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IN-SITU RH MEASUREMENTS IN CONCRETE IN A VARIABLE TEMPERATURE ENVIRONMENT

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Abstract. EDF studies the behavior of concrete containment buildings since delayed strains of concrete cause the pre-stress to decrease. Moreover, the permeability of concrete itself is vastly dependent on its saturation degree. For these reasons, a good prediction of strains and leak-tightness of concrete containment buildings must start with a good estimate of the moisture profile on concrete. In the framework of the VERCORS project, a large panel of experiments and studies are performed with the aim of improving the prediction tools for the behavior of concrete containment buildings. Traditionally, the identification of the parameters of concrete drying constitutive laws is based on mass measurements of samples exposed to a constant humidity and temperature. However, it has been observed for different drying laws that this methods leads to a multiplicity of solutions, potentially corresponding to different moisture profiles and also to different extrapolations of the mass-loss beyond the end-time of the experiment used for the identification [4]. As an attempt to validate the calibrations of the Granger [8] drying law performed using mass-loss measurements at different temperatures, RH measurements have been started in 40 cm thick blocks installed in the VERCORS mock-up following the protocol of [9]. Therefore RH profiles are available to validate the drying simulations in a variable RH and temperature environment. This paper presents these RH measurements and also a method to convert the RH into water concentration with the help of a temperature-dependent desorption isotherm. This step is necessary to compare the measurements with simulations which use the water concentration as the unknown.

1 INTRODUCTION

Electricité de France (EDF) operates 58 nuclear power plants (NPP) in France. On each plants (Pressurized Water Reactors technology, PWR), the final barrier against accidental release of radioactive fission products to the environment consist in a prestressed concrete containment building (CCB). This structure is not replaceable, and the issue of ageing management has to be addressed with specific care for Long Term Operation (LTO). Indeed, the average operation time of these facilities is currently around 25 years, and they are expected to provide electricity for 15 to 35 more years.

The prestressing forces are supposed to provide adequate resistance to withstand to a design basis accident, implying an internal pressure about 4 bars and a temperature around 140°C.Then, the containment strength depends on the remaining forces of the prestressing tendons at the end of operation time. However, as for any other civil prestressed structure, these tendons forces decrease slowly with time, due to the effects of the relaxation of the steel tendons and to the shrinkage and creep in concrete. In addition, for the CCB without steel liner, containment leak tightness seems to be closely linked to the available prestressing forces if the internal pressure rises.

It is well known that shrinkage and creep of concrete are depending on concrete moisture or water content [8]. In France, CCB are about 1 meter thick, or more, and then the drying is slow. Therefore effects of shrinkage and creep are still sensitive and can entail significant prestressing losses even near the end of operation time. A correct assessment of water content throughout the life of the CCB is then a critical issue for LTO.

The need of water content profile measurement

At EDF R&D, the VERCORS mock-up, a 1/3 scale CCB, is built to improve the understanding and the modeling capabilities of ageing and leakage of double walls CCB. The monitoring system of the VERCORS mock-up includes two innovative technologies which are tested to measure water content: pressure pulse decay technique "pulse" [1] and Time Domain Reflectometry (TDR) method [12]. A calibration on concrete tests specimen is necessary for both methods to establish the relation between the water content in the material and the measured value (apparent gas permeability or apparent relative permittivity). The characterization of the drying behavior of VERCORS concrete has been performed with two main different kinds of tests. First, the desorption isotherms have been measured at EDF R&D MMC using a testing protocol described in [11, 2]. Second, weighing of full samples of the same dimensions as samples of creep test campaigns is also performed. Such tests are currently under progress at EDF DI TEGG [5, 6] and LMDC [7].

The validation process of the drying models consists of calibrating the material properties on the mass loss kinetics tests and comparing drying prediction for the VERCORS model with the in-situ measurements of pulse and TDR. In the case of the Granger model [8], when it comes to carry out a parameters identification arises the question of ill-posedness of the inverse problem [4]. In order to properly address the drying identification issue, we propose to simultaneously calibrate the constitutive law parameters on kinetics mass loss and water content profiles. Therefore, RH profile measurements are currently under progress at EDF DI TEGG and a second campaign has been started directly in blocks inside the VERCORS mock-up in order to assess the effect of the variable ambient conditions on drying.

The aim of this paper is to share an acquired experience on RH profile measurement in these blocks inside the VERCORS mock-up. This paper, first of all, presents the material tested and the experimental device. Finally, RH profile are showed and an interpretation with a temperature-dependent desorption isotherm of VERCORS concrete is proposed and discussed.

2 EXPERIMENTAL PROGRAMME

2.1 Material et specimen tested

The specimens used for the RH measurement experiment are some massive VERCORS concrete blocks of parallelepipedic shape of 80x80x40 cm of dimensions. The blocks are made of reinforced concrete and sealed so as to force a unidirectional drying throughout their thickness. The blocks are distributed in the space between the containment double walls (EEE) and in the internal containment building (EI). The air conditioning system is set to 30°C and 30% $\pm$ 10% RH in the internal containment building and 20°C and between 50% and 60% RH in the space between the two containment walls. Thus, two thermo-hydric conditions are studied. The impact of the two different temperature and humidity changes between the EEE and EI on drying can be measured and studied.

2.2 Technique used

The RH profile measurement at different depths (5, 10, 15, 20 cm) in the blocks thickness is measured using a capacitive probe system based on the experimental setup proposed by [9] (Figure 1).

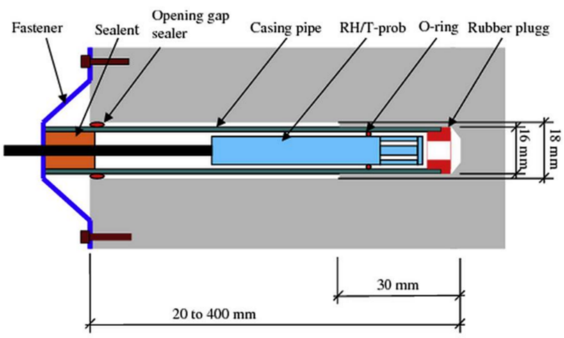

Figure 1: Implementation of RH probes according to [9].

The device has been reproduced fairly faithfully with one exception only: rather than inserting the probes at the bottom of the tube and sealing on the cable as [9], we positioned the probes at the entrance to the hole on advice of the supplier of RH probes, Vaisala (Figure 2).

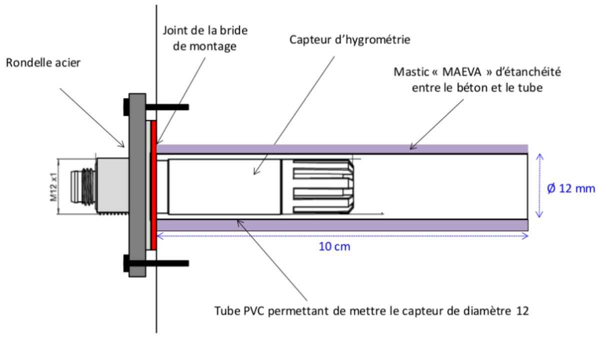

Figure 2: Implementation of RH probes proposed by EDF DI TEGG.

In addition, we proposed to add a large steel washer when the probes are installed to allow a good anchoring of the whole device (Figure 3). These large washers were installed instead of the small washers proposed in Vaisala design. This change was made because the holes of the small screws which fix the plate in the assembly of Vaisala were too close to the main hole in which one inserts a PVC tube glued to the concrete with the MAEVA resin and the probe.

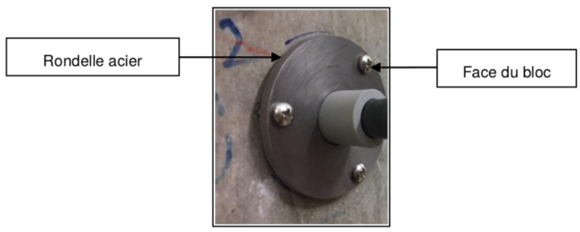

Figure 3: Location of a probe just before installation (the hole is clogged with a plastic plug) of a RH probe.

The measurements began on February 5, 2018 in the configuration described above, and have continued without incident since then. This demonstrate the robustness of the measurement and recording system set up by EDF DI TEGG, which has only been dismantled for a few days during the VERCORS 2018 decennial visit (VD2), which is a 4 bars pressure test during which the electricity is shut down in the containment building for leak-tightness reasons. A general view of the implementation of the probes in the "EEE2" block is given in Figure 4.

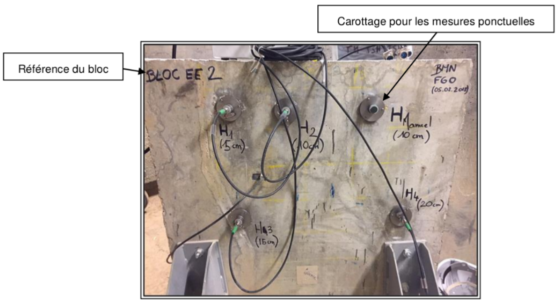

Figure 4: Implementation of RH probes in the block “EEE2”.

3 EXPERIMENTAL RESULTS

The measurements are carried out periodically with a laboratory computer on which an adapted Vaisala software is isntalled. Moisture and temperature are measured once an hour from the beginning of the test on February 5, 2018.

3.1 "EI" block

The temperatures measured in the inner containment building are shown in Figure 5, while the relative humidities are shown in Figure 6. The probes 1, 2, 3 and 4 correspond respectively to 5 cm, 10 cm ,15 cm, and 20 cm deep in the concrete.

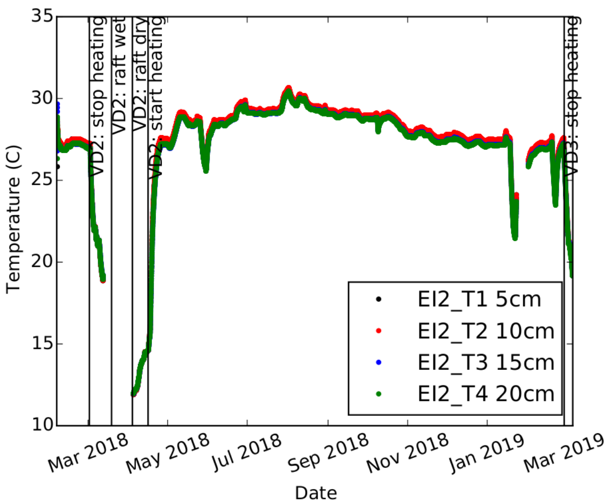

Figure 5: Temperatures measured on the "EI2" block of the internal containment building.

One can observe that the temperatures are all identical. This shows that the method of implantation of the surface probes does not make it possible to measure the actual temperature of the concrete to the desired depth. The measured temperature is rather the ambient one which is clearly a drawback of the probe implantation method, since to measure correctly the RH it is necessary to have access to the temperature at the exact same location. This will be changed in the future: the probes will be moved as deep as possible into the hole.

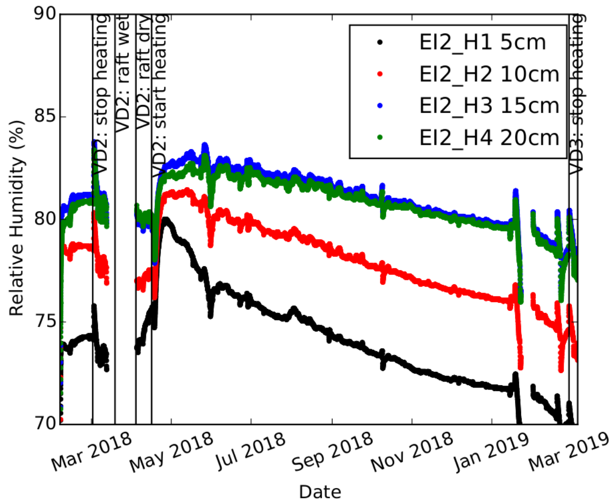

Figure 6: Relative humidities measured on the "EI2" block of the internal containment building.

Regarding relative humidity measurements, there is a drying profile as soon as the probes are implanted. This reflects the drying since the manufacture of blocks, dating back more than 2 years ago. A significant, increase in humidity occurs when the heating stops (in this period, the RH is not controlled anymore and increases significantly due to the presence of water at the bottom of the containment during the pressure test). The RH profile very quickly flattens. The drying the resumes when the heating is restarted, and the profile again becomes fairly marked.

3.2 "EEE" block

The Figures 7 and 8 show respectively the temperatures and the humidities in the "EEE" block.

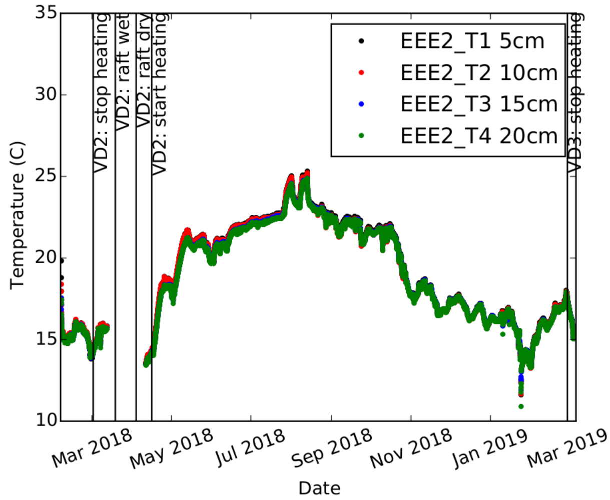

Figure 7: Temperatures measured on the "EEE2" block of space between double walls containment building.

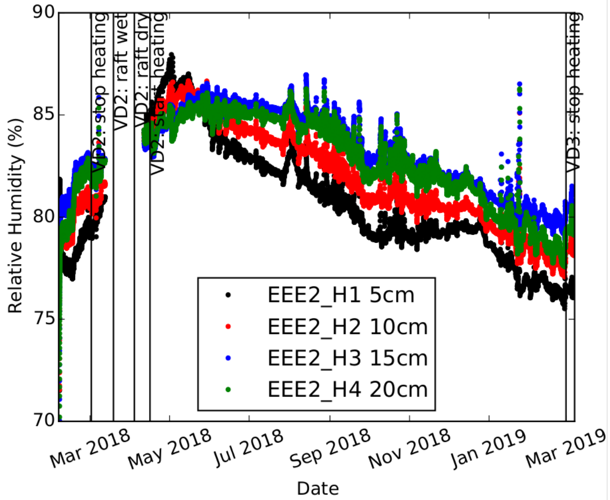

Figure 8: Relative humidities measured on the "EEE2" block of space between double walls containment building.

For the same reason as above, the temperatures are identical whatever the depths of the probes. While, for the humidities, there is also a profile, however this one is much less marked than that of the EI, and the value of the humidity is globally higher.

Another important drawback of the probe implantation method is that the probes have been installed with a linear spacing, while it would have been more interesting to refine the space between probe close to the surface, where the drying profile is steeper.

3.3 From humidity to water content profil evolution using VeRCoRs concrete temperature-dependent desorption isotherm

In order to convert the previous temperature and humidity measurements to the content we need to use the VeRCoRs concrete desorption isotherm as a function of temperature. In the preliminary approach, the desorption isotherms of VeRCoRs concrete as a function of the temeperature are constructed from the desorption isotherm measured at EDF R&D MMC at 25°C and the isosteric heat data of the concrete of the radioactive waste storage studied by [10]. The Clausius-Clapeyron formula is used to derive the temperature desorption isotherm of VeRCoRS concrete [10] :

$$\mathrm{RH}(T,w) = \mathrm{RH}(T_0,w)\frac{P_{vs}(T_0)}{P_{vs}(T)} \exp\left[\frac{Q_{st}(w)}{R}\left(\frac{T-T_0}{TT_0}\right)\right] \quad (1)$$

where $\mathrm{RH}(T,w)$ is the relative humidity at equilibrium with the mass water content w at the temperature T. In our case the isotherm desorption at T_0=25°C is used and $Q_{st}(w)$ stands for the amount of energy involved in the sorption process;it is known as the isosteric heat of sorption. The values of the isosteric heat of [10] was used. For a given temperature and humidity, the saturation ratio S_r is deduced from ratio of mass water content at equilibrium w on the mass water content at saturation w_{sat}, $S_r = w/w_{sat}$.

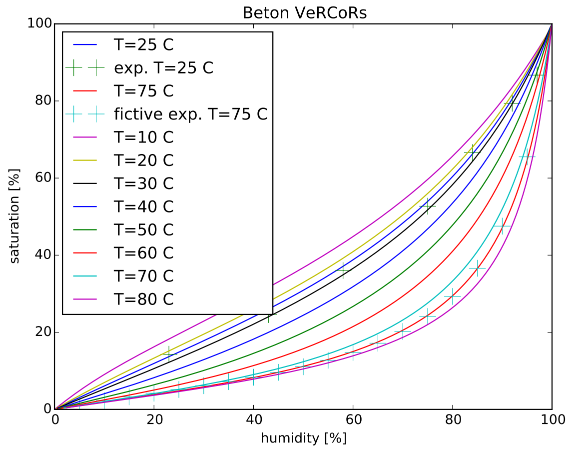

Figure 9: VeRCoRs concrete temperature-dependent desorption isotherm.

The Figure 9 shows the temperature-dependent desorption isotherm of VeRCoRs concrete based on the previous hypothesis. Temperature appears to have an important impact on the retention curve, as illustrated for example in the Figure 9. As in [3], the main following features appear when temperature increases are :

- the general isotherm curve shape is modified (more pronounced non-linearity),
- the saturation ate equilibrium with an arbitrary RH is reduced,
- the saturation decrease is observed over the whole RH range and the higher the temperature, the greater the reduction.

In the perspective to have a reliable temperature-dependent desorption isotherm for VeRCoRs concrete, desorption isothermal measurements at 40°C and at 70°C are respectively underway at EDF R&D MMC and at CEA.

Figures 10 and 11 show changes in volumetric water content C [L / m^3] in EI and EEE blocks. The volumetric water content C is deduced from saturation ratio S_r and concrete porosity ϕ by $C = 1000 S_r \phi$. These figures show a clear reduction of the measurement noise following the conversion of moisture into water content. This reflects the fact that a significant part of the measurement noise comes from instantaneous variations in temperature. The remaining measurement noise must be related to the transient effects of the temperature on the water content. Indeed, the use of the desorption isotherm assumes a local equilibrium state which in reality is not necessarily achieved. This effect will be investigated in the framework of finite element simulation of these blocks.

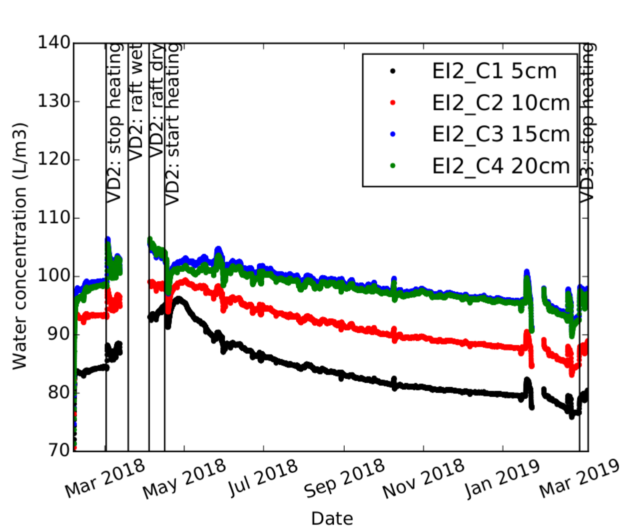

Figure 10: Water content profile on the "EI2" block of the internal containment building.

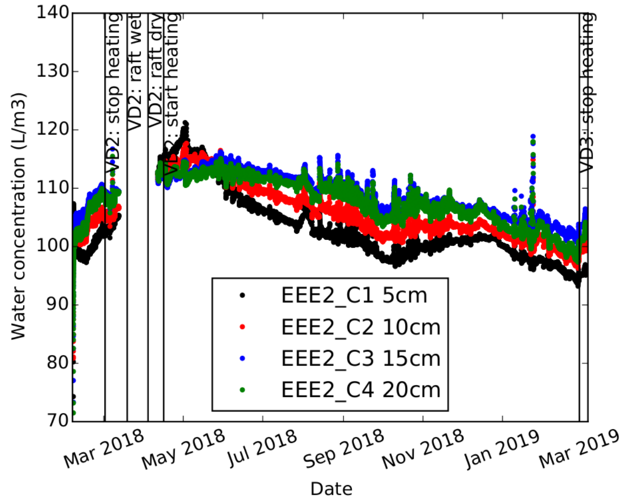

Figure 11: Water content profile on the "EEE2" block of space between double walls containment building.

In addition, an attempt to validate these measurements is proposed in Figures 12 and 13 by comparing them with measurements of the water content obtained from a coring of other blocks, locate near the instrumented blocks. Indeed, these other blocks are exactly the same thermo-hydric history as those instrumented by capacitive sensors. For these others blocks, each year a coring is realised and water content profil is measured. The profile of water content obtained on 09/04/2018 for EI block, 24/08/2018 for EEE block by coring and that obtained by direct measurement of RH at different depths of thickness on 08/04/2018 for EI block, 23/08/2018 for EEE block are compared in Figures 12 and 13. A difference of about 15 L/m^3 between the different water content profiles can be seen. In fact, VeRCoRs concrete cores, despite all the precautions taken, contain more water because of the addition of water to cool the sample during coring. The measurement of water content by gravimetric method following a coring and a cutting of the samples presents a fairly important uncertainty mainly related to the water supply during the cutting operations, or the temperature increase of the sample if its wetting is insufficient.

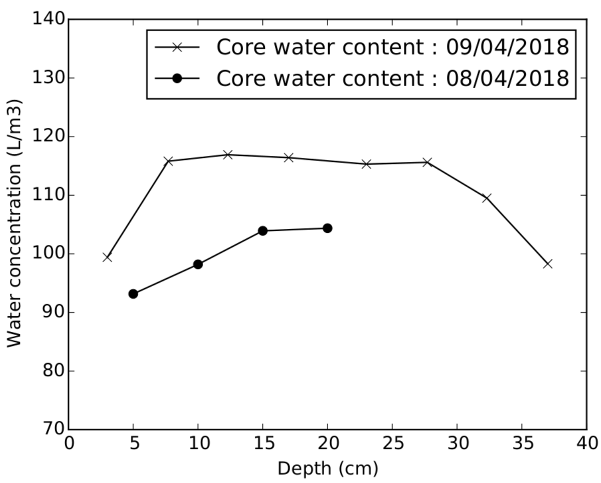

Figure 12: Comparison of water content profile on the "EI2" block obtained by RH measurements and by measure on carrots.

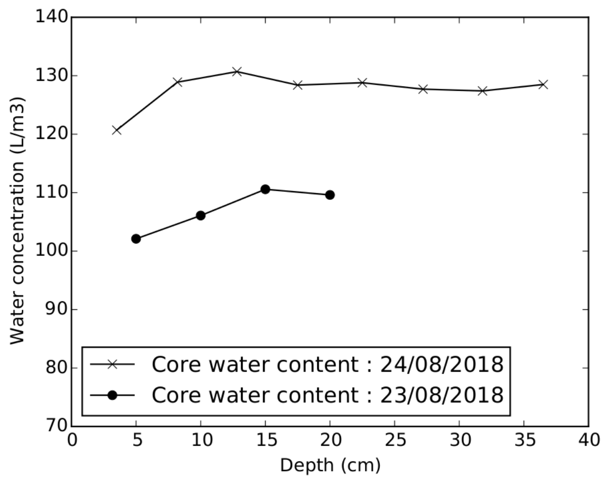

Figure 13: Comparison of water content profile on the "EEE2" block obtained by RH measurements and by measure on carrots.

4 CONCLUSION

In this contribution, our acquired experience on RH profile measurement in the in situ blocks inside the VERCORS mock-up is shared. The experimental device, temperature and RH profile measurements is presented. A conversion method of humdity profil into water content profil is proposed using temperature-dependent desorption isotherm of the concrete. In spite of the difficulty of measuring the water content profile by coring, the order of magnitude of the water content profiles by direct RH measurement is approximately validated by comparison with the profiles obtained by coring. This step is necessary to compare the measurements with simulations which use the water concentration as the unknown.

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