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Moisture Measurements with RFID based Sensors in Screed and Concrete

Christoph STRANGFELD, Sergej JOHANN, Maximilian MÜLLER, Matthias BARTHOLMAI

Bundesanstalt für Materialforschung und -prüfung,
Unter den Eichen 87, 12205 Berlin, Germany,
christoph.strangfeld@bam.de, sabine.kruschwitz@bam.de

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Abstract

To quantify the moisture in concrete, RFID based humidity sensors are embedded. Passive high frequency, ultra-high frequency RFID tags as well as active Bluetooth sensors are tested. After concreting, all sensors measure the corresponding relative humidity to monitor the concrete moisture. Two case studies are performed, embedding in an existing construction, i.e. the duraBASt test bridge, and embedding in cement based mortar in the laboratory. As basis for robust and long-life sensors in alkaline concrete, different casing materials are tested. Furthermore, signal strength measurements and their sensitivity to different moisture levels are performed.

1 INTRODUCTION

A safe and reliable infrastructure is the fundamental base for social coexistence and economical growth in our modern society. Aging and degradation processes of steel reinforced concrete structures require periodic maintenance and servicing activities. The yearly costs cumulate to ca. 13 billion Euro in Germany. Furthermore, 2/3 of all degradations are caused by chloride induced corrosion [1]. However, the current activities of ca. 10 billion Euro per year are not sufficient to cover the maintenance and service costs. Hence, the net invested capital of our infrastructure is decreasing in Germany since 2002 [7]. Similar problems are also known in other countries in Europe and North America. In short, we live on the substance of our infrastructure.

To overcome the negligence of our infrastructure from the past, more intensive and efficient repairing is required. Thereby, it has to emphasise that the basis of any repair activity is a detailed damage diagnose and assessment. Nevertheless, it is difficult to obtain the required information for distinct damage mechanism, especially if these damages start inside the concrete structure. For example, chloride induced corrosion occurs at the rebars in steel reinforced concrete. The initiation of this process cannot be detected by traditional visual inspections [3]. In general, the opposite is the case. The degeneration acts over years or even decades until obvious damages on the surface are noticed, i. e. cracks, rust stains, delamination of the concrete cover, etc. At this point, massive damage is already present and the repairing work is expensive. Early detection of the onset of corrosion reduces costs, ensures building security, and may increase the lifetime of the construction [2]. Thus, a proper monitoring of crucial infrastructure like bridges, pavement, foundations will reduce the overall costs of our infrastructure significantly.

Additional to visual inspections, sensors are able to acquire further information. Foundations, bridge bearings, the bottom side of bridge decks, etc., all these are locations hard to access. Appropriate sensors measure several quantities which give a deep insight into the structural condition. Hence, the Bundesanstalt für Materialforschung und -prüfung (BAM, Federal Institute for Materials Research and Testing) develops sensors which support bridge inspectors and bridge engineers. In the current study, the focus is on corrosion detection at an early stage. In particular, two quantities (among others) are the basic requirements for active chloride induced corrosion [8]. On the one hand, the presence of moisture is important. A minimum moisture level is required to couple anode and cathode of this electrolytic system. On the other hand, the oxidation of iron ions provokes a shift of the electrochemical potential at the rebars. Hence, moisture and corrosion sensors are developed and installed in field test at the duraBASt bridge as well as in test specimens in laboratory.

The wireless sensors are based on radio frequency identification (RFID) and are embedded completely in concrete. High frequency (HF) and ultra-high frequency (UHF) RFID are able to establish energy supply and communication wirelessly. Thus, the systems are of large interest for non-destructive testing (NDT) in civil engineering. The RFID based sensors are passive and robust, they are able to record data for several decades and detect corrosion at its initial state. Thus, the concrete cover is intact without any opening. Non-destructive evaluation of the building condition based on the accumulated RFID sensor data enables a robust and reliable way of monitoring the constructions and further contributes to an efficient maintenance of our infrastructure.

2 RFID BASED HUMIDITY SENSORS EMBEDDED IN THE duraBASt TEST BRIDGE AND IN CEMENT MORTAR SAMPLES

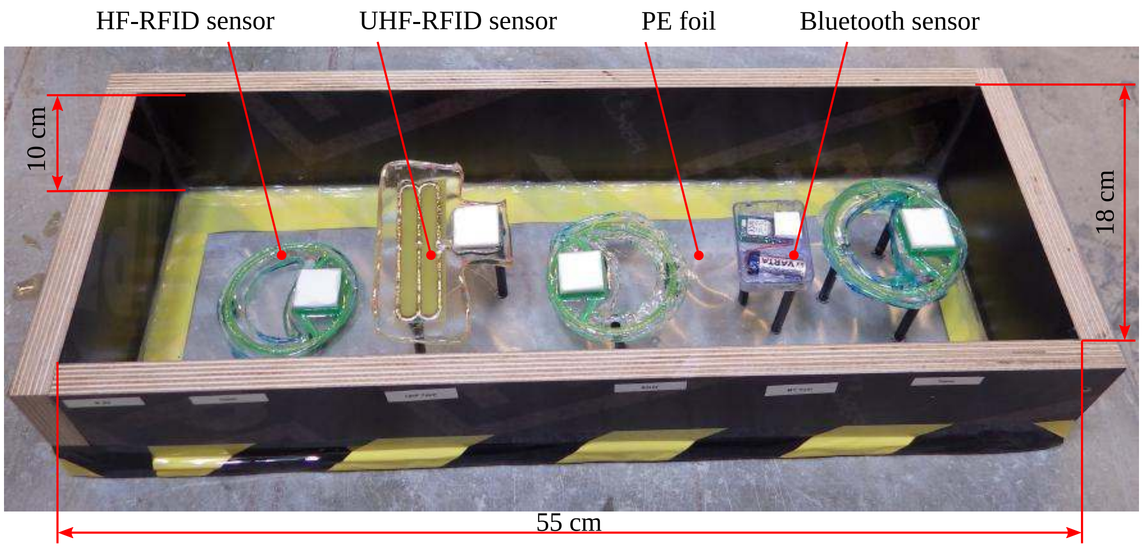

Figure 1: Empty mortar sample with the positioned embedded sensors at different depths

Figure 1 depicts a sample before concreting. Each sample is 55 cm long, 18 cm wide, and 10 cm high. In the shown setup, three HF RFID are positioned. The sensor on the left hand side is 1 cm, the one in the middle is 4 cm, and the sensor on the right hand side is 7 cm above the bottom. The bottom itself is a 1 mm thick polyethylene foil which is stapled directly on the casing. The green ring represents the casing for the RFID antenna with a diameter of 72 mm. The antenna provides the required supply voltage of 3 V for the sensor. The HIH-5030 sensor has a surface mounted device (SMD) layout and measures the relative humidity. To protect the sensor membrane against the cement paste, it is encapsulated by a filter membrane. This membrane is a standard VitraPOR filter provided by the company ROBU Glasfilter Geräte GmbH. It is made of sintered Borosilicate glass 3.3 with approx. 80% quartz glass. The claimed mean pore diameter is between 10 and 16 μm. It fulfils the requirements of alkali resistance of class ISO 695-A2 [5]. Tests with very wet cement paste show that water is able to run through the filter whereas the other small parts are blocked by the filter. This ensures that the filter does not disturb the humidity measurement and protects the sensor against debris or contamination. In the current setup, all parts are covered by epoxy resin. The HF antennas are designed as a coil as the energy supply is achieved via electrical induction.

	CEM I 52.5R	CEM I 42.5 R	CEM III/A 32.5N	CEM I 52.5R
w/c	0.5	0.5	0.5	0.4
density in kg/cm^3	2151	2138	2186	2237
flow spread in mm	156/159	168/169	170/171	152/158
air content in V%	6.4	6.0	5.8	4.7

Table 1: Properties of the used cements

Furthermore, one UFH RFID is installed 7 cm above the bottom. The board and the humidity sensors are covered by the quartz glass filter again. The antenna design is different. In this case, the energy supply is achieved by generating an electrical dipole. The sensor and the antenna are covered by transparent epoxy resin as well. As a third sensor, an active Bluetooth sensor is embedded as well. The connected battery delivers the required energy for the sensor. The battery as power source is embedded as well. The battery capacity is sufficient to run the sensor system for at least one year. At the moment, four samples are concreted including embedded HF and UHF RFID sensors.

Table 1 represents the four different cement mortars which are investigated [6, 4]. The first three mixtures possess a water/cement mass-ratio (w/c) of 0.5. The last mortar is identical to the first one except a lower w/c ratio of 0.4. To achieve a similar viscosity of the mixed mortars, MasterGlenium SKY 591 from "BASF" is used as a liquifier. In total, 300 g, which corresponds to 3 M% of the used cement (10 kg), are added to the mixture to attain a similar spread rate compared to w/c=0.5. This may lead to similar pore structures and sizes of the resulting mortars although the w/c values vary. 30 M% of the aggregates posses a diameter between 0.1 and 0.5 mm, 40 M% have a diameter between 0.5 and 1 mm, and the last remaining 30% have a diameter between 1 and 2 mm. After concreting, all samples are shaken via a concrete vibrator for 15 s.

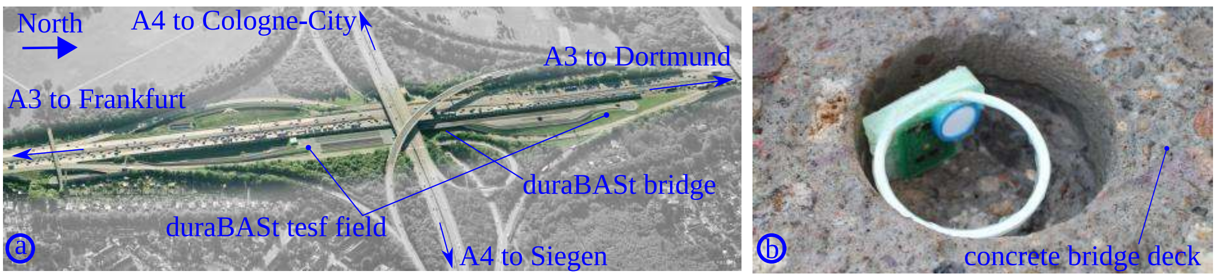

Figure 2: a) Depiction of the planned duraBASt test field including the duraBASt test bridge at the highway intersection "Köln-Ost"; b) Photograph of one RFID based humidity sensor before concreting in the duraBASt test bridge

Beside the presented mortar samples in the laboratory, RFID based sensors are also embedded in the duraBASt test bridge. This bridge is planned and operated by the department bridge and civil engineering of the Bundesanstalt für Straßenwesen (BASt, Federal Highway Research Institute). The duraBASt area at the highway intersection Köln-Ost is a large test field for road testing. It includes the duraBASt test bridge which is ca. 66 m long and 14.25 m wide. This bridge is part of the "road in the 21st century" project and is equipped with several sensors for structural health monitoring. This feasibility study is realised to construct intelligent bridges in the future. Quantities like temperature, strain, moisture, corrosion, etc. are measured by embedded sensors [9].

Figure 2a) illustrates the planned test field at the highway intersection of the A3 and A4. The duraBASt test bridge itself is located parallel to the A3 to Dortmund. Large pavement test tracks are connected to the bridge on both sides. This allows pavement tests under realistic environment conditions. Additionally, roll over tests with the load generator MLS10 are possible [12]. Load cycles up to several millions are realised in a short period of time. However, at the moment, the entire area is under construction. The asphalt pavement is removed and the concrete structure is accessible. Holes with a diameter of 120 mm are drilled for the RFID based sensors. Figure 2b) depicts a RFID before concreting into the bridge. In this case study, an older RFID sensor design is used. The board is much larger. Hence, the board and the sensor are oriented perpendicular to the antenna to avoid the artificial generation of a diffusion barrier.

3 DESIGN OF THE SENSOR CASING

material	mass variation after 1 day in %	mass variation after 14 day in%
PLA	-11.9	dissolved
epoxy resin	-0.08	+1.79
PVC	0	0.009
quartz glass filter	+0.9	-2.65

Table 2: Mass variation of the tested casing materials after one and 14 days in an one molar NaOH solution with a mean pH-value of 13.03

In general, constructions made of reinforced concrete have an experted lifespan between 50 and 80 years or even more. Most damages and degenerations occur during the last third of the lifespan. Hence, embedded sensors have to measure reliably for several decades. Therefore, the electronics, the sensors itself, the antenna have to be covered by a robust casing. The high pH-value of around 12 to 14 in concrete represents an aggressive environment for the sensor materials. Thus, all materials are tested preliminary in a NaOH solution (pH-value of 13.03) for 14 days. As depicted in table 2, the polylactic (PLA) already loses 11.9% of its initial weight after one day. After 14 days, it is completely dissolved. Hence, PLA is unsuitable for application in concrete. The epoxy resin remains stable after one day and reveals a mass increase of 1.79% after 14 days. This suggests a swelling of the material. This undesirable behaviour indicates a diffusion of the NaOH solution into the epoxy resin. After a long time, the diffusion process may reach the antenna or the electrical board and destroys the RIFD-based sensor. Therefore, epoxy resin seems to be suitable for tests with a duration of few months. Another tested material is polyvinyl chloride (PVC). Although PVC is not a pure hydrocarbon chain, it is often used in chemical facilities and as waste water pipes. Thus, in practice, PVC withstands aggressive and alkaline environments. Furthermore, PVC parts are easy to glue together in contrast to pure hydrocarbon materials like polyethylene. However, the tests reveal that PVC remains unaffected by the alkaline environment. Thus, PVC is ideally suited for embedding in concrete over decades.

After a mass increase of 0.9% after one day, the used quartz glass filter shows a small mass deficit of 2.65% after 14 days. An optical inspection indicates the onset of surface degradation. It remains unclear whether this behaviour is an interaction with the dissolved PLA. Based on this ambiguous result, further tests are performed with the quartz glass filter.

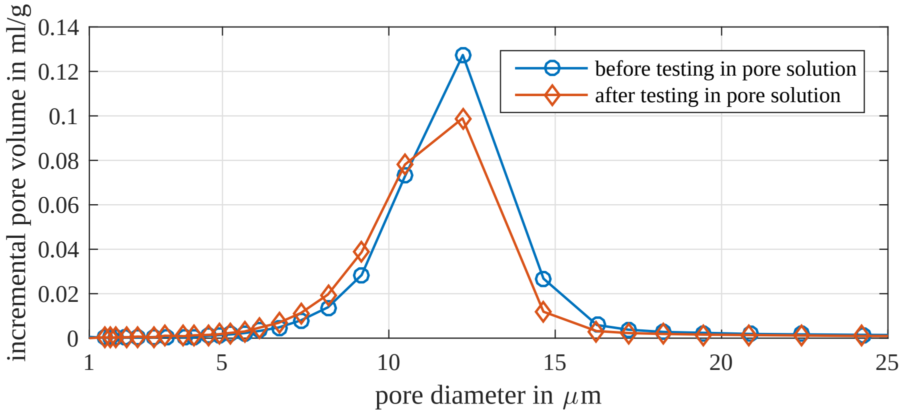

Figure 3: Pore diameter of the quartz glass filter before and after testing in concrete's pore solution for 14 days based on mercuy intrusion porosimetry

During the second test of the quartz glass filter, concrete's pore solution is used instead of pure NaOH solution. The pore solution is more realistic considering the conditions in concrete. Furthermore, no other material is placed in the solution to avoid undesired interaction. The initial pH value of the pore solution is 12.4 and reduces to 9.2 after 14 days. It is assumed that the concrete's pore solution interacts with the CO_2 from the ambient air. However, four filters are tested and they show a mass difference of 0.17% in maximum after 14 days. This slight decay is within the measurement accuracy of the balance. Hence, no significant mass reduction is observed. Based on these results in the pore solution, the filters are robust enough to withstand the aggressive environment of concrete. Furthermore, the pore size of the filter is checked before and after the tests in the pore solution by means of mercury intrusion porosimetry. One new filter is separated into two individual parts. As shown in figure 3, the modal value of the new filter part (blue line) is around 12 μm. After 14 days in the pore solution, the other filter part is tested as well. The modal value remains constant at 12 μm. The variations in amplitude are in the range of the measurement accuracy and the variation of the pores of the two filter parts. However, the porosimetry yields a constant modal pore size, hence the pore structure remains unaffected by the pore solution.

4 DATA ACQUISITION

Each mortar sample is weighted before measuring the humidity of the embedded sensors and the signal strength. A high precision balance with a maximum load of 72 kg and an accuracy of 0.1 g is used as reference measurement system. All screed samples are weighed at each measurement day. Thereby, the empty weight of the casing and the embedded sensors are subtracted. These gravimetric measurements give a precise and reliable reference of the averaged water content of each sample.

Figure 4 shows a photograph of the measurement setup to determine the signal strength. The used scemtec SAT-A4-LR-P transmitter reads out the embedded HF sensors with a design frequency of 13.56 MHz. The transmitter is positioned directly on the surface of the cement mortar sample. The wooden made template encompasses the mortar sample and enables a reliable and aligned transmitter positioning. The estimated positioning variance is approx. ± 1 mm. In preliminary tests, the position with the lowest transmit power is evaluated experimentally with a hole spacing of 1 cm. The Voyantic Tagformance reveals the RFID tag performance by measuring the transmit power and the magnetic field strength. The frequency band is set to 13 to 14 MHz with a step width of 0.01 MHz. The transmit power steps are 0.25 dBm in the range of -7 to 29 dBm.

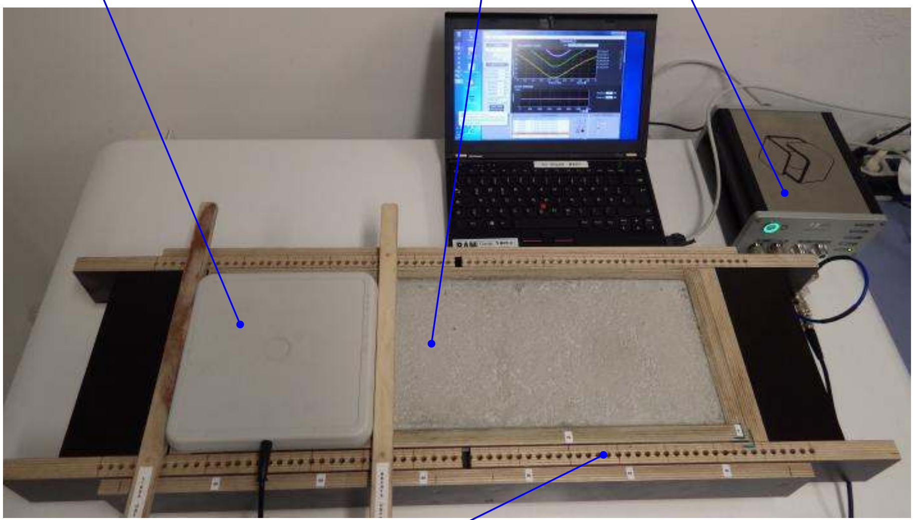

Figure 4: Cement mortar sample encompassed by the wooden made template for positioning the HF transmitter; the Voyantic Tagformance evaluates the tag performance between 13 and 14 MHz and -7 to 29 dBm transmit power

5 MOISTURE AND SIGNAL STRENGTH MEASUREMENTS

5.1 Moisture measurements

The RFID based humidity sensors are embedded in the duraBASt test bridge on the 18th of December in 2015. The last measurements are recorded on the 25th of April in 2016. All the time, all humidity sensors remain in saturation. The humidity sensors are positioned as close as possible to the surface. Thus, rain and snow during the winter time penetrate the concrete cover for months. Therefore, it is expected that free liquid water still remains in the pores of the concrete, which leads to saturation. These days, a new moisture barrier is layed on top of the steel reinforced concrete structure. Later on, an additional asphalt layer will be installed and no more water will affect the concrete. Thus, the relative humidity in the concrete should tend towards the corresponding equilibrium humidity of around 50%.

Figure 5 depicts the evolution of the weights of the four mortar samples. The CEM I 52.5R with the lower w/c-ratio of 0.4 possesses the highest total weight. This is consistent with the density measurement shown in table 1. However, the sample weights are decreasing due to vaporisation on the surface. The samples already lose between 70 and 120 g water and an equilibrium is not reached yet. Hence, hydration and vaporisation are still in process. This is confirmed by the embedded sensors as well. All RFID based humidity sensors remain in saturation and reveal a relative humidity of 100%. Thus, 36 days after concreting, free liquid water still exists in the cement mortars. It will take months more until the equilibrium moisture content is reached. At this point, all humidity sensors reveal the same humidity as the ambient relative humidity of the climatic chamber of 50% rH [11].

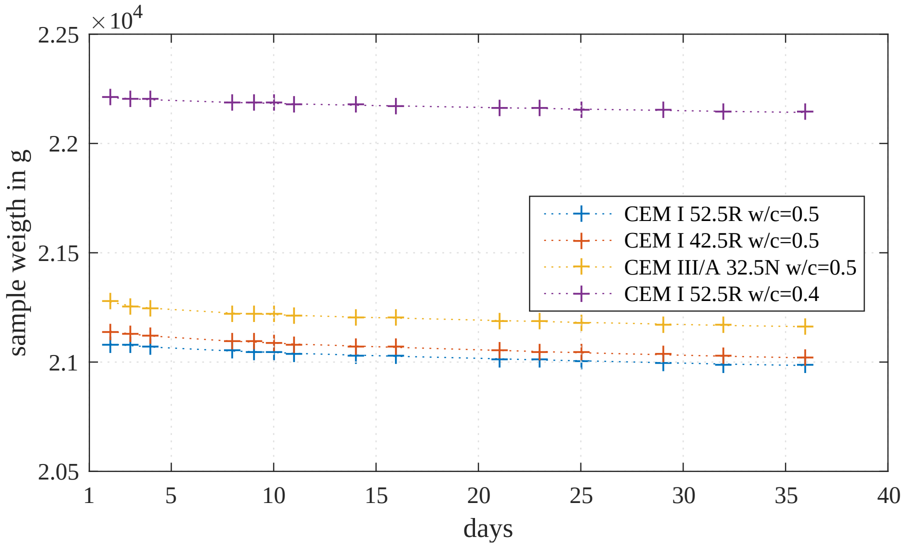

Figure 5: Weight of the four cement mortar samples over time

5.2 Signal strength measurements

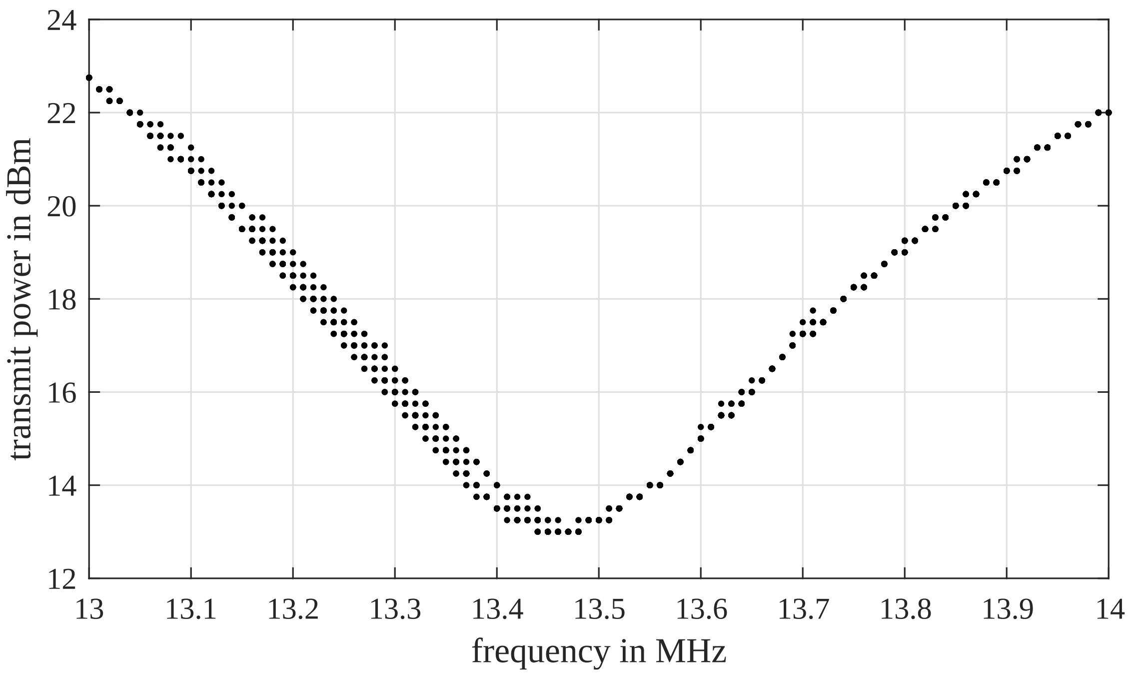

Figure 6: Measured transmit power of 16 repetitions on measurement day 23

First of all, the repeatability of the system is determined. For this purpose, the signal strength measurements are conducted as shown in figure 4. This measurement is repeated 17 times in the exact same configuration for one HF RFID tag in the CEM I 52.R w/z=0.5 sample at a depth of approx. 3 cm. The HF transmitter and the mortar sample remain at their position during this time. The measured maximum standard deviation is std_{max} =0.1406 at a frequency of 13.06 MHz. Variations may be caused by electromagnetic noise and the Voyantic Tagformance data acquisition system itself. However, std_{max} =0.1406 is considered to be the over all measurement uncertainty of the data acquisition. Furthermore, the standard deviation is independent of the frequency and randomly distributed. A second source of uncertainty is the positioning of the transmitter relative to the RFID tag. Furthermore, the position of the mortar sample itself on the desk may also have an influence due to an interaction with other external electromagnetic fields. However, figure 6 shows the measured transmit power of one HF RFID tag in the CEM I 52.R w/z=0.4 sample at a depth of approx. 3 cm. After each measurement, the transmitter, the wooden made template, and the mortar sample itself are removed and re-installed on the desk. This reproduces the measurement uncertainty of the positioning deviations. In total, 16 individual measurements are performed and the maximum standard deviation is std_{max} =0.272 at a frequency of 13.29 MHz. Based on these measurements, the optimal transmitter frequency for this tag and its environment is 13.47 MHz. As demonstrated in figure 6, frequencies below the optimal frequency are more sensitive to positioning deviations. Otherwise, frequencies above the optimal frequency are almost insensitive to positioning deviations. The standard deviation is in the order of the data acquisition uncertainty.

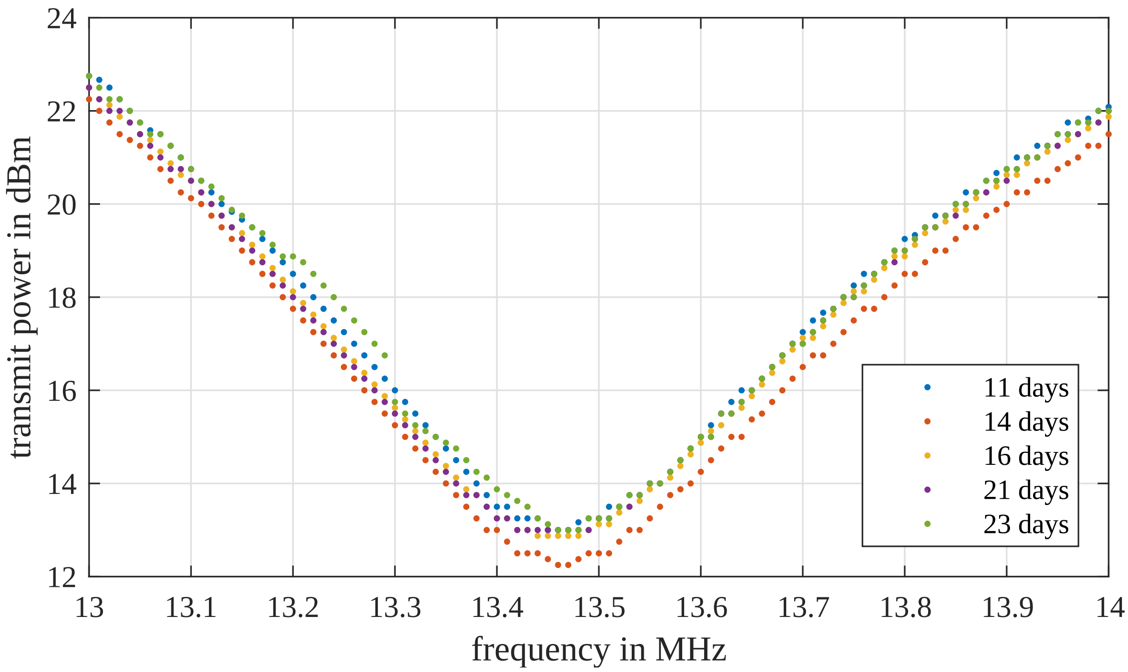

Figure 7: Measured transmit power of one RFID based humidity sensor

After quantifying the measurement uncertainty, the influence of the moisture content on the signal strength is of interest. In general, the dielectric loss factor of UHF is higher compared to HF due to the low transmission frequencies. Nevertheless, only HF measurements are presented in the following. Figure 7 illustrates the singal strength measurements on different days. Measurements are recorded between the 11th and the 23th day after concreting. In general, lower moisture contents lead to lower damping of the electromagnetic waves in the cement mortar. Based on these physics, the transmit power may decrease in time. In the presented setup, the lowest transmit power is observed after 14 days. The other 4 measurements are almost at the same power level. Thus, no significant trend is detectable and the HF signal strength seems to be independent of the moisture. On the one hand, the observation time in this case study with 12 days is limited and the moisture variations of the cement based mortar samples are small. On the other hand, these results confirm the statement that HF signal strength is almost insensitive to moisture variation due to the low dielectric loss factor.

Except the measurement after 14 days, the noise characteristic is similar to figure 6. Above the optimal frequency of around 13.47 MHz, the signal strength variations are in the range of that of the data acquisition systems. Below 13.47 MHz, the deviations between the measurement become larger probably due to positioning variations. The maximum standard deviation of std_{max} =0.4873 is reached at around 13.26 MHz.

In the future, similar investigations are planned also with UHF RFID tags and Bluetooth devices. The dielectric loss factor is remarkably higher for these frequencies and a higher sensitivity to moisture changes is expected. Furthermore, calcium sulphate based screed is applied instead of cement based mortar. This may increase the hydration and vaporisation process and larger moisture variations are expected. Especially the equilibrium moisture content with a humidity similar to the ambient relative air humidity is reached much earlier [10, 11].

6 CONCLUSION

Embedded RFID based sensors are able to yield valuable additional information in structural health monitoring. The humidity sensors are embedded in the duraBASt test bridge and in cement mortar samples in the laboratory. In all settings, the RFID based sensors show a robust behaviour and provide reliable measurements. Hence, embedded sensors are able to enhance the standard visual bridge inspection.

The two presented test cases, the duraBASt test bridge and the cement mortar samples, demonstrate the applicability of embedded sensors in new as well as in existing buildings and constructions. The detailed tests of the casing materials ensure robust and long-life sensors embedded in highly alkaline concrete. The measurement principle to measure the corresponding relative humidity of the concrete reveals promising results especially at low moisture levels.

Based on the shown results, the signal strength of the HF RFID tags seems to be independent of moisture of the surrounding cement mortar. Additional tests with different materials and longer observation time will be performed in the future to further confirm these results.

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