PRECISE MOISTURE MEASUREMENT

IMKO MICROMODULTECHNIK GMBH

General Requirements to Capacitive-, Micro Wave- and TDR- Sensors for precise Material Moisture Measurement

Learn more about the advantages and disadvantages of dielectric measurement principles and how moisture sensors can be verified.

Capacitive-, Micro Wave- and TDR- material moisture sensors must meet a multitude of various requirements within their industrial application range. The expert is consistently confronted with the problem, if and how his respective requirements can be fulfilled. The following abstract deals with the advantages/disadvantages of dielectric measuring principles and how material moisture sensors can be checked.

The dielectric measurement principle for material moisture measurement, for most applications, has found a firm footing within industry. Hereby, the dielectric constant (DC) of a material is measured via an electro-magnetic high frequency field which permeates the material. The DC of water at 20°C features a value of 80 and consequently differs from the DC of solid material which, depending on the material, feature DC values ranging from 3 to 30. At this significant dielectric contrast the DC can therefo e be deployed as a reference value for the water content, respectively material moisture.

The three different dielectric Measurement Principles:

At the **capacitive measurement principle**, the dielectric constant, respectively the capacity of the material intended for measurement is measured with a plate type or cylindrical capacitor deploying a high frequency measuring signal via the according high frequency field.

At the **micro-wave measurement principle**, the differences between the transmitted and received waves which are generated due to the attenuation of the amplitudes and phase displacement are measured. The transformations of the amplitude and phase results from reflection, refraction and scattering of the high frequency waves at the barrier layer of the dielectric and through absorption in the inner of the examined material.

The **TDR measurement principle** (Time-Domain-Reflectometry), also referred to as cable radar, has consistently asserted itself within the last 10 years in the industry as a precise measuring method for demanding applications. At the TDR technology, two or three wire, parallel waveguides (acting as the actual sensor) are deployed, which are inserted in form of rods or plates into the material intended for examination. A voltage pulse is applied which spreads along a coax cable which is connected to the waveguide. As soon as the voltage pulse passes to the sensor, a partial reflection will occur. The continuing part is completely reflected at the sensor end. The step response of waveguide can be measured via the period whereby the reflection period represents the reference value for the water content. The following physical interrelation represents the basis for the application of TDR:

$$c = \frac{c_0}{\sqrt{\varepsilon_r \cdot \mu_r}}$$

According to the same, the speed c of an electro-magnetic wave in a vacuum is equal to the speed of light c_0. Without vacuum, the propagation speed c is only dependant of the dielectric constant ε_r and the magnetic permeability μ_r of the material the wave/pulse propagates. The latter can be set equal to 1 in non-magnetic materials so that the propagation speed is only dependant of the dielectric constant. The challenge connected with the TDR measurement is the very short transit time of the electro-magnetic wave on the sensor so that very short-time and steep-flanking pulses (rise time < 300 picoseconds (ps) $=10^{-12}$ s) are required for the measurement. Using the example of a 15 cm long TDR measurement probe (l = 15 cm), the transit time in air t_l with a DC of 1 and the transit time in water t_w with DC = 81 is calculated as follows:

$$t = \frac{2l}{c_0} \cdot \sqrt{\varepsilon_r}$$

$$t_l = \frac{0{,}3m}{3 \cdot 10^8 ms^{-1}} \cdot \sqrt{1} = 1ns$$

$$t_w = \frac{0{,}3m}{3 \cdot 10^8 ms^{-1}} \cdot \sqrt{81} = 9ns$$

This results in a delay time of merely 8 ns between the two extremities 0% and 100% moisture. In order to be able to metrologically precisely register this minute time lag, it is necessary to deploy measuring devices which are able to resolve this period with an accuracy of $\pm 2x10^{-12}$ s (±2 picosecunds). This represents a task which can, for industrial material moisture sensors, be handled by TRIME measurement method provided by the company IMKO.

Which various requirements must be met by the dielectric material moisture sensors?

The **requirements** demanded of the dielectric **material moisture sensors** are diverse.
For the precise establishment of the moisture, material moisture sensors which operate according to the dielectric measuring principle must **meet various basic requirements** as depicted below:

1. Precise measurement of the real part of the DC under various conditions
2. Precise measurement of the moisture at high material conductivities
3. Long term stability after abrasion
4. Insensitivity towards dispersive materials
5. Precise measurements in materials with very high water contents
6. Precise measurement at very low moistures and material densities down to 100 kg/m^3
7. The taking into account of the temperature dependency of the DC of water
8. Reliable measurement of material moisture at different grain sizes of the bulk material
9. Temperature stability of the sensor electronics
10. Long term stability in monitoring operation

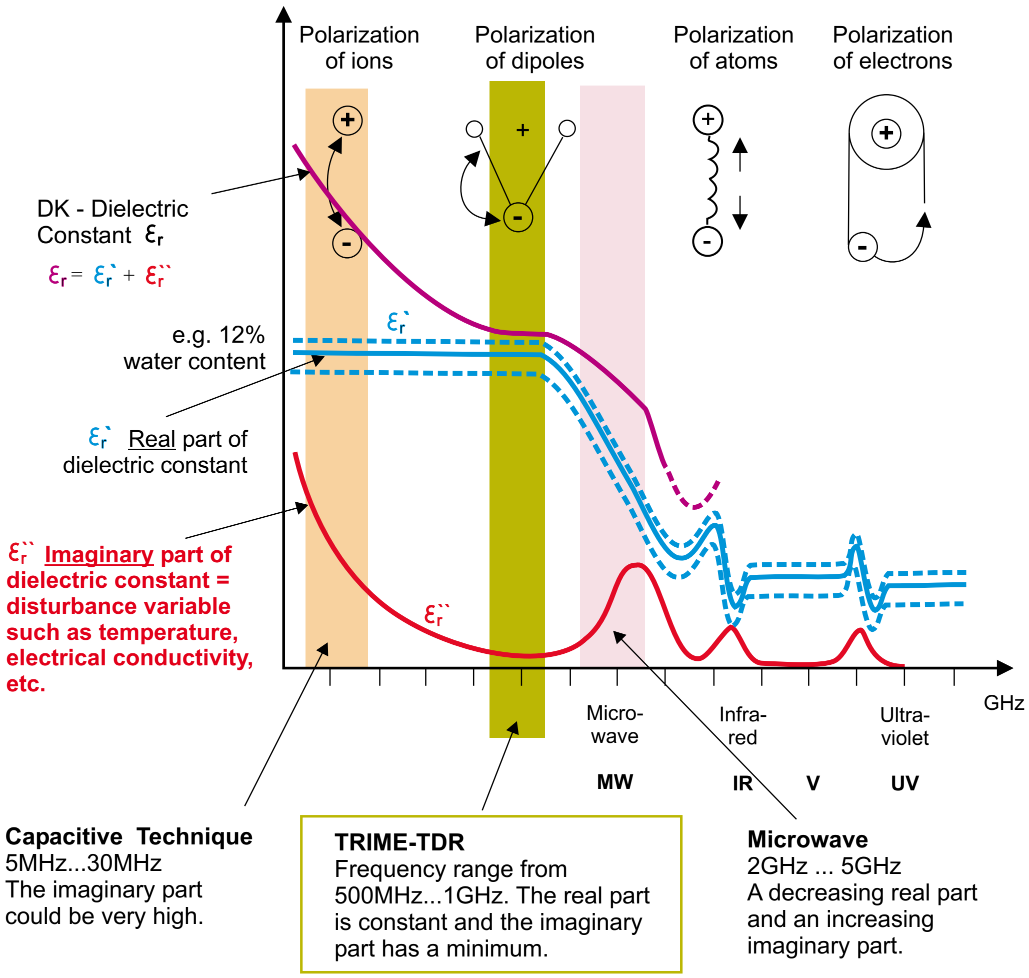
For the expert, in respect to the **evaluation of the quality of a material moisture sensor**, the aforementioned requirements must be able to be verified using relatively **simple testing methods**.

1. Test for the evaluation of the measuring accuracy of the real part at various mineral contents
2. Test for the maximum conductivity range
3. Test for the temperature dependency of the DC
4. Test for the long term stability under consideration of the abrasion of the sensor surface
5. Test in dispersive materials
6. Test in very wet materials
7. Test for the temperature stability of the sensor electronics

1. Requirement: Precise Measurement of the Real Part of the DC at different Conditions

This first requirement is allocated the highest priority as all further moisture value calculations measurement value compensations etc. depend on the real part of the DC. Only the real part of the DC is able to provide a statement regarding the water content in the measured material. The DC however principally consists of a **real** part and an **imaginary** part. Dielectric measuring methods and sensors are, depending on the applied method, not able to differentiate between these two parts of the DC. They measure the sum of the real and imaginary part (blue + red = purple graph) which, in practice, can lead to faulty measurements at the determination of the water content.

The following graphic depicts the basic physical conditions in water at various measuring methods/technologies within the respective frequency spectrum:



The **real part** (blue curve) represents the reference value for the water content. The **imaginary part** (red curve) represents the reference value for the dielectric losses, e.g. due to electrical conductivity, temperature etc. The imaginary part is not a constant value and can change dynamically due to changes of the ambient conditions such as temperature or varying mineral contents in the material intended for measurement. It therefore represents an interfering factor at the dielectric determination of the water content. The ratio of the real to the imaginary part of the DC varies with the method-dependent frequency. The various physical measurement principles are therefore influenced to a varying extent in accordance to their frequency range.

The TRIME-TDR radar method operates within the ideal frequency range between 500MHz and 1GHz

The **real part** (blue curve) is at the maximum and (still) constant in this frequency range. The interfering **imaginary part** (red curve) is at its minimum! This means that a definite allocation of the real part to the water content is warranted for and the disturbing influences of the imaginary part can be neglected to a large extent. **Amongst all these measurement methods, the TRIME-TDR technology offers the ideal physical prerequisites for an accurate measurement of the moisture, ... and this at temperatures of up to 150°C of the measured material.**

Image: TRIME-GW deployed in a brewery at 80°C. A moisture sensor awarded with the Silver Medal of the DLG (German Agricultural Association)

A Comparison with other Measuring Methods

Capacitive Measuring Technology

Capacitive measuring methods, depending on the device and the manufacturer, operate within a frequency range situated between 5MHz and 80MHz. The DC, within this frequency range, is partially influenced to a virtually identical extent by the real part (water content) and the imaginary part (mineral content, temperature). An isolation of these two influencing variables is not possible. For this reason, a precise measurement of the moisture is not possible under the influence of disturbance variables such as temperature and mineral content.

Microwave Technology

Microwave measuring systems operate with high frequencies >1GHz. Within this frequency range however, the real part of the DC decreases again. This leads to a reduction of the measurement resolution. In addition, the problematic proportion of the imaginary part or error contribution of the DC, the disturbance variable at the measurement of moisture, increases again. Therefore, microwave methods react significantly more sensitive to deviations of the temperature and electrical conductance. The microwave method is a technically and physically very complex measurement method at which various parameters like temperature, grain shape and sizes may interfere with the measurement result.

Measurement Technology based on the Resistance

The main problems of the moisture measurement technology based on the measurement of the electrical resistance are:

- The contact with the sample material
- Small measuring volumes, i.e. point-to-point measurement
- Significant temperature dependency
- The dependency of the electrical conductance (salt content) of the measured material.

Different conductivities can rapidly be generated by varying temperatures or deviating mineral contents.

At resistance-based measurement methods, the measured variable, due to the principle as such, also represents the disturbance variable at the same time. They are therefore virtually unsuited as an accurate measurement method.

NIR-Measurement Technology (Near-Infra-Red, reflexive or transmissive)

Reflexive NIR merely enables low penetration depths and is subject to considerable interference caused by surface moisture and dust. Transmissive NIR is merely able to penetrate a maximum material thickness of 3 cm. This consequently requires laborious and congestion-prone bypass constructions.

2. Requirement: Accurate Measurement of the Moisture at high Material Conductances

This second requirement applies to applications at which conductive materials require to be accurately measured. A material moisture sensor must deliver constant moisture measures even at deviating and high conductivities. In most cases, such users search in vain in data sheets for a statement in respect to the maximum possibly conductivity which is covered by the sensor. Quite often, the manufacturer states that the material conductivity does not significantly influence their sensor. This would however mean that that the conductivity range would be unlimited!?

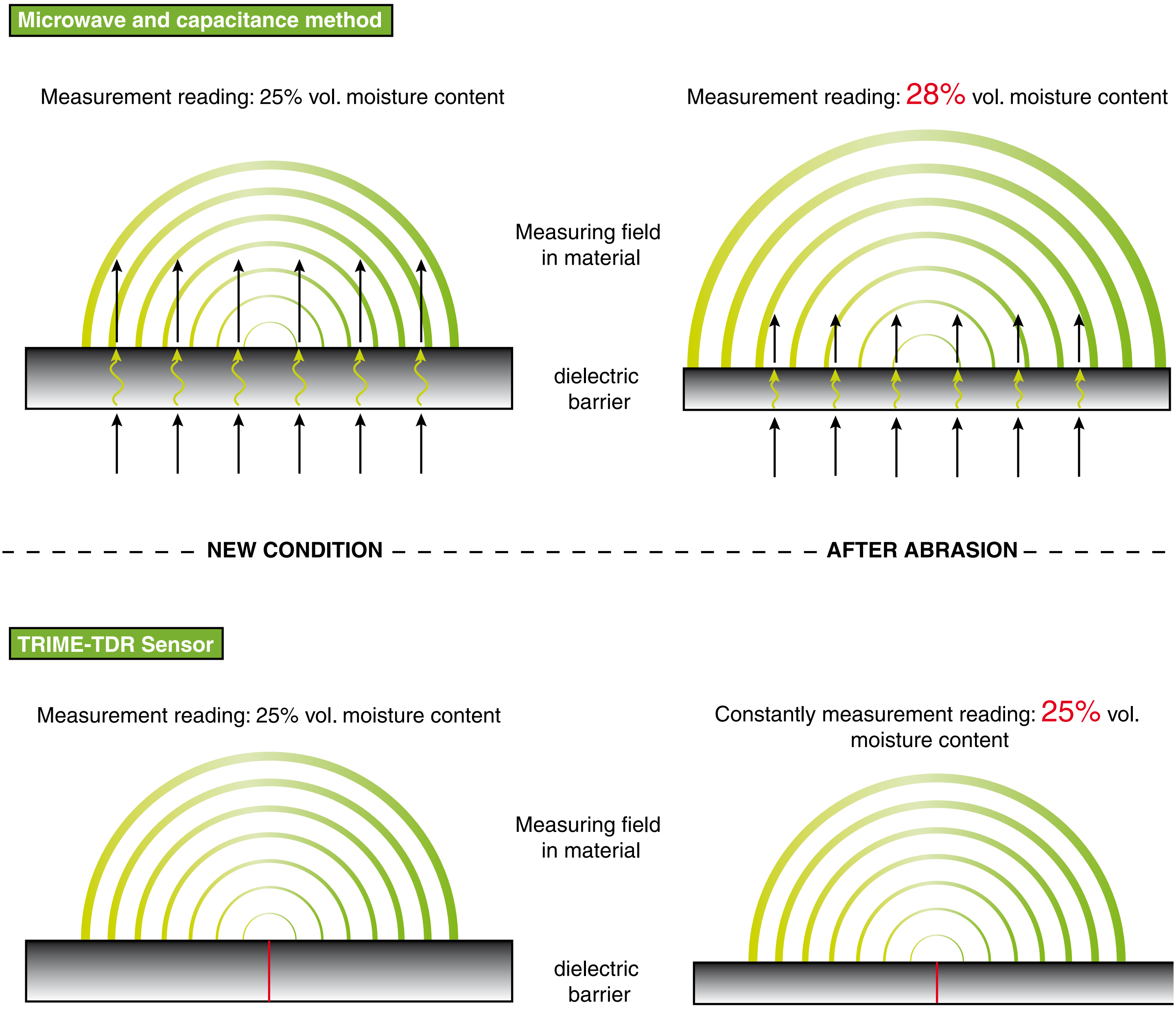
Exemplary for applications for materials which dispose of a high conductivity are:

1. **Fresh concrete**: Fresh concrete, depending on the moisture and the cement content (water/cement factor) can feature pore water conductivities of up to 40dS/m. In the ideal case, a moisture sensor (e.g. such as the SONO-MIX) measures both parameters, the moisture and the conductivity. The TRIME-TDR radar technology provides both parameters, the moisture and the Radar-based-Conductivity (RbC) and therefore ensures for a significantly improvement of the quality verification directly in the process. RbC also allows to make conclusions in regard to other parameters of a fresh concrete recipe such as the cement content or the slump of fresh concrete.
2. **Crude oil**: Crude oil can dispose of a high contents of minerals (salts, etc.). For this reason, a moisture sensor should be able to precisely measure up to a pore water conductivity of up to 40dS/m.
3. **Soils in arid areas**: The salinisation of soils is consistently increasing. Soils with a pore water conductivity of up to 20dS/m are not uncommon.
4. **Further materials** which feature medium conductivities are, e.g. sewage sludge, clay, coal, suspensions, mash, moulding sand, limestone sand, organic material for the production of bio-gas, malting barley, grain at higher temperatures, liquids such as acetone, and many more.

Image: SONO-MIX with indication of the conductivity range up to 40dS/m, the measurement of the moisture and via RbC the cement concentration and slump.

3. Requirement: Long-Term Stability after Abrasion

Many probes deployed for the material moisture measuring are equipped with a dielectric screen (ceramic or plastic plate). If this screen is exposed to wear and a regular recalibration is not conducted, these probes will provide faulty measurement values as the intensity of the measuring field subsequently increases due to the wear. Even minor abrasions of 0.5 mm, depending on the application, can lead to measurement deviations up to 5% absolute. At the SONO series with the TRIME TDR radar-based method, the innovative probe design ensures for the automatic calibration of the sensor in case of changes to the dielectric screen caused by abrasion. This consequently means continuous reliability and longer maintenance intervals at the SONO probes.



Graphic depicting both Methods

4. Requirement: Insensitivity towards dispersive Materials

Dispersive materials feature a strong dependency of the measured variable (dielectric permittivity) of the frequency of the measuring signal and influence the characteristic wave impedance of a measuring arrangement. Material such as, e.g. ceramic suspensions dispose of a high dispersion, i.e. the impedance of the sensor setup is considerably influenced. Material moisture measurements in such media demand higher requirements to the sensor electronics.

Image: SONO Sensor in special design covered by ceramic suspension

5. Requirement: Precise measurements in materials with very high water contents

Materials with very high water contents up to 90% represent an extreme challenge to material moisture sensors because the signal attenuation at high water contents can be quite large. Depending on the application, moisture ranges from 40% to 90% must be covered from the sensor with a required accuracy of ±0.3%. Exemplary for this are the following materials: sludge, emulsions, water based paints and other materials.
To obtain accurate measurements in these materials the material moisture sensor must be able to cover a dynamic range up to 90%. The TDR technology due to the principle of measuring the radar transit time is not limited concerning the maximum water content and thus provide representative and accurate measurements even in high material moisture contents up to 90%.

6. Requirement: Precise Measurement at very low water contents and Material Densities down to 100 kg/m^3

Materials with a very low moisture content and a density as low as 100 kg/m3 represent also an extreme challenge to material moisture sensors as the dynamic range at the moisture measurement can be very small. Depending on the respective application, it may be necessary to cover moisture measurement ranges of, e.g. 0 to 2% at a demanded measurement value resolution of 0,05 to 0,1% . The DC of the materials may respectively shift within ranges of 1.5 to 5. Exemplary for this are the following materials: hops, insulating wool, plastic granules, powder in fluid bed driers.
In order to be able to achieve precise measuring results in such materials, a very extensive measuring field of the material moisture sensor is required, which, depending on the application, should cover up to 3 to 10 litres of the material. The TDR technology, in respect to the sensor size, due to the principle to apply the method of measuring the radar transit time, is not limited. The image depicts a moisture sensor constructed for the direct installation into a barley drier, which, with a sensor length of 4 m, is able to measure a measuring volume of approx. 40 litres and can consequently deliver representative and accurate measurement results in this problematic material.

Image: SONO-LINE with hops

7. Requirement: Taking into Account the Temperature Dependency of the DC of Water

The DC of water is temperature-dependent DK (see the blue dotted curve in the frequency spectrum). At 20°C, water features a DC of 80. At a temperature of 50°C this decreases to merely 70. It is essential to take into account this temperature dependency at the measurement using material moisture sensors. A compensation of this temperature sequence can be conducted externally in an evaluation unit (SPC or PC). In the ideal case, it is directly conducted in the sensor parallel to the measurement of the material temperature. The prerequisite for this is however the prior precise measurement of the real part of the DC.

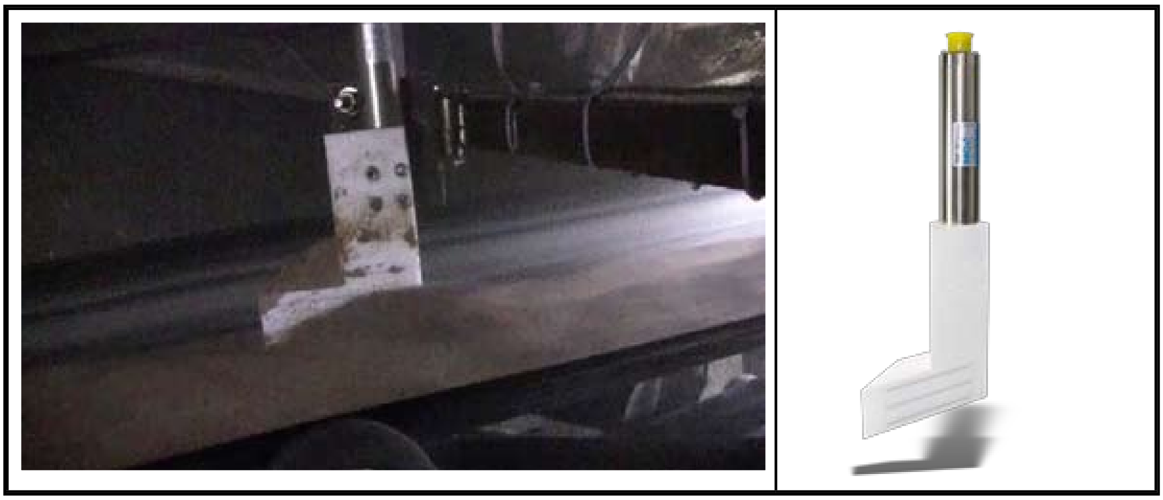


Image: SONO-MOVE PTFE probe above a conveyor belt deployed for the measuring of adhesive limestone sand.

8. Requirement: Reliable measurement of material moisture at different grain sizes of the bulk material

Bulk goods and aggregates such as sand and gravel have different shapes and grain sizes. Material moisture sensors should not be influenced by such different conditions. Capacitive and TDR sensors show negligible influences on the grain and shape size distribution.
Microwave probes show considerable dependencies on particle size and shape resulting in scattering effects that cannot be neglected. It has been found that the different absorption and scattering behavior of the microwave method is so marked that this sensor can even be used for measuring the composition of the mixed material, provided the moisture is known.

9. Requirement: Temperature Stability of the Sensor Electronics

Electronic circuits of material moisture sensors may be exposed to considerable temperature deviations. The accuracy of the moisture measurement at deviating ambient temperatures should accord to the specifications provided by the manufacturer.

10. Requirement: Long-Term Stability in Monitoring Operation

In monitoring operations over very long periods, i.e. 10 to 20 years, moisture probes have to measure the water content in hardened concrete or in concrete constructions. And this with an accuracy requirement of ±0.1%, without aging occurrences. In such applications it must be ensured that no metallic sensor surfaces are in contact with the concrete. Even very small electronic signals in the range of ±1V form in the long-term use over several years, chemical and electrical surface effects at the metallic sensor surface, caused by salts and minerals in the concrete. These surface effects would falsify the measurement signal gradually.
The moisture probes in the PICO series of the TRIME technology are completely galvanically isolated and fulfill this requirement. After a dismounting of installed TRIME probes for more than 10 years of operation, no long-term effects had occurred.

Literature: Electromagnetic Aquametry: Electromagnetic Wave Interaction with Water and Moist Substances (Springer publishing) by Klaus Kupfer

Test Methods for the Evaluation of the Quality of a Material Moisture Sensor

The tests depicted in the following are intended to enable the user to verify the quality of a material moisture sensor using relatively simple methods.

1. Test for the Evaluation of the Measuring Accuracy of the Real Part at varying Mineral Contents

This test of a material moisture sensor is relatively easy to perform. A material such as sand or glass beads is dampened once with tap water featuring a conductance of approx. 0,5dS/m, as well as with salt water with a conductance of e.g. 2 to 40dS/m (depending on the application) in different moisture ranges from 0% up to saturation. The material moisture sensor should indicate the same moisture value at the same water content but with different salt contents.

2. Test for the Maximum Conductivity Range

It is advisable in this case, to deploy a material which can be additionally saturated. Salt can be gradually added to the blended and saturated material up to the point where the sensor respectively significantly deviates in regard to the indicated measurement value. If one adds more water than is required for material saturation, it is possible to determine the maximum possible pore water conductivity with conventional conductometers. At this test, one should deploy the uncalibrated measurement data of the sensor as a downstream calibration curve can limit the display of a sensor and consequently generates a false constant.

3. Test of the Temperature Dependency of the DC

This test is not simple to perform. The material moisture at two different temperatures is determined with the sensor in an air-tight closed receptacle (the measured material may not dry out). The respectively measured deviation of the material moisture acts as a reference value for the temperature co-efficient of the measured material's DC. The prerequisite for the precise compensation of this temperature effect is however the compliance with the 1. Requirement together with the correct measurement of the real part of the DC. The test can be performed in a relatively simple manner by using suspension such as a ceramic suspension, as the respective density here is constant.

4. Long-Term Stability of the Measurement

A moisture measurement with a sensor is performed with a relatively homogeneous material. Once the dielectric screen (ceramic or plastic plate) has worn by approx. 0.5 mm a subsequently conducted measurement with the same homogenous material should indicate the eventual deviation of the material moisture sensor.

5. Test in dispersive Materials

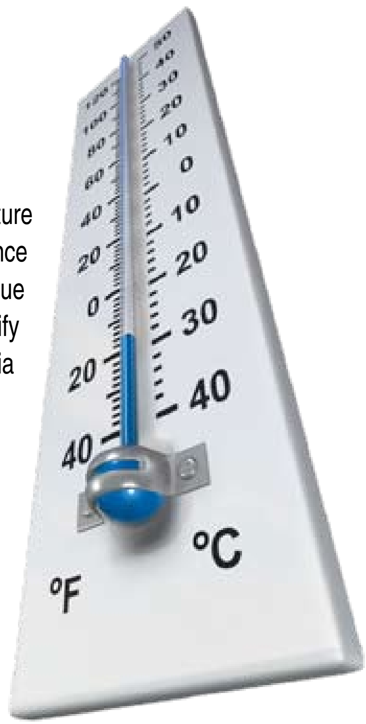
The main issue of this test is the evaluation of the general functional safety of the moisture measurement in dispersive materials such as ceramic suspension or water based paints. Even though the galvanic conductivity of such materials is relatively low, the absorption of the HF signal of a dielectric sensor is significant. One test can be performed with two differently moist suspensions (difference: 1 to 2%). The sensor should be able to register/measure a moisture difference of 1 to 2% . In the ideal case, even at different material temperatures.

6. Test in very wet materials

This test should be conducted with a very wet material such as water based paint. Water based paints have water contents in ranges of 40% to 50%. By dilution with water it is possible to achieve water contents up to 90%. The verification and calibration of the various tested materials can be made with commercial moisture analyzers based on drying method.

7. Test of the Temperature Stability of the Sensor Electronics

This test should be conducted with a dry media in order to exclude a change of the moisture during the temperature test. For the testing of the material moisture sensor, dry glass beads (with a diameter of 0.5mm) are for instance suited, whereby the sensors, depending on the calibration curve, should indicate a constant moisture value of <5% (but not zero % !). The whole arrangement is exposed to changing temperatures in order to verify the temperature sequence of the sensor electronics. The generation of condensation in the measured media should hereby be excluded!



Concluding Remark

The general requirements made to dielectric material moisture measurement sensors are very demanding. In times where quality and reliability assume a consistently more important role, new measuring technologies, such as the TDR method represent a contribution to generate more customer satisfaction. Users should however be aware of the respective limitations of the individual methods. The tests depicted in this abstract can be useful to users of material moisture sensors for the evaluation of the quality of a sensor in order to be able to recognise possible faulty measurements and disappointments in the forefront.

PRECISE MOISTURE MEASUREMENT

SONO Moisture Sensors for industrial Deployment

The sensors‘ decisive lead is generated by the deployment of state-of-the-art TRIME®-Radartechnology

www.imko.de

IMKO GmbH ■ Im Stöck 2 ■ Germany-76275 Ettlingen ■ Phone +49-(0)72 43-59 210 ■ Fax +49-(0)72 43-59 21 40 ■ e-mail INFO@IMKO.de ■ www.IMKO.de