s$$

In any medium other than vacuum, the constants obtain higher values and are usually expressed relative to the values in vacuum:

$$\varepsilon = \varepsilon_r \varepsilon_0 \tag{6}$$

$$\mu = \mu_r \mu_0 \tag{7}$$

where the subscript "r" stands for "relative". For para-/diamagnetic materials, $\mu_r \approx 1$. Therefore [4]:

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \approx \frac{c_0}{\sqrt{\varepsilon_r^{'}}} \tag{8}$$

The reflection coefficient of electromagnetic waves at an interface is given by:

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \tag{9}$$

where

ε_1: Permittivity of the first medium, e.g. air

ε_2: Permittivity of the 2nd medium, e.g. specimen [5].

In the microwave range, free (i.e. chemically non-bonded) water exhibits a much higher permittivity (both real and imaginary part) than most solid materials [4]. Therefore, by adding water to the solid, its moisture is increased, resulting in a substantial effect on permittivity. This difference in permittivity can be detected by microwave sensors.

Therefore a change in permittivity will affect the velocity and attenuation of microwaves in material, as can be seen from equation 5.

2. Experimental conditions

2.1 Samples

The two samples examined with microwaves consisted of anhydrite and cement screed. The samples' thicknesses were 38 mm and 37 mm, and they were cylindrical with a diameter of 50 cm (Fig. 1). The samples were placed on a thin plastic film and this, in turn, on two styrofoam plates of 57 mm in total. This layer package, resembling a realistic screed stack, was placed on a washed concrete pad on a laboratory bench.

Measurements started on day 3 (day 1 was the day of sample preparation) and were performed in intervals of several days until day 165 (complete curing). It was measured in a climate-controlled chamber at 23 °C and 50% relative humidity.

2.2 Microwave measurements

The measurement method applied was a frequency-stepped continuous-wave radar (FSCW radar) in the microwave range. In addition, a network analyzer type Anritsu/Wiltron 37225B was used. The frequencies were varied in 1600 steps between almost 0 GHz and 20 GHz. Measured variables were the real and imaginary parts of the reflection coefficient of the microwave. With the aid of an inverse Fourier transform, the frequency signals were transformed into the time domain, i.e., the time signals were generated synthetically. In reflection mode, only one antenna was used for sending and receiving the microwaves (scattering parameter S11).

The antennas were very wideband double-ridge horn antennas of the types Schwarzbeck BBHA 9120C (nominal frequency range 2 GHz to 18 GHz, antenna 1) and A. H. Systems SAS 571 (nominal frequency range of 0.7 GHz to 18 GHz, antenna 2, Fig. 1).

In order to suppress possible interference, low-pass filtering (0-10 GHz) was performed. The distance between the antenna aperture and the specimen was 21 cm and 13 cm, respectively. This ensured that the dispersion of the microwaves at the border and edge of the sample represented only a minor interference influence. In addition, due to the air gap between the antenna and sample, the reflections were largely decayed.

The reference object was a thin steel sheet, which was placed on the sample and can be assumed to reflect the irradiated microwaves completely (S11 = -1).

In order to optimize the reflected signal time for further evaluation, the complex frequency data were supplemented with zeros (zero padding). By applying a Hamming window in the frequency domain before the transformation into time domain, the formation of transformation artefacts was mostly suppressed.

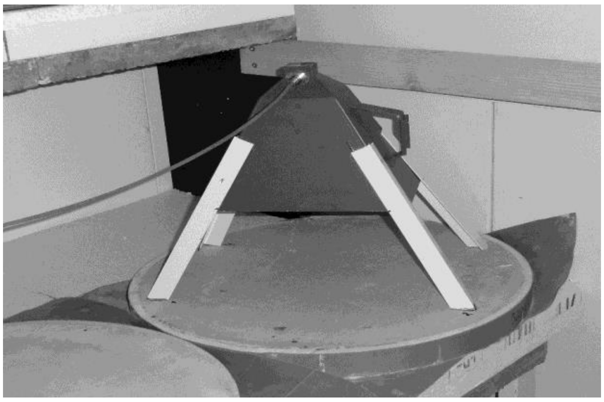


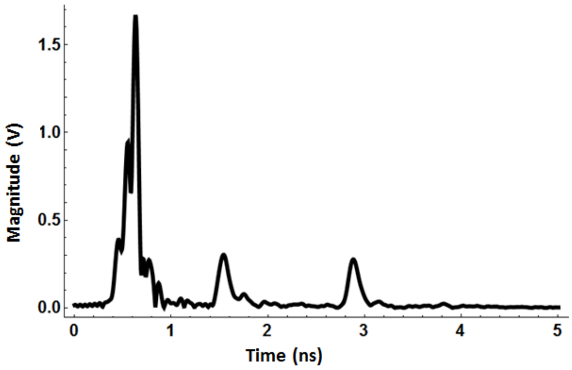
Fig. 1. The wideband antenna (antenna 2) placed on the cement screed sample

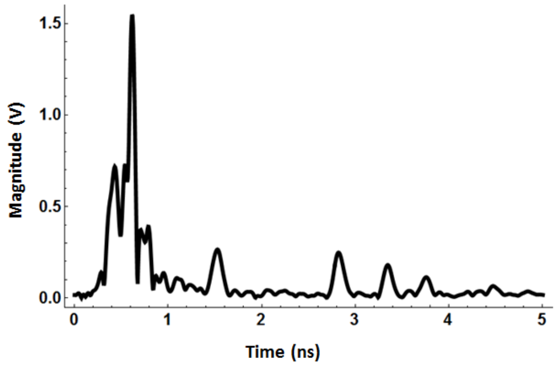
3. Results

Fig. 2 and 3 show the time signals captured by antenna 1 and 2 for both anhydrite and cement screed samples. The large echo to the left originates from reflections in the antenna. The front wall echo, i.e. the reflection at the interface between air and screed sample, occurs at approximately 2.8 ns to 2.9 ns.

This time includes, in addition, the time-of-flight between the antenna and the sample (both ways) as well as the times in the cables and the measuring device. The echo related to the front wall echo could be verified with a thin metal sheet placed on the sample, which resulted in a significantly higher peak at the same time, caused by the total reflection. It was attempted to eliminate the antenna signal by subtracting a signal recorded without sample from the total signal. However, a complete elimination could not be reached. The slight variations in the time position of the echoes are due to the fact that only two samples were available and the antennas had to be re-positioned several times.

Depending on the sample and antenna type, a back wall echo (screed/styrofoam interface) could be detected after a curing time of several days or weeks at about 3.4 ns. In Fig. 2 and 3, another echo, resulting from the reflection of the laboratory bench can be seen in the right part of the images at approximately 3.8 ns. The post-pulse oscillation of the signal of antenna 2 is stronger than the antenna 1.





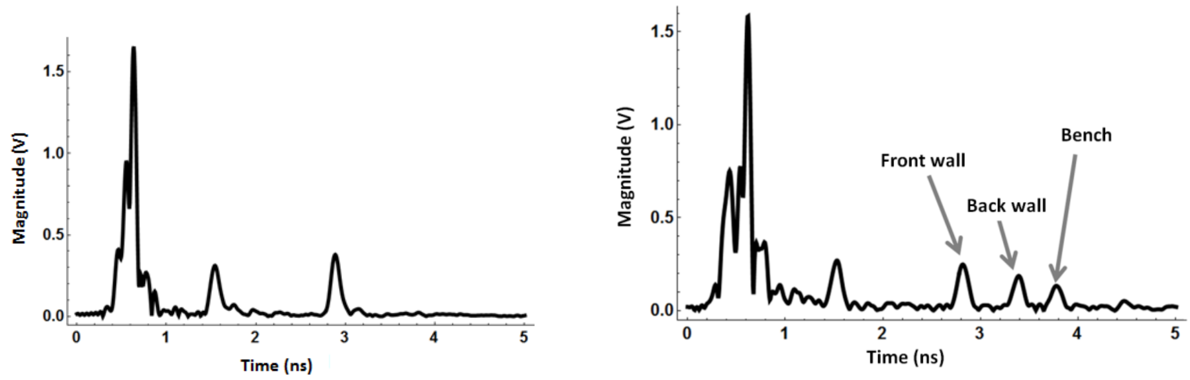


Fig. 2. Magnitude of time signals with antenna 1: top left: cement screed on day 3, top right: cement screed on day 165, bottom left: anhydrite on day 3, bottom right: anhydrite on day 165

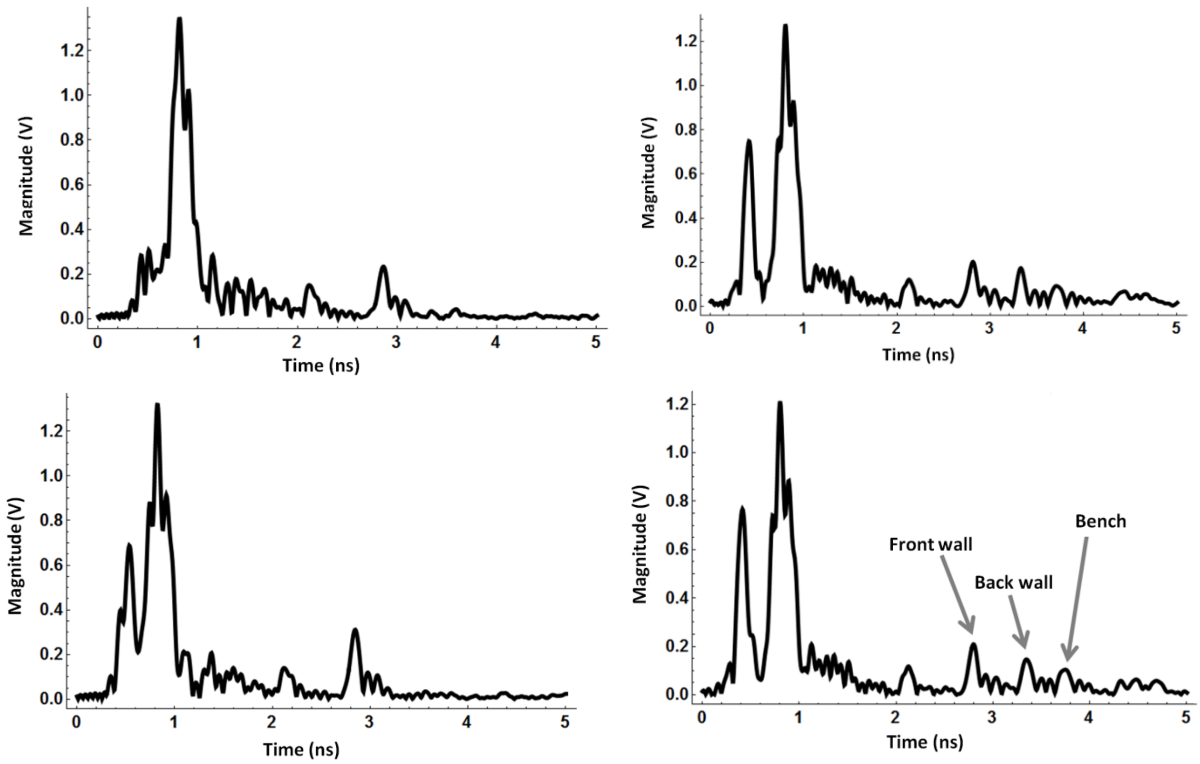


Fig. 3. Magnitude of time signals with antenna 2: top left: cement screed on day 3, top right: cement screed on day 165, bottom left: anhydrite on day 3, bottom right: anhydrite on day 165

In addition to the echoes identified at the interfaces no further echoes were found, e.g. due to a moisture gradient inside of samples.

4. Discussion and Conclusions

Free water compared to most other materials has very high permittivity (dielectric constant). Correspondingly, aqueous mixtures compared with the dry fabric have increased permittivity [6], which reduces with decreasing content of free water in the process of drying, whereby also the reflection coefficient decreases (Fig. 4). At the start of drying due to the high absorption of microwaves by the free water, the back wall is not visible. However, decreasing in the water absorption by drying made it visible (Fig. 2, 3 and 5).

The shift of the echo position towards smaller times (Fig. 6), i.e. lower signal transit time through the sample, is because of increasing propagation velocity of the microwaves in the material with progressed drying, where the permittivity of initially wet approached the dry samples' permittivity. This process is, for the cement screed, faster than in case of the anhydrite screed (Fig. 5). For the first mentioned one, a plateau value is reached after approximately 20-25 days and for the last mentioned one after 30 - 40 days.

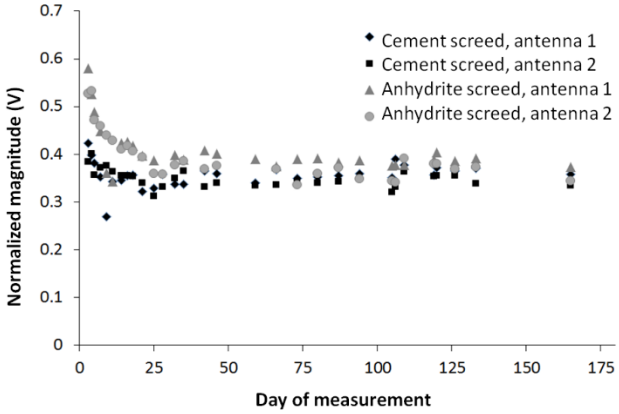


Fig. 4. Height of the front wall echo normalized to metal plate versus drying time

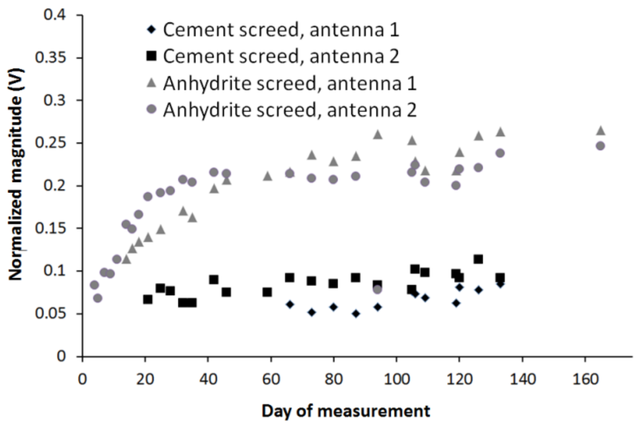


Fig. 5. Height of the back wall echo normalized to metal plate versus drying time

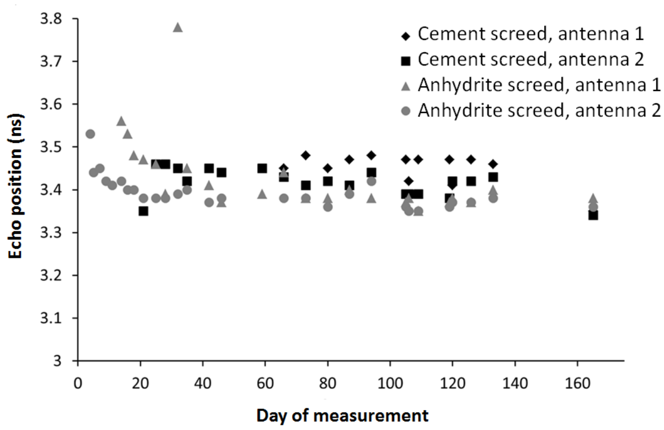


Fig. 6. Temporal position of back wall echo for both cement types and antennas versus drying time

5. Conclusion

The investigations show that a microwave measurement is suitable to characterize the drying behavior of screed. The echoes originating from the sample front wall show characteristics similar to those from the back wall. Thus, also a simplified microwave method, in which the individual echoes could not be differentiated, would be applicable for screed drying tests.

6. Acknowledgments

The authors thank the Robert Bosch GmbH - Power Tools, Engineering Detection Systems, for providing the samples and the Federal Institute for Materials Research and Testing (BAM), Department 8.2, non-destructive damage assessment and environmental measurement methods, for the accomplishment of experiments.

7. References

[1] M. Skolnik, Introduction to radar systems, Japan: McGraw-Hill, 1981.

[2] R. Collin, Grundlagen der Mikrowellentechnik, Berlin : VEB Verlag Technik Berlin, 1973.

[3] R. Zoughi, Microwave Non-Destructive Testing and Evaluation, Dordrecht: Kluwer Academic Publishers, 2000.

[4] E. Nyfors and P. Vainikainen, Industrial Microwave Sensors, Norwood, MA: Artech House, 1989.

[5] M. Born and E. Wolf, Principles of optics: electromagnetic theory of propagation, interference and diffraction of light, Cambridge: Cambridge University Press, 1980.

[6] K. Kupfer, Electromagnetic Aquametry : Electromagnetic Wave Interaction with Water and Moist Substances, Berlin, Heidelberg : Springer, 2005.