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Scientific paper

Hygrometric Assessment of Internal Relative Humidity in Concrete: Practical Application Issues

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Abstract

The use of embedded relative humidity (RH) sensors for assessing the internal humidity in concrete is widely spread, dully backed by existing standards. Even though the approaches adopted in the literature seem to have several differences between each other, few or none research works were found to focus on the comparison of performance of sensors and methods for RH measurement. In view of this, several sets of experiments comparing the performances of different sensors and monitoring procedures will be presented in this paper, discussing the main findings and providing recommendations for the strategies to be adopted in what concerns the measurement technique. The main points addressed in this work are: (i) comparisons between readily available systems for RH measurement in concrete, as well as custom measurement strategies reported in the literature; (ii) issues related to calibration procedures and re-calibration necessity; (iii) relevance of the existence of an interface porous material between the embedded sensor and the measurement spot in concrete; (iv) importance of the size of the embedment body into which the RH sensor is inserted; (v) equivalence of results obtained when the probe is constantly inserted into the embedment body, or placed inside it at discrete instants.

1. Introduction

An adequate knowledge of the internal moisture state of concrete elements is of relevant importance in several concerns. One of them is the execution of concrete floors onto which finishes are to be applied. At the age of application of the layer of finishing material, which hinders moisture movements in concrete, the internal humidity of the concrete must be under threshold levels to avoid subsequent damages to the system (Åhs 2007).

The moisture present within concrete strongly influences its properties at early ages, as well as its long-

term behaviour (Kim and Lee 1999; Zhang *et al.* 2011; Norris *et al.* 2008). A typical example is the occurrence of shrinkage and the consequent cracks that it can form. Concrete shrinks as the internal humidity decreases, either by exchange with the environment (evaporation) or by self-desiccation (hydration of cement particles). Shrinkage amplitude is normally proportional to the amount of moisture lost from the cementitious matrix (Bissonnette *et al.* 1999). In the particular case of drying shrinkage concrete strains are known to be non-uniform, with the tendency to occur faster at the surface than within core regions (Ayano and Wittmann 2002). Even without external restrains to deformation (e.g. stiff adjacent members/supports), the concrete core ends up restraining the free deformation of the surface regions, inducing here stresses that frequently reach the tensile strength, and thus induce cracking. These complex distributions of shrinkage-induced concrete strains and stresses, as well as the formation of cracks, are often difficult to predict or characterize without the application of hygro-mechanical simulations (Azenha *et al.* 2007b).

Recognizing the importance of assessing the internal distribution of moisture in concrete, the capacity of measuring moisture-related parameters within this material has been sought by the practising and research communities for several decades (Parrott 1990; Roels *et al.* 2004; Grasley 2002; Craig and Donnelly 2006). One of the possibilities of measuring internal humidity within cement-based materials is based on the production of specimens (or cores taken from the concrete element in concern) subjected to uniaxial drying. Then, at a selected ages, the specimens are sliced at predefined depths from the drying surface. Upon oven-drying of

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the obtained separate samples, their internal free water can be determined through the corresponding weight variations (Akita *et al.* 1997), thus allowing to profile the water content. Even though this is a rather direct method, it is also totally destructive, the sample preparation has a relevant workload and the final measured values are often affected by imprecisions related to the slicing process. Alternatively, several non-destructive methods exist, such as the use of Gamma rays (da Rocha *et al.* 2001), X-rays (Hansen *et al.* 1999), micro-waves (Al-Mattarneh *et al.* 2001), nuclear physics methods (de Beer *et al.* 2004) or electrical methods (Berg *et al.* 1992). Most of these techniques combine one or more of the following inconveniences, which end up hindering their practical application: (i) they are expensive or (ii) not feasible to use in-situ, or (iii) they record indirect values that cannot provide absolute indication about the actual internal moisture content (or humidity), supplying instead relative variations only (Parrott 1990).

A relatively cheap and straightforward alternative for in-situ assessment of internal moisture state of concrete relies on the measurement of internal RH. It is nonetheless worth remarking that this approach is an abstraction, in the sense that the humidity in a given pore is intrinsically related to its diameter. Therefore, in the same cementitious matrix the smaller diameter pores may be totally saturated, whereas larger pores at the same location may be unsaturated. The internal RH of a material can therefore be defined as the relative humidity of the gaseous phase in equilibrium with the interstitial liquid phase in the pore network, for a given temperature (Baroghel-Bouny *et al.* 1999).

Concrete RH has been assessed either by collecting samples of concrete powder of the matrix at predefined depths, or through the use of embedded RH sensors. In the case of powder collection, the sample is immediately placed inside a container (e.g. a test tube) and totally sealed, while measuring the resulting equilibrium RH in such container, which should match the humidity of the cementitious matrix (Nilsson and Åhs 2010; Nilsson 1980). A more practical and generally applied approach that allows continuous measurement of internal RH at the same location, consists in embedding RH sensors in concrete. The embedment is made through the introduction of the sensor into a previously created air void inside the specimen to be tested (usually materialized through a sleeve). The utilization of embedded RH sensors is devised in regulations (ASTM 2011), and its application is quite generalized, particularly in pavement construction (Craig and Donnelly 2006; Åhs 2007). The study of internal RH distribution with embedded sensors has both been studied with custom systems (Lee *et al.* 2011; Grasley *et al.* 2006b; Zhang *et al.* 2009; Chang and Hung 2012; Zhang *et al.* 2012b; Zhou *et al.* 2011; Rodden 2006; Zhou *et al.* 2010; Ekaputri *et al.* 2010), as well as with commercially available systems (Vaisala, 1999, Proceq, 2012, Wagner Meters,

2012, GE, 2005, Tesco AG, 2006). In all the mentioned applications of RH sensors to measure internal humidity of concrete, a significant variability exists in terms of assemblies and methods, namely in what concerns to: the size of the internal macro-pore into which the sensor is embedded; the type of RH sensor; the technique adopted to materialize the macro-pore; the existence of interface materials between concrete and the macro-pore (e.g. Gore-Tex®); or even the procedure of measurement (e.g. permanently inserted RH sensor, or sensor inserted at discrete instants). In the literature review conducted for this paper, just a single reference was found tackling with some of the above issues (Nilsson and Åhs 2010), leaving however several questions unanswered.

Bearing in mind the knowledge gap that has just been identified, this work aims to contribute to better understand the influence of considering different RH monitoring strategies for cement-based materials on the quality and robustness of the obtained results. Apart from the present introduction, the paper discusses a set of tested systems (including readily available apparatus and custom devised ones) in Section 2. Then, Section 3 deals with relevant calibration issues through the use of salt solutions, as well as the relative performance of the tested humidity sensors in measuring environmental RH. Afterwards, a set of experiments targeted to specific strategies in measuring RH in concrete is presented in Section 4, which is followed by the presentation of the main conclusions.

2. Tested concrete RH measurement systems and sensors

2.1 General remarks

All studies found in literature regarding measurements of the internal RH of concrete with non-destructive methods involve the assessment of the RH of the air contained in a given material macro-pore, using relative humidity sensors (Andrade *et al.* 1999; El-Dieb 2007; Jiang *et al.* 2006; Kim and Lee 1999; Grasley 2002; Lee *et al.* 2011; Ryu *et al.* 2011; Ekaputri *et al.* 2010; Grasley *et al.* 2006b; Zhang *et al.* 2009; Chang and Hung 2012; Zhang *et al.* 2012b; Nilsson and Åhs 2010). The following Sections provide a brief description of the measurement systems used in the scope of this research work. The description will be divided in two main categories: integrated commercial systems available on the market (Section 2.2) and custom systems based on the use of moisture sensors introduced in macro-pores (Section 2.3).

2.2 Integrated commercial systems: Vaisala and Proceq

The existence of readily available commercial systems for measurement of internal RH in concrete is strictly related to the important role of humidity in the support to decision making in pavement construction, namely in

the application of waterproofing layers (ASTM 2011). In fact, there are already several commercial systems available in the market that are used to measure the material internal RH (Vaisala 1999; Proceq 2012; Wagner Meters 2012; GE 2005; Tesco AG 2006). In the context of this work, the measurement systems from Vaisala HM44 (Vaisala 1999) – here termed as VS – and from Proceq Hygropin (Proceq 2012) – here termed as PR – were used. Both systems are based on measurements taken at localized holes in concrete, materialized with hollow plastic sleeves, which may be embedded prior to casting or inserted after drilling of hardened concrete. According to the scheme shown in **Fig. 1a**, the bottom extremity of the sleeve is open and in direct contact with concrete, whereas the opposite extremity is closed by a plastic cap. This creates an internal macro-pore with the diameter/length of the sleeve, intended to be in hygrothermal equilibrium with its extremity in contact with concrete. Whenever the internal moisture needs to be assessed, the RH of the macro-pore is measured through the following procedure: (i) the top sealing cap is opened for the shortest period of time as possible; (ii) the humidity sensor is introduced in the plastic sleeve, thus occupying most of its space; (iii) the macro-pore is sealed again at its top extremity around the wire of the RH sensor (special rubber caps that allow passage of the wire) – see **Fig. 1b**. The sensor is then left undisturbed until stabilization of its RH readings. After collecting the necessary data (RH of the macro-pore and temperature measurement), the sensor is removed and the macro-pore is sealed over again until the next measurement. Both integrated systems used consist of capacitive humidity sensors with claimed accuracies of $\pm 2.0\%$ for VS and $\pm 1.5\%$ for PR. These systems also differ in terms of the diameters used for the plastic sleeves: 16mm for VS and 6mm for PR. The use of these integrated systems in scientific context, with the aim of monitoring RH profiles in concrete specimens, has al-

ready been reported by several authors (Kim and Lee 1999; Andrade *et al.* 1999; Zhang *et al.* 2012a).

2.3 Systems based in relative humidity sensors: Sensirion and Honeywell

In the context of research works related to the monitoring of moisture inside the concrete, several custom experimental systems have been suggested, which are very similar to the aforementioned integrated ones, insofar as in all cases the measurements are conducted with the use of sensors in a macro-pore created specifically for this purpose (Lee *et al.* 2011; Grasley *et al.* 2006b; Zhang *et al.* 2009; Chang and Hung 2012; Zhang *et al.* 2012b; Zhou *et al.* 2011; Rodden 2006; Zhou *et al.* 2010; Ekaputri *et al.* 2010). The main difference concerns to the fact that the humidity sensors remain within the macro-pore during the entire measurement period, thereby avoiding the recurrent need for sealing/unsealing the macro-pore, which might induce disturbances in the internal humidity field. Taking this into account, this methodology becomes potentially more reliable when compared to the use of integrated systems. In addition, humidity sensors can be more comfortable to work due to the possibility of using automatic acquisition systems, which allow autonomous and continuous recording of the RH.

The systems found in the literature for this type of test are relatively similar (Lee *et al.* 2011; Grasley *et al.* 2006b; Zhang *et al.* 2009; Chang and Hung 2012; Zhang *et al.* 2012b; Zhou *et al.* 2011; Rodden 2006), with pre-embedding of an impermeable hollow element in concrete during casting, filled with a material that prevents the concrete to access the hole or macro-pore. After concrete setting the filling material is removed, the humidity sensor (usually capacitive) is placed inside the hollow element, and the extremity that is opposite to the sensor placement is sealed (see **Fig. 2a**). In the works of Grasley *et al.* (2006b) and Rodden (2006) a

Fig. 1 Application of a commercial humidity measurement system: (a) sleeve sealed by plastic cap; (b) probe inserted into the sleeve during measurement (adapted from Vaisala 1999).

more comprehensive approach was reported, since the RH sensors were pre-placed and sealed within the hollow element (sleeve) before casting. For such purpose, the measurement system is protected from fresh concrete through the use of Gore-Tex[®] fabric (see Fig. 2b), which is impermeable to liquid water but permeable to vapour. Using this type of approach Grasley *et al.* (2006b) reported continuous measurements of RH since casting, and even managed to observe the progressive reductions in the internal moisture associated with concrete self-desiccation at early ages. More recently, an additional system has also been proposed by Chang and Hung (2012), which consists of encapsulating the humidity sensor in a cube composed of water vapour permeable walls (with similar properties to Gore-Tex[®]), enabling full embedment of the sensor, without need for extending the casing to the concrete element surface. The utilized sensors also support wireless technology, which simplifies *in situ* applications.

Within this study several experimental configurations were adopted for placing the sensors, as to be detailed in Section 4, aiming for example the assessment of possible influences caused by the use of Gore-Tex[®] protections on the RH measurements. In regard to the utilized humidity sensors, there are different types based on electrical properties, such as resistive and capacitive. However, only capacitive sensors were selected for this work, as they present the best features for measuring RH inside concrete specimens, since they are relatively inexpensive, accurate, easy to use, less sensitive to environmental effects, have an adequate range of measurement (usually able to measure RH from 0% to 100%) and have a shorter response time (Yamazoe and Shimizu

1986; Chen and Lu 2005; Kulwicki 1991). Furthermore, this type of sensor is the most commonly used (Rittersma 2002). More specifically, the following sensors were used for this particular study: Sensirion SHT75 (here termed as SHT) (Sensirion 2011) and Honeywell HIH4000 (here termed as HW) (Honeywell, 2010), whose external casings have reduced dimensions: $13.5 \times 3.7 \times 3.1 \text{ mm}^3$ and $4.17 \times 21.29 \times 2.03 \text{ mm}^3$, respectively. The essential difference between SHT and HW resides in the data transfer/acquisition strategies, which are rather distinct. SHT, which announces an accuracy of about $\pm 2\%$, incorporates an analogue-to-digital signal converter, requiring therefore a specially designed acquisition system that communicates directly with the sensor to gather the processed measurement. In turn, sensor HW, with an accuracy of about $\pm 3.5\%$, allows the direct reading of the analogue signal, which can thus be interrogated by any system that is capable of measuring a potential difference (e.g. a multimeter), and consequent transformation into RH according to a pre-defined calibrated law. Both sensors have specific calibration sheets provided by their manufacturers.

3. Use of salt solutions to ensure constant RH environments

3.1 General remarks

Undertaking experimental programmes that involve long-term drying of concrete specimens (e.g. shrinkage) demand for the availability of controlled environments in terms of temperature (T) and humidity. For such purpose, one of the most widespread strategies is the use of climatic chambers that simultaneously control T and RH,

Fig. 2 Customized systems for internal concrete RH measurement: (a) without interface material; (b) with Gore-Tex[®] in the interface between the macro-pore and the concrete.

which are expensive and thus limit the capability of performing multiple tests simultaneously. In fact, when the test specimens are small, the use of large and/or expensive laboratory equipment may not be feasible from an economic point of view. Furthermore, in many cases of drying studies, different controlled environments within the same experiment are required, in which T is constant but RH ranges from very low to very high values (e.g. from 11% to 100%). Therefore, small scale controlled RH chambers with solutions of sulphuric acid, calcium chloride, glycerol or saturated salt are commonly used (Wexler and Hasegawa 1954; Stokes and Robinson 1949; Young 1967; Greenspan 1977; Rockland 1960). In fact, as reported by several authors (Stokes and Robinson 1949; Greenspan 1977), two phase systems (liquid-vapour) of sulphuric acid and glycerol have a good capacity for generating and establishing a wide range of RH environments, with apparent independence in regard to ambient T . Nonetheless, the stability of the RH assured by these systems has been reported to be easily affected by the concentration of the solutions (Stokes and Robinson 1949; Greenspan 1977). Thus, the water released by a concrete specimen may easily influence the concentration of the solution, causing a change in the resulting environmental RH.

Salt solutions are generally more useful, since the three phase systems (solid-liquid-vapour) are less sensitive to disturbances caused by vapour releases into the controlled environment, as shown in the work of Stokes and Robinson (1949). Accordingly, for the present research work only salt solutions are used in detriment of the other reported possibilities, due to the expectable problems that might arise due to evaporation from cement-based specimens in the controlled environment.

3.2 Performance of the salt solutions

Salt solutions have been used to generate environments with controlled RH for several decades (Greenspan 1977). However, despite knowledge on the behaviour of saturated or unsaturated salt solutions is already well established, and several authors refer that they are very stable (Stokes and Robinson 1949; Wexler and Hasegawa 1954; Young, 1967; Rockland 1960; Robinson 1945; Lu and Chen 2007; Carotenuto and Dell'Isola 1996), no reference has been found in literature regarding the influence of water release (induced by drying of cementitious specimens) on the RH generated by these salt solutions.

Therefore, an experiment was performed to analyse the influence of the water released by a tested cementitious specimen on the RH of a container with a saturated salt solution for internal humidity control. The experiment consisted in monitoring the RH inside a container ($22.8 \times 13.2 \times 10.7 \text{ cm}^3$) with a given salt solution, whilst a disturbance was deliberately introduced. Such disruptive perturbation was either induced by introducing a cylindrical cup filled with water (W) (with a diameter of 4cm and a height of 5cm) or a cup of the same volume con-

Table 1 Tests carried out in containers with saturated salt solutions.

Container	W@75%	CP@75%	W@33%	CP@33%
Salt	NaCl	NaCl	MgCl ₂	MgCl ₂
Mass of salt (g)	53.33	53.33	53.33	53.33
Salt-to-water ratio (R)	2.0	2.0	10.0	10.0
Expected RH (%)	75.5	75.5	33.1	33.1
Material subjected to drying	Water	Cement paste	Water	Cement paste

Table 2 Salt-to-water ratio presented in literature (Carotenuto and Dell'Isola, 1996).

Salt	Salt-to-water ratio	
	Maximum	Minimum
MgCl ₂	10	2
NaCl	2.5	0.35

taining fresh cement paste (CP) (cement CEM I 42.5R and a $w/c = 0.5$) inside the container. Combination of two possible humidity control salts (NaCl and MgCl₂, to obtain target humidities of 75% and 33%, respectively) and the above referred two disruptive perturbations led to the four different tests presented in **Table 1** (W@75%, CP@75%, W@33% and CP@33%: target humidities of 75% and 33% disrupted by both the cups of water and cement paste). Before starting these tests, a preliminary trial-and-error study was conducted to optimize the minimum amount of salt solution required inside the container to target the intended RH. It was concluded that the use of 53.33g of salt was enough to reach the desired RH in the container. Regarding the salt-to-water ratio, a wide range of values was found in literature, as reported in **Table 2**. However, for this particular case the recommended values provided in the Vaisala Humidity Calibrator datasheet (Vaisala, 2006) were adopted, as presented in **Table 1**.

The test procedure initially consisted in placing the salt solution inside the container, and monitoring the internal RH with a SHT sensor (**Figs. 3a** and **3b**). After two days of stable readings matching the target RH of the salt solution, the disruptive cup (of water or cement paste) was introduced (**Fig. 3c** and **3d**), while keeping the internal humidity monitoring sensors (see **Table 1**). For control purposes, the weight loss of the disruptive cup was assessed at several instants, by removing it from the container during brief periods and weighing it.

Figures 4a and **4b** reproduce the RH evolutions inside the containers with saturated salt solutions, as well as the cups' weight losses throughout the experiment. It is worth remarking that each specimen has two plots of results, in correspondence to the repetition of the whole experimental programme, which has shown very similar results, thus proving a good repeatability.

As it can be observed in **Fig. 4a**, in containers with sodium chloride (W@75% and CP@75%) the RH did not endure any relevant change during the first 7 days subsequent to introduction of the cup. However, from 7

Fig. 3 Performance of the salt solutions: (a) container, placement of the salt solution and RH sensor; (b) period of RH stabilization; (c) cup dimensions; (d) final test scheme [dimensions in cm].

Fig. 4 Results with the disruptive perturbations: (a) RH evolutions inside the containers; (b) weight losses of the cups with water and cement paste. (time=0 d corresponds to the instant at which the disruptive perturbation is introduced).

days onwards the container into which a water cup was placed (W@75%) started to deviate from the stable humidity of 75% (point 1 in **Fig. 4a**), and increased progressively at a rate of approximately 0.3% per day until 21 days.

If at any stage of testing, the air RH in the container is coincident with that of the beginning of the experiment, R can be estimated with basis on the assumption that all the water lost from the disruptive element (measured by successively weighting the cups) is captured by the salt solution. Based on such procedure, it is possible to infer that R had a decrease from 2.0 at the beginning of the test to $R = 1.47$ at the age of 21 days. This increase of salt dissolution induced an efficiency loss of the three phase (solid-liquid-vapour) saline solution, which led to a progressive increase of the air RH inside the container. Disruption changes due to the water or to the cement paste cups can be compared in **Fig. 4b**: the cement paste ceases losing weight after the age of 3-4 days (due to a diffusion controlled evaporation, as identified in Azenha *et al.* (2007a, 2007b), whereas in the water cup a constant rate of evaporation is observable for significant later ages.

In the containers with magnesium chloride solutions (W@33% and CP@33%) an even more significant disturbance was found. Since the instant at which the disruptive cup was placed inside the container, a sudden RH shift from 33% to 40% was observed when a water cup was introduced. This RH increase is related to the balance between the rates of release of water into the air inside the container, and the water consumed by the salt. Nevertheless, although the RH was slightly higher than expected, it remained almost constant during the first days of the test. Such situation of apparent equilibrium was clearly lost at the 11th day of testing (indicated by point 2 in **Fig. 4a**). Once again, this fact can be explained by the decrease of the required salt solution concentration for enabling the generation of the desired RH. In fact, due to water loss to the air at the age of 11 days, the salt-to-water ratio drastically decreased to $R = 2.0$, which is significantly lower than the original value of $R = 10.0$.

In regard to the container at 33% humidity into which the cement paste cup was introduced, a rather strange behaviour was observed during the first 4 days. In the first 1.5 days the RH had an upward shift of 18% (in-

stead of the 7% observed upon insertion of the water cup). This might be explained by the higher amount of water released by the cement paste, as can be seen in **Fig. 4b**. In fact, in this initial period the mass loss was ~30% higher in the cups with cement paste than in the ones with water. Despite this peculiarity, after this initial period the $MgCl_2$ solution was able to recover the relative humidity in the container to values that are very close to the target humidity of 33% (point 4 in **Fig. 4a**), probably due to the decreasing amount of water release identified in the cement paste between the ages of 3 to 7 days, as depicted in **Fig. 4b**. Nonetheless, it must be pointed out that occurrence of a stronger evaporation from the cement paste specimens than that with the water was not expectable, in view of previous experiences (Azenha *et al.* 2007a), and leads to inferring that a chemical interaction may have occurred between the paste and the surrounding ions present in the air (due to the salt solution).

Based on the experimental findings collected through the aforementioned experiments, it can be concluded that the sodium chloride salt solutions are quite satisfactory for creation of a stable environment with RH=75%. However, caution is recommended in the case of specimens where relevant water evaporation is to be expected, as they may induce undesirable disturbances in the target humidity. On the other hand, the use of magnesium chloride solutions (RH=33%) is highly discouraged for cement-based specimens in fresh state, as these salt solution are unable to absorb at the necessary rate the high initial release of water to the container environment.

3.3 Relative performance of RH measurement systems: calibration issues

Before comparing the sensors adopted for measuring the RH of concrete, a comparison of their performances regarding the monitoring of ambient RH was made. For this preliminary experiment the following sensors, with the characteristics reproduced in **Table 3** and **Fig. 5**, were adopted: 1 Vaisala (VS), 1 Proceq (PR), 3 Honeywell (HW1, HW2 and HW3) and 3 Sensirion (SHT1, SHT2 and SHT3).

Even though some of the tested sensors had been un-

Table 3 Characteristics of the sensors used in this work (Vaisala, 1999, Proceq, 2012, Honeywell, 2010, Sensirion, 2011).

Manufacturer		Proceq	Vaisala	Honeywell	Sensirion
Model		Hygropin	HM44	HIH-4010	SHT75
Operating range	RH [%]	0 to 100	0 to 100	0 to 100	0 to 100
	T [°C]	40 to 85	20 to 60	-	40 to 125
Accuracy at 20°C	T [°C]	±0.3	±0.4	-	±0.3

der use for several months, often enduring high humidity conditions (reported to shift the calibration of sensors by Kulwicki (1991) and Yamazoe and Shimizu (1986)), this experiment was deliberately not preceded by any *in situ* lab calibration, therefore using the calibration data originally provided by the manufacturers. The initial comparison test took place inside a climatic chamber at $T=20^\circ\text{C}$, making use of salt solutions inside small containers equal to those presented in Section 3.2, to induce variable RH environments; the containers were sealed with the sensors inside. The tested sensors underwent the following RH history (marked in **Fig. 6a** as “RH imp.”), separated in phases: Phase 1: RH=75.47%, with a NaCl salt solution from 0h to 4.4h; Phase 2.1: RH=33.07%, with a $MgCl_2$ salt solution be-

Fig. 5 Accuracy of the RH sensors as announced by the manufacturers (Vaisala 1999; Proceq 2012; Honeywell 2010; Sensirion 2011).

Fig. 6 Exposure of the sensors to controlled RH environments: (a) measurements before calibration of the sensors, and (b) after calibration.

tween 4.4h and 21.5h; Phase 2.2: replacement of the salt solution of MgCl_2 by an identical one at 21.5h, which remained until 45.5h; Phase 3: $\text{RH}=97.59\%$, with a K_2SO_4 salt solution between 45.5h and 51h; Phase 4: $\text{RH}=11.31\%$, with a LiCl salt solution between 51h and 75h. A summary of the phases and adopted salt solutions can be seen in **Table 4**.

Comparison of the performances of the various sensors is shown in **Fig. 6a**. The collected results show high dispersion, reaching $\pm 10\%$ of the RH at the 10th hour of the test. The sensors that showed highest deviation in regard to “RH imp” were those that had been previously subjected to more extensive usage in the laboratory. It is also worthy to be remarked that deviations in the sensors’ measurements were consistent across all levels of HR, i.e., the results had almost always the same shift. The only exception occurred when the “RH imp” was 97.59%.

After this test all the sensors were subjected to calibration procedures with equipment that is specifically designed for this purpose (also based on salts) - HMK15 from Vaisala (2006) -, which allowed the establishment of new calibration constants for the sensors, with significant differences when compared to the original values provided by the manufacturers’ datasheets. However, despite these differences, it should be noted that the linearity of the sensors response was kept unchanged. Such linearity can be verified, for example, in the summary of calibration procedures of sensor Proceq (PR) and sensor Honeywell (HW1), shown in **Fig. 7**, where R^2 values of 0.9998 are obtained with linear fits for the response of the sensor. Nonetheless, deviations are found between the new calibration lines and the line of 45° (measured RH = real RH) that would correspond to the adequacy of the initial calibration line.

Table 4 Salt solutions used in the test.

Phase	Salt	Amount of salt [g]	R	Expected RH [%]
1	NaCl	53.33	2	75.47
2.1-2.2	MgCl_2	53.33	10	33.07
3	K_2SO_4	53.33	2.93	97.59
4	LiCl	53.33	1.25	11.31

Fig. 7 Typical RH correction equations: Proceq (PR) and Honeywell (HW1).

Application of the new calibration constants to the data collected from the sensors (**Fig. 6a**) yielded the results shown in **Fig. 6b**: it can be seen that a remarkably good coherence between various types of sensors was obtained, with differences between them that were $\pm 1\%$ in regard to “RH imp”. In addition, the response time of the various sensors proved to be quite similar (only slightly slower when humidity transitions are more abrupt – for example, from Phases 2.2 to 3 and from Phases 3 to 4). Hence, the conducted experiments clearly remark the importance of undertaking regular calibrations of the humidity sensors to ensure their accurate performance, as also reported by several authors (Kulwicki 1991; Chen and Lu 2005).

4. Experiments concerning the monitoring of internal RH in concrete

4.1 General remarks

Given the scarcity of works in the literature regarding comparative studies of hygrometric methods for monitoring moisture in concrete (Grasley 2002), and taking into account several difficulties identified by the authors in previous experimental programmes, a series of laboratory tests was devised for better understanding the limitations and possibilities associated to the adopted monitoring strategies. The tests were conducted with basis on the methodologies generally described in Section 3, and are divided into four main categories, according to Subsections 4.2 to 4.5, encompassing: (i) the relative performance of several available systems for measuring RH in cement-based materials (Section 4.2); (ii) the influence of using Gore-Tex[®] as a protective interface between the measuring sleeve and the material under testing (Section 4.3); (iii) the relevance of the volume of air inside the sleeve where the RH sensor is inserted (Section 4.4); and (iv) the possible disrupting effect of having inclusion/removal cycles of the sensors inside the measurement sleeves (Section 4.5). As temperature was not an issue to be tackled in this research, all the reported tests were performed at $T=20^\circ\text{C}$ inside a climatic chamber that also ensured a $\text{RH}=60\%$. It is however remarked that temperature effects are very important for moisture measurement (Nilsson 1988; Fredin and Skoog 2005; Paroll and Nykanen 1998), and therefore reliable temperature measurements are needed in parallel. In this research, temperature measurements were made through several types of pre-calibrated temperature sensors, providing confidence in near-isothermal conditions of $20\pm 0.1^\circ\text{C}$ in all experiments (except for slight disturbances due to hydration heat at very early ages, where applicable).

4.2 Performance of the RH measurement systems

All the humidity sensors presented in this study are capacitive, thus relying on a measurement principle that implies exchange of water with the surrounding air on

which humidity is being measured. This exchange is related to the fact that the sensors are composed by two metal plates, separated by a hygroscopic material (see **Fig. 8**) (Kulwicki 1991; Yamazoe and Shimizu 1986). This hygroscopic material captures or releases water from the air, with a corresponding capacitance variation, which in turn can be measured with a Data Logger. However, since the sensors available on the market have different characteristics on the sensing part, the water capture/release by the sensor can be distinct, which may possibly affect the results in the context of RH sensing in concrete, where a macro-pore of limited size is used. Furthermore, this difference may also influence the sensor response time, causing delays in the measurements.

The performance of various types of sensors under conditions that are equivalent to their use for measuring concrete's internal RH (i.e., within an embedded macro-pore) was assessed by carrying out a systematic experimental study. This consisted in placing each sensor to be tested within a PVC tube with a diameter of 15mm and a length of 70mm, as shown in **Fig. 9a**. One extremity of the tube was sealed with several overlapping layers of plastic tape (technique that showed positive results in previous experiments), whereas the opposite end was covered with a 3mm thick disk of fresh cement paste (CEM I 42.5R, with $w/c=0.5$), with a diameter equal to the interior one of the PVC tube (see **Figs. 9b,c**). The experimental assembly and procedure for specimen preparation can be described according to the following sequence: (i) short segments of a PVC tube with 3mm length were cut; (ii) a plastic film was glued on the segment bottom part (**Fig. 9b**); (iii) the mould was filled with cement paste, carefully avoiding overtopping the 3mm segment (**Fig. 9c**); (iv) immediately after placing the cement paste in the mould, the final test setup was

Fig. 8 Structure of the RH sensor's capacitors used in this work.

Fig. 9 Experimental scheme: (a) assembly; (b) and (c) preparation of the cement paste disks.

assembled by coupling the cement paste disk to the bottom end of the 70mm long PVC tube (with plastic tape, ensuring a perfectly sealed macro-pore); and (v) during the first 24h the tube was kept in a vertical position, to ensure hardening of the cement paste with the desired disc-shape and thickness.

As previously described, during execution of the cement paste disks special attention was addressed to controlling their thicknesses. Despite this fact, at the end of the test the thickness of each disk was measured, being observed a variation of $\pm 0.30\text{mm}$ ($\pm 10\%$) in regard to the target value. The discs had however a perfectly cylindrical shape, with no gaps between the PVC wall and the cement paste.

During the first 68h of testing the cement paste was kept in sealed conditions on the bottom of the tube, provided with a plastic tape. After 68h of curing the plastic tape was removed, promoting drying of the cement paste towards the environment (see **Fig. 10a**). At this stage the samples were placed inside a container with a NaCl salt solution, with the dimensions indicated in Section 3.2, allowing therefore the creation of an environment with $\text{RH}=75\%$ ($T=20^\circ\text{C}$). This test was conducted on four specimens, each containing one of the types of sensor being studied, with the following designations: VS-7 (Vaisala), PR-7 (Proceq), SHT-7 (Sensirion) and HW-7 (Honeywell). The position of the sensors within the humidity controlled container during the conducted experiment is schematically illustrated in **Fig. 10b**. It should be noted that the RH sensor was placed inside the PVC tube simultaneously with the casting operations in all experiments, which resulted in a continuous exposure of the sensor to the inner air of the tube, without any intermediate removals, even in the case of VS-7 and PR-7.

Results of this experimental program are shown in **Fig. 11**, but it should be noted that only two types of sensors worked properly during the early period ($t < 68\text{h}$): the Proceq (PR) and the Sensirion (SHT) ones. The remaining sensors have not acquired the RH values due to failures of the data acquisition equipment. After removing the insulation of the cement paste, the sensors were re-wired and the failure of the acquisition system

Fig. 10 (a) Scheme of the specimens [dimensions in mm]; (b) ongoing test in the drying phase, with RH=75%.

was corrected. Unfortunately, the SHT sensor failed to respond at this stage (even upon re-wiring). Despite these problems, a good coherence of the RH measurements is confirmed in **Fig. 11**: the sensors behaved as expected during the first 68h, with a measured RH close to 100% in correspondence to the effective sealing of the tube, and low self-desiccation of the cement paste (high w/c ratio). It can be observed that a very good coherence was obtained between the different sensors at the end of the test (18 days), with RH deviations smaller than $\pm 2.5\%$. The monotonic decreasing trend of the humidity between 3 and 18 days is also quite similar in several sensors, however with more relevant differences between the ages of 4 and 6 days. It should be noted that such dispersion of results has been reported as well by other authors (Hansen *et al.* 1998). In the case of this research work it is assumed that the observed behavioural differences may be related to discrepancies in the thickness of the utilized cement paste disks, as explained above. It is also worth noting that when the humidity sensors are exposed for long periods to very high RH (above 95%), they may undergo decalibration and/or a delay in the measurements when the air humidity returns to lower values. The latter situation can be identified in **Fig. 11** for sensor PR-7, which underwent a delay of ~ 1.6 h (point (1)) right after removal of the cement paste surface insulation, and almost 1 day during the drying phase (zone (2)).

4.3 Influence of using Gore-Tex® to protect the sensors

When the macro-pore to host the RH sensor is materialized by a pre-placed sleeve in concrete, into which the RH sensor is embedded since casting, it is necessary to avoid filling of the sleeve with cement paste and to protect the sensor from liquid damage. However, this macro-pore needs to contact with the surrounding material, in order to allow a vapour exchange between the

cementitious material and the air inside the pore. In several works of Grasley *et al.* (2002, 2006b, 2006a) a Gore-Tex® fabric was used as an interface between the macro-pore and the material during casting, allowing for continuous RH monitoring since early ages, even before the structural setting time. In fact, Gore-Tex® responds to the requirements by being impermeable to liquid water and permeable to liquid vapour (Brownlie 1986; Dolhan 1990; Dobrusskin *et al.* 1991). However, given the lack of studies regarding the influence that this interface material can have on the accuracy of concrete RH measurements in embedded macro-pores, the experimental programme underwent for this section was devoted exclusively to the study of this aspect. If it is taken into account that the water vapour permeance of the Gore-Tex® is between 10^9 and 10^{15} higher than the one of a typical cement paste (see **Table 5**), no adverse effect is to be expected. In spite of this, it is plausible to fear that some of the Gore-Tex® inter-fabric spaces may be occluded by cement hydration products, or even endure chemical interactions, with loss of permeance. This doubt provides grounds to the necessity of specific testing in such concern. For this purpose two types of Gore-Tex® tissue were studied, which have different water vapour resistances (see **Table 5**), hereinafter referred to as Civil and Military Gore-Tex®.

The principle of the test is very similar to that ex-

Table 5 Water vapour permeances and resistances of the cement paste (Picandet *et al.* 2011) and of two types of Gore-Tex® (values provided by the supplier).

Material	Water vapour permeance [m/s]	Water vapour resistance [s/m]
Cement paste	10^{-16} to 10^{-10}	10^{+10} to 10^{+16}
Civil Gore-Tex® (GT1)	0.1111	9.00
Military Gore-Tex® (GT2)	0.0769	13.00

Fig. 11 Test results concerning the behaviour of the sensors in the macro-pore.

plained in the previous section, differing only in the dimensions of the PVC tube (with a length of 40mm, in this case) and the inclusion of a Gore-Tex® tissue between the cement paste and the internal air of the macro-pore, as shown in **Fig. 12a**. In this test, only SHT and HW sensors were used. In all remaining aspects (environmental conditions and experimental procedure) this test is identical to the one described in Section 4.2. Six samples were tested: two without Gore-Tex® (HW-4 and SHT-4), two with Civil Gore-Tex® (HW-4GT1 and SHT-4GT1) and two with Military Gore-Tex® (HW-4GT2 and SHT-4GT2). Due to a failure of the sensor SHT-4GT1, that failed to respond even after re-wiring, the corresponding information is not shown in **Fig. 12b**. By observing the collected results, it can be noticed that the inclusion of Gore-Tex® tissues in the interface between the macro-pore and cement paste had no significant effect, irrespective of its type (Civil or Military). In fact, the level of scattering obtained for these results is in all aspects similar to the one reported in **Fig. 11** of Section 4.2.

4.4 Relevance of the macro-pore size

Another important issue in the measurement of relative humidity in cementitious materials through RH sensors embedded in sleeves is the macro-pore volume. In fact, regarding this topic considerable discrepancies were found in the literature (Andrade *et al.* 1999; El-Dieb

Table 6 Characteristics of the macro-pores.

Macro-pore	Diameter [mm]	Height [mm]	Volume [mm ³]
2.5	15	25	4.42
4	15	40	7.07
7	15	70	12.37

2007; Jiang *et al.* 2006; Kim and Lee 1999; Grasley 2002; Lee *et al.* 2011; Ryu *et al.* 2011; Ekaputri *et al.* 2010; Grasley *et al.* 2006b; Zhang *et al.* 2009; Chang and Hung 2012; Vaisala 1999; Proceq 2012). Different pore volumes require different amounts of water exchange for reaching equilibrium between the air inside the pore and the concrete surface from which RH needs to be measured, thus possibly influencing in the measurement accuracy.

To evaluate the relevance of the macro-pore size, an experimental procedure similar to the one described in the Section 4.2 was performed, by solely varying the length of the macro-pore on the several test specimens. The study was conducted using Sensirion and Honeywell sensors on macro-pores with lengths of 2.5cm, 4cm and 7cm (referenced as SHT-2.5, SHT-4, SHT-7, HW-2.5, HW-4 and HW-7, respectively), all having the same diameter of 15mm (see **Table 6**). In order to have additional references, results will be compared with those already presented for PR-7 and VS-7 in Section 4.2.

Results reproduced in **Fig. 13a** and **13b** show that the length of the macro-pore does not seem to be relevant, since the dispersion of results is quite similar to what is shown in **Fig. 11**.

This kind of behaviour was expected, since only a small amount of water is necessary to vary the RH inside the pore. It is possible to estimate the total amount of water vapour in a given volume with a reasoning based on the ideal gas law (Eq. (1)) (Çengel and Boles 2006):

$$p_v \cdot v = R \cdot T \quad (1)$$

where p_v is the vapour partial pressure of the gas (in Pa), T is the absolute temperature (in K) and R is the

(a)

(b)

Fig. 12 (a) Test scheme with Gore-Tex® [dimensions in mm]; (b) test results with Gore-Tex®.

Table 7 Water vapour in each macro-pore as a function of RH (at 20°C).

Macro-pore	RH	Amount of water vapour [μg]									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
2.5		8	15	23	31	38	46	54	61	69	76
4		12	24	37	49	61	73	86	98	110	122
7		21	43	64	86	107	128	150	171	193	214

universal gas constant ($R = 8.3143 \text{ J}/(\text{mol} \cdot \text{K})$). v is the specific volume of the gas (in m^3/kg), which can be expressed as:

$$v = \frac{V}{m} \quad (2)$$

with m being the mass of gas (in kg) and V being its volume (in m^3). The vapour pressure of water vapour can be obtained from the relative humidity of the air through Eq. (3):

$$\phi = \frac{p_v}{p_{v,\text{sat}}} \quad (3)$$

where ϕ is the RH and $p_{v,\text{sat}}$ is the vapour saturation pressure (in Pa). Thus, it is possible to obtain analytically the amount of water present in a volume of air through the combination of Eqs (1), (2) and (3):

$$m = \frac{\phi \cdot p_{v,\text{sat}} \cdot V}{R \cdot T} \quad (4)$$

Accordingly, as the water vapour saturation pressure of the air at 20°C is equal to 2.34 kPa (Çengel and Boles 2006), the amount of water vapour in each macro-pore is listed in **Table 7**. As it can be observed in this table, the values are manifestly small in comparison to the amount of water that can be released by the cement paste disk. Therefore, it can be concluded that the larger need for water to achieve the moisture content equilibrium in the largest macro-pores has a negligible influence on the measured RH.

Even though the above reasoning is quite plausible, it is a rather simplified one due to the overlooking of other phenomena such as internal diffusion and convection within the macro-pore may play relevant roles. Fur-

Table 8 Mortar composition.

Component	Content (kg/m^3)
Cement (CEM I 42.5R)	280.0
Water	143.0
Fly ash	40.0
Super-plasticiser	6.25
Sand (0/4)	245.6

thermore, the experimental research has solely focused in changing the length of the macro-pore, whereas changes in its diameter and consequently on the ratio of volume to the surface facing the measured material (e.g. cement paste or concrete) can possibly have distinct impacts on the measurement. This is surely a topic that deserves further experimental work as to obtain definitive recommendations.

4.5 Use of permanently installed sensors vs discrete monitoring

A potentially criticisable aspect of the commercial integrated systems for RH measurement analysed in the context of this work concerns to the possible moisture exchanges between the measuring sleeve and the surrounding environment when the RH sensor is being installed or removed. Taking into account the results reported in Section 4.4, and assuming that there is an adequate sealing of the macro-pore end between different measurement instants, no undesirable effect on the accuracy of results is to be expected. However, to thoroughly assess this issue an additional experiment was performed using two Vaisala systems in two $5 \times 5 \times 5 \text{ cm}^3$ mortar specimens, the latter with the composition shown in **Table 8**, and according to the scheme reproduced in **Fig. 14**.

Both systems were used with the plastic sleeve provided by the manufacturer (with a diameter of 1.6 cm

Fig. 13 Test results on the influence of the macro-pore size: (a) evolution along time; (b) measured RH according to the macro-pore size at 6, 10 and 15 days.

Fig. 14 Specimen used in the test [dimensions in mm].

and 7.0cm long). To accelerate the drying process, the measuring extremity of the sleeve was positioned 1cm away from the drying surface (see Fig. 14). Military Gore-Tex® was placed to prevent the entry of cement paste into the tube during casting.

The samples were kept in sealed conditions during the first 7 days of curing at 20°C. Afterwards, the two surfaces of the specimen that are perpendicular to the axis of the plastic sleeve were exposed to drying. The other four surfaces of the specimen were sealed with paraffin, ensuring a unidirectional moisture flow. During the drying period specimens were kept under controlled temperature and RH ($T=20^{\circ}\text{C}$ and $\text{RH}=60\%$) inside a climatic chamber. One of the sensors was used according to the manufacturer instructions: placement and removal of the sensor in the macro-pore for each measurement (VS-N) was performed as depicted in Fig. 15. The other sensor was permanently placed inside the macro-pore, which remained sealed throughout the entire experiment (VS-F). Additionally, in the specimen where discrete measurements were performed, two different sensors were used: a Proceq sensor (PR-N), intercalated with a Vaisala sensor (VS-N).

Results collected since the instant of exposure to drying until the end of the experiment, 2.5 months later, are shown in Fig. 16. It can be observed that the measurements recorded by the two different methods were identical in all analysed instances.

5. Conclusions

The present paper dealt with a set of experiments targeted to better understanding the relative performance of several experimental strategies for monitoring internal RH in cement-based materials with embedded sensors. The following main conclusions can be systematized:

- The use of salt solutions to ensure humidity conditions for testing of cement-based materials should be considered with care, due to potentially disrupting interactions. Such interactions were found to be particularly important in the attempt of attaining $\text{RH}=33\%$ (using a MgCl_2 solution).

Fig. 15 Procedure to perform each discrete RH measurement.

Fig. 16 Test results for evaluating the influence on RH measurements of macro-pore access at discrete instants.

- Relevance of calibration of the humidity sensors has been confirmed in an experiment involving several RH sensors, some of which being under use for several months. Even though the extensive use of sensors tends to shift their response, the new calibration constants can be easily obtained through standard calibration procedures.
- Comparison of the performances of distinct humidity sensors under the same conditions of measurement, which emulated an embedded sleeve in a cement-based material, led to coherent results. Thus, no preferential indication could be given among the four types of tested sensors, which behaved adequately.
- The use of Gore-Tex® fabric as an interface material between the cementitious material and the measuring sensor did not induce any behavioural change in the measured humidity.
- A variation in the size of the macro-pore inside which the embedded RH sensor was inserted did not seem to have any effect on the accuracy of measurements. This may be explained by the quantity of water that is necessary to shift the humidity of the macro pore being very low, in comparison to the quantity of water that the cementitious matrix can release upon drying.

- An evaluation was made in regard to the consequences of either constantly keeping the embedded RH sensor inside the measuring sleeve, or adopting a strategy with discrete embedment of the sensor at every instant of measurement. No relevant performance differences were observed, thus providing confidence in the comfortable and economic possibility of only utilizing the sensor in the measuring sleeve whenever it is really necessary to do so.

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