Abstract

Moisture in construction materials is an important parameter during construction or in cases of water leakage. In this article results of moisture measurements with a new radar sensor are presented. The radar sensor measures the complex reflection coefficient of building material that is then further processed. It is shown that the permittivity of the surface and the dielectric thickness of the material can be measured very accurately, while the determination of the geometric thickness, and thus the mean permittivity, is still challenging. To validate our results we make a comparison to measurements conducted with state-of-the-art resistive and capacitive moisture meters as well as to gravimetric measurements of drying cement and anhydrite screed.

Keywords: moisture, permittivity, drying, screed, radar

1. Motivation

In civil engineering the determination of the moisture content in building materials is especially important during construction. Concrete consists mostly of binder, aggregates and water. A part of the water is used in the hydration process with the binder. The rest either forms water vapor inside the pores or is bound as liquid water at the surface of the pores. This moisture content needs to decrease to an equilibrium state with the ambient air before the next construction step can follow. The drying process can take weeks or months. If e.g. the flooring is laid too early, the moisture can cause mould or damage to the flooring material and lead to devastating damage.

2. Material and methods

2.1 Material

For the evaluation of different measurement devices, a measurement series has been conducted in cooperation with the Materialprüfanstalt (MPA) in Stuttgart, the Bundesanstalt für Materialforschung in Berlin (BAM), the Materialforschungs- und Prüfanstalt (MfPA) in Weimar, the KIT Karlsruhe, and the Fraunhofer IZFP. The production of the samples took place on 10th of June 2014 at the MPA Stuttgart with bagged mortar. The cement screed (CT) Sakret Beton / Estrich BE (CT-C35-F5) has been mixed with 4.8 l water per 40 kg mortar and the flowing anhydrite screed (CA) Knauf FE 50 Largo (CA-C25-F5) has been mixed with 6.25 l water per 40 kg mortar in a concrete mixer. Immediately after production, the samples were covered, moved to the climate chamber at the MPA, MfPA and BAM on 11th of June 2014 and measured for the first time on 12th of June 2014. The samples at the MPA consisted of 6 samples for each material with two different thicknesses of approximately 35 mm and 70 mm respectively.
Figure 1. Schematic illustration of the test setup as a replication of a floating screed for (a) the thick samples with ca. 70 mm and (b) the thin samples with ca. 35 mm. Screed, PVC-tube, silicone und PE-foil are permanently joined.

Temperature and humidity of the climate chamber has been documented with the device “Extech RH520”. The temperature in figure 2 has a very constant value besides the peaks caused by entering the climate chamber during measuring. Humidity could not be controlled in the climate chamber and thus has strong fluctuations.

Figure 2. a) Temperature and b) humidity in the climate chamber at the MPA Stuttgart.

2.2 Methods

2.2.1 Reference

For evaluation of the dry mass the samples were kiln-dried at 105°C and 0% relative humidity for CT and 40°C and 5% relative humidity for CA in the oven „CTS C-40/600/S“ until constant mass has been reached [1]. The moisture content is calculated according to equation (1) using the mass of the moist sample $m_F$, the mass of the dry sample $m_T$ and the mass of sample container $m_H$.

\[
 w_M = \frac{m_F - m_T}{m_T - m_H}
\]
2.2.2 Electronic devices

Different state-of-the-art electronic moisture measurement devices have been used. In this article the “Laserliner MultiWet-Master®” is used as an example for resistive devices and the “Testo 616®” as an example for capacitive devices. Resistive devices measure the resistance between two electrodes. Capacitive devices establish an electric field penetrating the material and thus measure differences in the permittivity. The permittivity of pure water is high with a value of approximately 80 compared to dry building materials with values below 8. The drawback of both methods is that the readings strongly depend on surface moisture and only marginally on moisture in the depth of the material.

2.2.3 Radar

Radar or microwave methods also measure the permittivity. However, the device emits a wave of which a part travels through the whole cross section of the material and is reflected at the backside. This signal part is equally dependent on near surface moisture as on moisture in deeper layers and thus determines the mean permittivity directly, which can be correlated to the mean moisture content. The radar sensor in figure 3 is a stepped-frequency continuous wave radar in the frequency range from approximately 2 to 8 GHz and has been developed by the Robert Bosch GmbH. The radar sensor measures the complex scattering parameter $S_{11}$ for each frequency. For calibration, a 3-Term Error Model is used with the calibration standards air, metal plate in reference plane and metal plate shifted out of reference plane [2].

![Figure 3](image)

Figure 3. (a) Controlled by computer, the radar sensor emits a sine wave via (b) two Vivaldi antennas and receives (c) the reflected sine waves. The sum of the reflected waves in correlation to the emitted wave is the reflection parameter $S_{11}$. For certain frequencies the surface reflection and the backside reflection will cancel each other out and thus show a local minimum in the spectra.

According to equation (2) and (3) the reflection $S_{11,S}$ can also be calculated with the product $R_k$ of the reflection parameters by Fresnel, the product $T_k$ of the transmission parameters and the total dielectric thickness $D_{el}$ for each course of beam $j$. 

\[
S_{11} (f) = \frac{\Sigma \text{Received}}{\text{Emitted}}
\]
For the processing of the radar data two different fitting methods have been used. Both minimize the difference of the measured signal $S_{11}$ and the calculated signal $S_{11s}(d, \varepsilon)$, depending on the thickness $d$ and the complex permittivity $\varepsilon$. The first method is used only on single measurements [2], while the second method is simultaneously used on multiple measurements.

3. Results and Discussion

3.1 Reference measurements

The measurement of the moisture content $w_M$ by kiln-drying shows a strictly homogeneous decrease over time for all samples. As the moisture content of similar samples differ, measurement values need to be correlated to the moisture content of each sample respectively. Thin samples have already reached the threshold value for flooring at day 92, while the thick screeds are still too moist.

![Figure 4](image)

Figure 4. Drying of (a) cement screed with a thickness of about 35 mm (CT35) and about 70 mm (CT70) und (b) anhydrate screed with a thickness of about 35 mm (CA35) and about 70 mm (CA70).

3.2 Electronic measurement devices

As the pins of the „Laserliner MultiWet-Master“ are not able to penetrate the surface of the screed, the measurement values strongly depend on the surface moisture. At the beginning of the drying process with a high moisture content, the measurement values steeply decrease to a constant reading of about 150 after a short time. The same reading correlates to moisture range of 3.5% to 6.5% for CT and 0.2% to 2% for CA. Therefore it is impossible to evaluate the moisture content in this moisture range.
As a capacitive device, “Testo 616” is able to penetrate the material and detects the decrease of the moisture content during the entire 92 days. However the values for the thin and thick samples of the CT decrease similarly over time (Fig.6), even though the moisture content differs (Fig.4).

Figure 5. Measurement of a) CT and b) CA with the “Laserliner MultiWet-Master“ in „Index-Mode“

Figure 6. Measurement results of “Testo 616” with setting “M1” for CT and setting “M2” for CA for a) b) at different times and c) d) different moisture contents. Especially CT shows similar values in correlation to time for thin and thick samples while the values differ in correlation to moisture.
The reason is that the measuring volume is mostly near the surface and dries similarly for thin and thick samples. Thus the measured values are shifted for different thicknesses in correlation to the moisture content. Without knowledge of the correct thickness it is not possible to determine the correct moisture content - i.e. a reading of 6% represents a moisture content of 4% for 35 mm thick screed or 5.6% for 70 mm thick screed. This problem is smaller for anhydrite screed, as the values are shifted over time and not over the moisture content, indicating that the moisture content in deeper layers is decreasing similarly to the measuring volume.

3.3 Radar

Depending on thickness and moisture content, the measured reflection parameter $S_{11}$ differs in quality as high moisture content and thickness cause attenuation of the signal part from the backside reflection. On day 2 (Fig.7) the attenuation of the electromagnetic waves for all samples in the material is so strong that the signal part of the backside reflection disappears. On day 10 the backside part can be distinguished for thin samples and is, as expected, attenuated stronger for higher frequencies. On day 31 the backside reflection is also recognizable for thick CA samples, while thick CT still absorbs most of the backside part, considering the moisture content is still at about 5%. However, for moisture contents around the threshold value for flooring, the backside signal can also be detected for thick CT.

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<th>Day 31</th>
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Figure 7. Reflection $S_{11}$ by radar measurement at different times.

Signal processing can provide different parameters calculated from the measured reflection coefficient. The most exactly determined parameter is the dielectric thickness $D_{el}$. For CA the dielectric thickness $D_{el}$ shows a very homogenous trend (Fig.8) for lower moisture content. If the moisture content is very high and thus the backside signal too weak, the fitting algorithm is not able to find a distinct minimum.
Assuming that the thickness of the sample is known, the mean permittivity $\varepsilon_M$ can be directly calculated from the dielectric thickness $D_{el}$. The permittivity $\varepsilon_M$ in Fig.9 was determined by measuring the thickness of the samples in the center. CT shows a much bigger variance compared to CA. At least partially the cause is the thickness measurement. Linear errors in the thickness cause quadratic errors of the mean permittivity. As a flowing screed, the CA can be produced with a more even surface compared to the CT.

If no information about the thickness is available, the fitting can be enhanced. Using multiple measurements of different samples or times simultaneously, the fitting gets more robust by avoiding ambiguity. The results in Fig.10 show that the values for thin CT got more precise, while the values for CA got extended to a higher moisture content.
4. Conclusions

Resistive moisture measurement devices mainly measure the surface and are not able to determine the mean moisture content. In comparison to that the capacitive devices have a better penetration behavior. However, the disproportionately high weighting of the surface moisture makes it impossible to get the mean moisture content over the cross section of the material without additional information. For anhydrite screed the problem is minimized due to a flat moisture depth profile.

Radar measurements provide precise values for dielectric thickness and good results for any given thickness for the mean moisture content. However, the estimation of the thickness and thus the mean moisture content is still challenging. One possibility is the simultaneous fitting over multiple samples or times.

References: