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IN SITU CONCRETE MOISTURE MEASUREMENT USING GAS PERMEABILITY

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Abstract

Water saturation of concrete is a key factor when dealing with the durability of structures. Indeed, moisture variation may induce effects capable of affecting the mechanical integrity of the structure, its durability or the confinement capability of a dedicated structure.

A new method has been developed for in situ measurement of moisture content of concrete structures. The “pulse” method is based on the relationship between gas effective permeability of a porous material and moisture content.

This article will focus on the advantages and limitations of this measurement technic. This discussion will be based on ongoing case study. The results of concrete characterization and its effect on moisture measurement accuracy will be discussed. Indeed, this sensor has been implemented in the French European Pressurized Reactor (5 sensors), in the VeRCoRs mockup (20 sensors) managed by Electricity of France and in the underground lab managed by ANDRA for the confinement of long life and high activity nuclear wastes (4 sensors) etc.

Finally, using the dependency between gas tightness and moisture content, a solution to improve the tightness of nuclear power plant building has been proposed, based on controlled imbibition of the concrete structure. The “pulse” sensor has been proposed to monitor this treatment process.

1. Introduction

Measuring water saturation of concrete structures is becoming of direct crucial interest when the latters are intended to waste storage or are designed for confining purposes (nuclear plant, waste storage etc.). Many concrete properties depend on its saturation state (creep, Young modulus, permeability, thermal conductivity, diffusivity etc.) [1]. These properties are involved in numerical simulations used to predict the long term behavior of the structure and its ageing.

Electricité de France (EDF) has operated 58 nuclear power plants in France for an average time of 30 years; they are expected to provide electricity for 15 to 40 years more. A significant part of safety assessment of nuclear structures relies on validated numerical simulations and calculations which also have to be compared to results of *in situ* monitoring from which three major properties of concrete must be identified: thermic, hydric and mechanic. They are necessary to check the structure integrity with time and are linked to the long and short term shrinkage. The recent construction of the VeRCoRs mock-up (at EDF Lab Les Renardières, near Fontainebleau, France) enables to highlight significant advances in temperature, strain and moisture monitoring in concrete of the inner pre-stressed containment. The “gas-pressure-pulse-decay” (i.e. “pulse”) technology has been setup in this structure since September 2014, in order to measure the concrete water saturation. The pulse technique is not only a new sensor but also a strategy of measurements. The main idea behind the design of this new technique is to use the strong link between the concrete effective gas permeability and its water saturation. The main goal in this presentation is therefore to present the “pulse” method, to discuss the advantages and limitations of this measurement technic and to present the first results obtained in-situ.

It is well known that concrete effective gas permeability is strongly linked to its water content (or its water saturation) [2, 3, 4] and can be considered as a material property. Hence local water saturation (i.e. close to the probe) could be deduced from small gas injections leading to the material effective permeability. Such a methodology would have the advantage of not being influenced by strains (i.e. structural effects) but, on the other hand, could be sensitive to micro-cracking in the vicinity of the probe.

Therefore this paper will present experimental design and laboratory material investigations that have allowed in situ installations of our system in a superficial radioactive waste storage.

2. Use of gas permeability to determine water saturation

2.1 The relative gas permeability

The effective gas permeability ($k_{eff,g}$) of a partially saturated porous media depends on the amount of available porosity for gas percolation, its connectivity, tortuosity and pore throat diameter. It is well known that gas permeability varies significantly with the distribution and the amount of moisture present in the porous network [5, 6]. Water saturation S_w is defined as the ratio of accessible porosity filled by water. It can be calculated through equation (1).

$$S_w = \frac{M_{ps} - M_{dry}}{M_{sat} - M_{dry}} \quad (1)$$

Where M_{sat} is the mass of a sample fully saturated with water, M_{dry} its dry mass and M_{ps} its mass when partially saturated.

The relative gas permeability ($k_{r,g}$) of a porous material is designated as the ratio between its effective gas permeability (for a given water saturation) and its intrinsic permeability (k_i):

$$k_{r,g}(S_w) = \frac{k_{eff,g}(S_w)}{k_i} \quad (2)$$

Where S_w is concrete water saturation. The relative gas permeability varies from 0 (porosity saturated with water) to 1 (porosity saturated with gas). As illustrated in Figure 1, existing literature shows [7] that in a first approach, for a given cementitious material, gas relative permeability can be seen as depending on the water concrete saturation only.

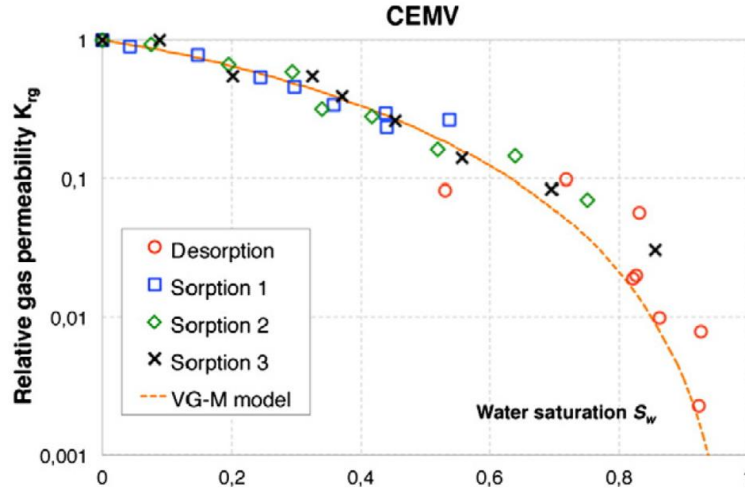


Figure 1. $k_{r,g}(S_w)$ for CEMV concrete (W/C=0.39): during desorption and sorption paths 1, 2 and 3 lasting 120, 340, 490 days respectively [7].

The $k_{r,g}(S_w)$ curve can be predicted using fitting models. The Van Genuchten–Mualem's model [12, 14] is one of the most often used in articles related to relative permeability of rocks and concretes [10, 11, 13]. The analytical formula proposed by Van Genuchten allows to fit the water vapour desorption and adsorption isotherms curve using two fitting parameters (a and m) which depend on the microstructure (in particular on the connectivity of the pore system) of the material. Those fitting parameters are then used to predict both relative gas and liquid permeability of the material:

$$p_c(S_w) = a \cdot (S_w^{-\frac{1}{m}} - 1)^{1-m} \quad (3)$$

$$k_{r,g}(S_w) = (1 - S_w)^\xi \cdot \left(1 - S_w^{\frac{1}{m}}\right)^{2m} \quad (4)$$

Where ξ is another fitting parameter equal to 5.5 for cementitious materials according to Monlouis ([9]) cited by [8].

Such models may also be used “for lack of anything better”, i.e. in the absence of direct measurements of fluid transport properties [7]. On another hand, when actual hydraulic properties are measured, they may be fitted using Van Genuchten's relationship, which is useful for numerical modelling.

2.2 “Pulse” principle

Following these results, it was thought that an efficient measurement method of *in situ* concrete water content could be designed and based on gas permeability evaluation and variation. This method has been applied in a recent publication by Liu *and al.* [15] and is designated as “Pulse Test Protocol”. The moisture content measurement protocol lies in three steps:

- Defining the characteristic $k_{r,g}(S_w)$ curve of the tested material,
- Measuring effective gas permeability $k_{eff,g}$,
- Deducing the water saturation S_w of the material.

3. “Pulse Test protocol”

3.1 Determination of characteristic curve $k_{r,g}(S_w)$

The relative gas permeability of the concrete is determined through a laboratory study. For an efficient measurement, the concrete used for this characterization study has to be as representative as possible of *in situ* concrete. In the case of the study on VerCoRs mock up, four cylindrical samples (160mm in diameter and 320mm in height) have been casted for each concrete lift in which “pulse” sensors have been implanted. The concrete is then coming from the same batch even if the conditions of casting are different, especially regarding the vibration energy and homogeneity.

Cylindrical samples (65mm in diameter and 30mm in height) were used for this purpose. After coring and cutting, the mass of the samples is measured and is assumed as the saturated mass M_{sat} . The apparent volume (V_{app}) is also measured. The samples are then stored in controlled relative humidity at 98, 92, 85, 75, 70, 59, 43 and 11% of RH, until mass stabilization. The stabilized mass at $x\%$ of RH is referenced as $M_{x\%}$. The effective gas permeability for a stabilized RH of $x\%$ ($k_{eff,g}(x\%)$) is measured under steady state flowing conditions. The material and methodology used for effective permeability measurement, and validated by more than 20 years of studies, is detailed in [12, 15, 16, 17, 18]. At this stage, the liquid saturation of the samples is still unknown. Samples are then dried at 60°C, until mass stabilization and the dried mass (M_{dry}) is measured. This value allows calculating the porosity (ϕ) of the samples and the liquid saturation (S_w) obtained for a relative humidity of $x\%$ ($S_w(x\%)$). The effective gas permeability for a liquid saturation of 0% ($k_{eff,g}(0\%)$) is measured, this value is considered as the intrinsic permeability (k_i). For each sample, the relative gas permeability for the obtained water saturation ($k_{r,g}(S_w)$) is calculated according to relation (1).

3.2 Measuring *in situ* effective gas permeability

Basically, gas permeability designate the ability of a gas or a fluid to flow across a porous media under a gradient of pressure. The “pulse” sensor must then allow to measure the gas flow rate around it under a given gas pressure. Different analytical relations have been established to calculate gas permeability in steady state conditions, knowing the gas flow rate and the geometry of the gas flow. For a cylindrical flow, in steady state conditions, Darcy’s law can then be used to determine effective permeability through equation (5) [19]:

$$Q_m = \frac{k_{eff,g} \cdot \pi}{\mu} \frac{P_i^2 - P_0^2}{P_i} \frac{L}{\log \frac{R_0}{R_i}} \quad (5)$$

Where Q_m is the volumetric flow rate under the pressure P_i in the injection chamber, L is the length of the chamber, μ the dynamic viscosity of the gas, P_0 the atmospheric pressure, R_i the radius of the chamber and R_0 the influence radius (i.e. the radius at which pressure is equal to P_0).

The gas flow geometry has to be known to use Darcy’s law and to further analyze the pressure measurements. Theoretically, once defined the $k_{r,g}(S_w)$ curve, any device allowing to measure accurately *in situ* gas permeability should allow to determine the liquid saturation. At the present time, the “pulse” sensor is the only gas permeability measurement device which has been used for that purpose.

The “pulse” device is composed of a sensor which consist in a cylindrical stainless steel porous cylinder put inside the concrete structure and fixed between reinforcing bars (see Figure 2) connected via a stainless steel capillary tube to a gas injection device (see Figure 3).



Figure 2. Pulse probes before casting of a reinforced concrete structure.

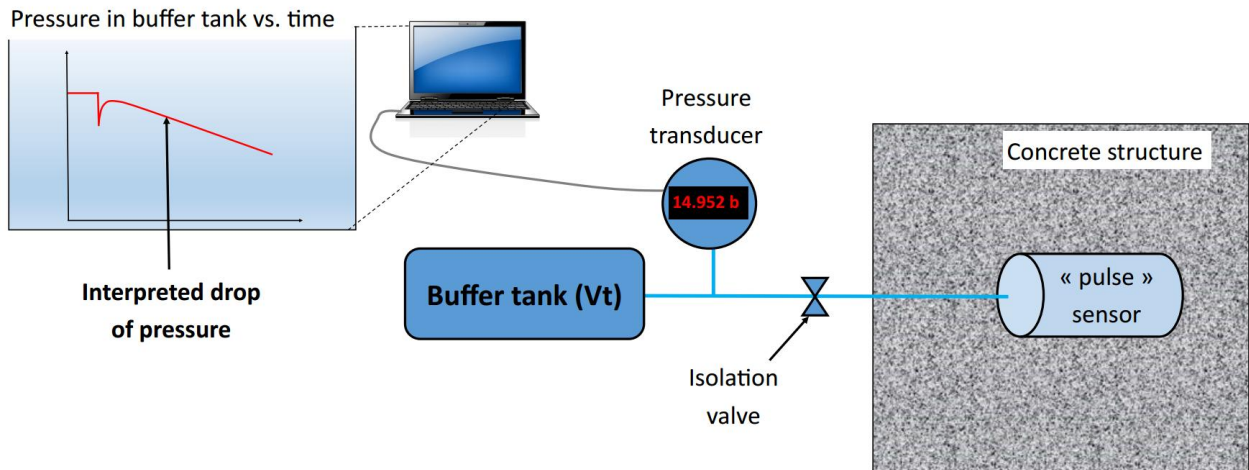


Figure 3. Schematic diagram of the “pulse” technic

The mean volume flow rate (Q_m) is calculated through equation (6) knowing the volume of the buffer tank and of the piping (V_t) and assuming that the gas is ideal and the test realized in isothermal conditions. ΔP is the variation of gas pressure in the buffer tank during the time Δt , and P_m is the mean pressure in the tank during this same time.

$$Q_m = \frac{V_t \cdot \Delta P}{\Delta t \cdot P_m} \quad (6)$$

3.3 Determining liquid saturation

The “pulse” protocol consists in rapidly increasing the pressure in the “pulse” sensor (including the buffer tank), halting the injection and then measuring the fall in pressure caused by the flow. In unsteady condition, which is the case for the “pulse” protocol in a large concrete structure, the radius R_0 after a given time of testing, is indefinite. Indeed, it depends on both effective permeability and water saturation (through available porosity), which are the unknowns of the problem. Furthermore, the geometry of the flow may be significantly different from the supposed cylindrical one. Numerical simulations are then used to determine the drop of gas pressure in the buffer tank for a given couple of parameter $k_{eff,g}$ and S_w . Experimental drop of pressure are compared to simulated one to deduce both $k_{eff,g}$ and S_w .

4. In situ results on VeRCoRs mock up

4.1 Description of experimental plan

18 pulse sensors have been implemented in the VeRCoRs mock-up. They allow to obtain four saturation profiles. In the first lift of the containment structure, two profiles have been realized using six sensors for each one (for the 1st lift, the thickness of the wall is equal to 600mm). The 1st lift has been casted on the 27th of august 2014. In the 14th lift (400mm of thickness), casted on the 22nd of January 2015, two profiles have been realized using three sensors for each one. The concrete of the structure has been characterized through a laboratory study (see paragraph 3.1).

4.2 Interpretation of *in situ* “pulse” tests

The interpretation of the measures performed *in situ* from October 2014 to May 2016, are presented in figure 4 (for one of the profiles of the 1st lift). The sensors are numbered from 17 near the intrados (i.e. inner side of the structure wall) to 22 close to the extrados (i.e. outer side of the structure wall).

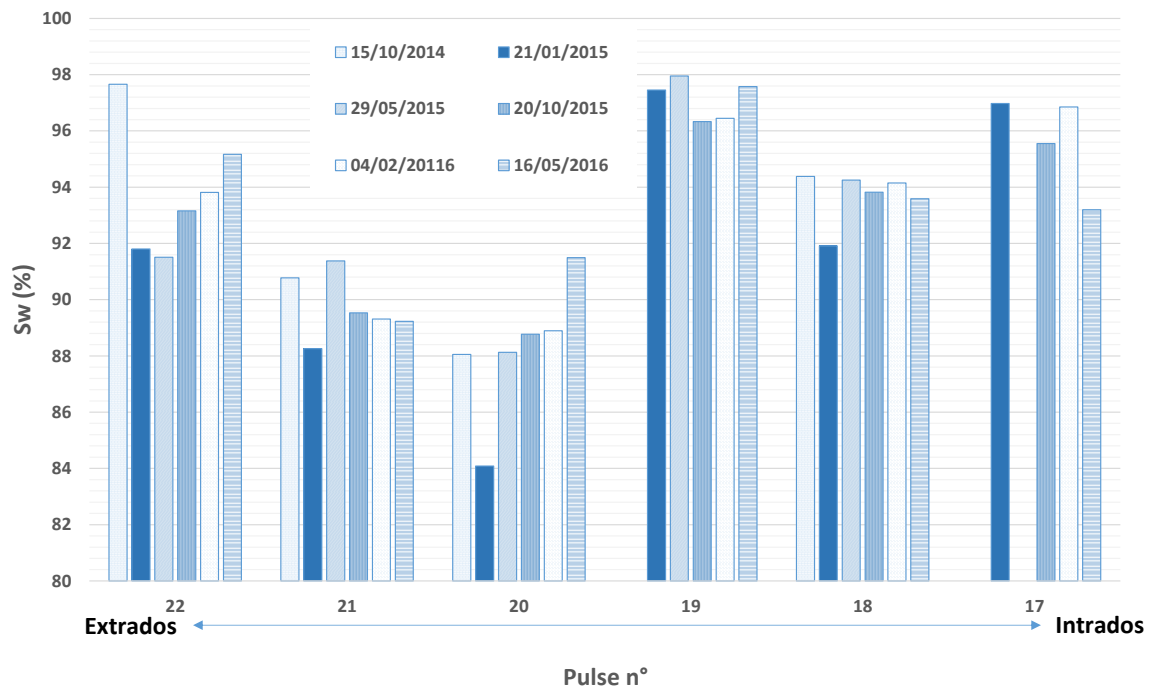


Figure 4. Interpreted water saturation from “pulse” tests along one of the profile of the 1st lift of VeRCoRs mock-up from October 2014 to May 2016.

The calculated liquid saturation ranges from 0.84 to 0.98. It seems difficult to validate these results with a high level of confidence, due to the lack of an alternative method to measure *in situ* water saturation in concrete structures. However, those values are consistent with those available in the literature addressing drying behavior of massive concrete pieces without hydric exchanges with the environment (which can be assumed to be the case for the concrete surrounding the “pulse” sensors casted in a thick wall). For example, Yssorche [20], has shown that, after one year, the internal relative humidity of concrete protected from atmosphere exchanges could vary from 88 to 99%, for concrete having a W/C ratio ranging from 0.44 to 0.59 which is the case of the concrete set in place in VeRCoRs (W/C=0.52).

In situ results show a good reproducibility, but the water saturation profile is quite different from the one expected for a thick wall during drying. This result may be due to the watering of the surfaces of the VerCoRS mock-up during its erection, which was undertaken to prevent any early drying involving lower shrinkage and creep after the prestressing of the cylinder.

5. Discussion

Other technics are available to determine liquid saturation in concrete structures. Using gas permeability presents some advantages and drawbacks.

The expected accuracy of this measurement technic lies in the fact that previous studies have shown that gas permeability mainly depends on the moisture content [3]. There is no hysteresis effect due to climate history, sensitivity to the amount of salts in the pore solution, and the effect of external temperature is limited (especially in the core of a massive concrete structure). Nevertheless, the accuracy of the method largely depends on the accuracy of the gas permeability measurement itself. Several apparatus exist to measure gas permeability, but they are mainly dedicated to characterize cover concrete. Among them we can cite, the “Vacuum Permeability Test” [21], the “Torrent” permeability test [22, 23], the “Autoclam Water and Air Permeability Test”. The suitability of those apparatus for liquid saturation measurement has not been assessed. The “pulse” test apparatus has been designed to investigate the core of concrete structures and the results presented by Liu [15] and in this presentation show that the accuracy of this method may be sufficient for this application.

Regarding the “pulse” method, the accuracy of the measurement depends on the *in situ* conditions, i.e. length and material of the tube used to connect the probe to the measurement device, thermal insulation of the measurement device, accuracy of the pressure manometer etc. The quality of concrete casting is also of importance. The concrete characterization laboratory study has shown that the results (porosity, permeability, desorption isotherm...) obtained from different 160x320mm samples were quite reproducible. Nevertheless, it can be objected that the concrete tested from samples, even if coming from real *in situ* batches, may not behave like the structural concrete. However, as the saturation measurement is not directly evaluated, whatever the measurement method, every result will be based on laboratory investigations carried out on witness material. The real material can be obtained only by coring the structure which is obviously impossible for storage ones. Even if it was possible, the concrete property spatial dispersion does not ensure that the properties of the cored sample are homogeneous into the whole structure.

One of the main source of error is then an inappropriate characteristic $k_{r,g}(S_w)$ curve. This may be due to the use of an unsuitable predictive models (see paragraph 2.1), or a laboratory characterization performed on a material which is not representative of *in situ* material. It is likely that the difference between the interpreted saturations between “pulse” sensors 20 and 19 (see figure 4) is due to the fact that the concrete surrounding those two sensors has different hydraulic properties. Indeed, they are too close from each other (less than 10cm) to explain a variation of liquid saturation of about 10% in the middle of a 60cm thick wall.

Microcracking can also lead to important differences between the $k_{r,g}(S_w)$ curve of a sound laboratory sample and the one of the *in situ* concrete. The influence of microcracking on the mass transport properties of concrete has been largely studied [5, 24, 25, 26, 27, 28, 29]. A large increase of apparent gas permeability is then observed when microcracking occurs, and the $k_{r,g}(S_w)$ curve obtained on sound concrete is no more valid. This microcracking may be caused by drying shrinkage [24, 30] or mechanical loading [26].

6. Conclusions

New devices to measure apparent gas permeability and water saturation within thick concrete structures have been designed, build and tested on the VeRCoRs reduced scale containment mock-up in France. The first measurements campaigns have clearly shown the “pulse” method efficiency and its consistency with expected initial water saturation of *in situ* concrete. The *in situ* measurements reveal a good reproducibility despite no real evidence of a concrete drying around the “pulse” probes up to now. This is consistent with the usual kinetics of this phenomenon for such large structures. Some saturation discrepancies are sometimes observed. As they cannot be attributed to the concrete drying, they can be assumed to come from the natural concrete dispersion or from microcracking. This method also reveals sensitive to any change in water saturation that was one of the main goal of the design of such methods.

Additional research will be conducted to assess the heterogeneity of concrete properties in large structures. The effect of casting operations on local variations of W/C and its influence on self-desiccation, porosity and permeability would allow a significant improvement on the interpretation of the results. In parallel to VeRCoRs project experiments, a set of pulse sensors have been implemented in a thick wall of the aircraft shell of Flamanville 3 EPR, France, to demonstrate the feasibility on a real nuclear site and to test this technique on a full scale building.

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