In situ concrete structures moisture measurement using a pulse test method

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ABSTRACT: The evaluation of the in situ moisture state of concrete is of great importance to understand the behavior of a structure and ensure its durability and integrity. A measurement device based on relative gas permeability measurement to determine concrete moisture has been designed. The results of a laboratory validation study are presented in this article and show the efficiency of this moisture measurement method. The device has been installed on a nuclear waste disposal site in France and the feasibility of an in situ experiment is also discussed.

1 INTRODUCTION

In situ moisture monitoring of cementitious structure, is of particular importance when they are dedicated to the confinement or to the disposal of dangerous materials (for example radioactive wastes). Indeed, moisture variation may induce effects capable of affecting the mechanical integrity of the structure or its durability. Dessaturation, for instance, implies a shrinkage which may lead to microcracking, due to structural effects. Furthermore, dessaturation increases the gas permeability of the material, which is an important parameter for the confinement capability of a structure. Moisture content measurement and its long term monitoring, in situ, is delicate and very few non destructive techniques are available. A study initiated by the French National Radioactive Waste Management Agency (ANDRA) and Electricity Of France (EDF) which is in charge of French nuclear plants management, aims to test and validate different monitoring devices and implement them in their structures. This comparative study is carried out on a reference material: a mortar with siliceous sand and CEM II cement with a high W/C of 0,8 ratio to increase connected porosity and water exchanges. Samples equipped with different measurement sensors are continuously monitored and placed in climatic chambers to ensure a regulated relative humidity and temperature, and then to obtain a stable and measurable moisture content. The study presented in this article focuses on a new measurement device designated as the “pulse sensor”. The measurement principle lies on the link between moisture content and relative gas permeability of a cementitious material. The measurement consists in measuring the in situ effective gas permeability, which allows determining the liquid saturation state. The measurement can only be performed if the material has been formerly studied in the laboratory. Such study provides the “input data” which are used to analyse the in situ measurement.
2 Presentations of the Laboratory Validation Study

2.1 Laboratory Determination of the Relative Permeability $K_{rg}(S_w)$ Curve

2.1.1 Darcy’s Law for One-Dimensional Flow and Experimental Device

Gas permeability ($K_x$) is measured using Darcy’s law for a one-dimensional flow (cf. Equation (1)). Argon is the gas used for the measurement; its dynamic viscosity is equal to $2.2 \times 10^{-5}$ Pa.s. The experimental apparatus consists of a hydrostatic cell, a gas pressure generator and controller, a gas tank and a pressure manometer (cf. Figure 1).

$$V_x = -\frac{K_x}{\mu} \frac{dP}{dx}$$  \hspace{1cm} (1)

The measurement is conducted by applying a gas pressure ($P_i$) on one side of a cylindrical sample while the other side is at atmospheric pressure ($P_0$). When the steady state injection state is reached, the mean entry gas flow ($Q_m$) is calculated by analyzing the drop of pressure through the tank. Permeability is then obtained from the following equation:

$$K_x = \frac{\mu Q_m}{S} \frac{2 \Delta P_i}{P_i^2 - P_0^2}$$ \hspace{1cm} (2)

where $S$ is the sample cross section area and $L$ its length.

The material and methods used in this study have been validated in many past studies (see for example Loosveldt (2002) or Chen (2009)).

![Figure 1. Simplified diagram: mean flow rate measurement.](image)

2.1.2 Material

To calibrate the method, a mortar with high porosity and permeability has been chosen. The idea is to obtain a stabilized state of water content in a reasonable time for samples put at different levels of relative humidity. The mortar used for the calibration has a water-to-cement (W/C) ratio of 0.8 and is composed of a siliceous 0/4mm sand and CEM II32.5R cement in a mass ratio of 3:1. The mortar is stored in limewater at 20°C three days after casting. At 28 days of maturation, cylindrical samples (65mm in diameter and 30mm in length) are cored. The porosity of the obtained mortar is equal to 21% and its intrinsic gas permeability is about $4.10^{-17}$ m².

2.1.3 Sample Saturation Measurement

The mass of each sample after coring is measured and considered as the fully saturated mass (M100). Samples are then stored in a controlled relative humidity, at 98, 29, 85, 75, 70, 59, 43 and 11% of R.H, until mass stabilization. The mass (Msw) and the effective permeability ($K_e(S_w)$) to gas are then measured. The dry mass (M0) is obtained after drying in an oven at 60°C. Considering those data and the volume (V) of each sample, the porosity ($\theta$) and water saturation ($S_w$) can be deduced from the following relations:
2.1.4 Relative permeability $K_{rg}(S_w)$ curve

The intrinsic permeability to gas ($K_{ig}$) is measured on each dried sample. The relative permeability to gas ($K_{rg}$) for a given water saturation is then obtained from equation 5. It varies from 1, when the material is fully dried, to 0 when the sample is fully saturated. Figure 2 represent the evolution of $K_{rg}$ versus moisture content. Experimental points are then fitted using a classical Van Genuchten - Mualem model (see Van Genuchten (1980). This leads to a continuous relationship between the relative permeability and the water saturation of the sample.

$$K_{rg}(S_w) = \frac{K_\varnothing(S_w)}{K_{ig}} \tag{5}$$

Figure 2: experimental measurements of relative permeability vs. liquid saturation, and Van Genuchten-Mualem fitting.

2.2 Relative permeability measurement using the “pulse sensor”.

2.2.1 Sensor design and experimental procedure

The pulse device sensor consists of a cylindrical stainless steel sintered of 3cm for its external diameter and 5cm in length. It is linked to an argon gas cylinder (holder) through a buffer tank. The buffer is connected to the sensor by a nylon tube. A manometer, linked to a computer, allows a continuous monitoring and recording of the gas pressure in the “pulse sensor”. The sensor is positioned before casting. This allows an optimal interface between the cementitious material and the sensor and avoids preferential flow paths around the tube.

For the laboratory experiment, the sensor is placed in a cylindrical mould of 11cm in diameter and 22cm in length. The mortar defined previously (see paragraph 2.1.2) is casted around the device and the nylon tube is accessible to be connected to the buffer tank. The manufacturing protocol of the sample equipped with the “pulse sensor” is the same which has been applied to the cored samples which have permitted to determine the $K_{rg}(S_w)$ curve (see paragraph 2.1.2 and 2.1.3) excepted that it has not been cored. After 28 days of curing, the mass (considered as the fully saturated mass) is measured. The sample is then placed in a climatic chamber with controlled temperature and relative humidity. The sample is then regularly weighed and its effective gas permeability is measured.
2.2.2 Measurement protocol

The effective permeability is obtained using a pulse test technique. The principle of this test is to increase rapidly gas pressure into the chamber, stop the injection and then measure the recovery pressure (see Skoczylas (1995)). At $t=0$, pressure in the hole is increased up to a relative pressure of 15 bars. The fall in pressure in the borehole is recorded and plotted against time.

3 DATA INTERPRETATION

3.1 Flow in cylindrical configuration

Governing equations at steady state are well known and documented (see, for example, Skoczylas (1995)). The effective permeability ($K_e$) is calculated from equation (6).

$$ Q = \frac{K_e \pi r_i^2 - r_0^2}{\mu} \frac{L}{\log \frac{r_o}{r_i}} $$

Where $L$ is the length of the chamber, $P_i$ the pressure in the chamber, $P_0$ 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 $P_0$). This equation cannot be applied in our case. Indeed, in an in situ configuration, the steady state could never be reached due to the size of the structure, or the measurement time may be unacceptable. Therefore, the effective permeability is determined using a numerical method to analyse the transient state.

3.2 Finite difference scheme

A one-dimensional (1D) finite difference scheme has been built using the MATLAB software, to obtain the evolution of pressure around the chamber as a function of time. The main equation is diffusion equation type, which is nonlinear, due to the high gas compressibility, and is written for cylindrical flow in equation (7):

$$ \frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} = \frac{\mu \phi (1 - S_w) \partial P}{\mu K_e \partial t} $$

$r$ ranges from $R_i$ to $R_o$. For $t=0$, $P$ is equal to atmospheric pressure for $r > R_i$ and equal to $P_i$ for $r = R_i$.

The pressure in the device is deduced by calculating the flow through the wall of the chamber deduced from mass balance equation and Darcy's law (see Skoczylas (2003)):

$$ \frac{dP_i(t)}{dt} = \frac{K_e S}{\mu V} P_i(t) \frac{\partial P}{\partial r} (R_i, t) $$

where $V$ is the volume of the chamber and the tube, $S$ is the surface of the chamber wall, $P_i(t)$ is the pressure in the chamber at the instant $t$, and $R_i$ is the radius of the chamber.

The drop of pressure in the chamber is simulated for a liquid saturation which varies from 0 to 100% by steps of 1%. Several curves are used to determine the liquid saturation of the material from the experimental drop of pressure.

4 LABORATORY RESULTS

4.1 Comparison between measured and real moisture

As described in 2.2.1, the sample is placed in climatic a chamber in a regulated relative humidity. Two de-saturation steps have been performed using a R.H of 92 and 72% until mass
stabilization of the sample. Water saturation is calculated from the mass of the sample and its porosity. This saturation is then compared to the one obtained from pulse pressure drop interpretation.

4.2 Interpretation

Figure 3 presents the results of liquid saturation measurement through weighing of the equipped sample and the numerical calculation obtained by analysis of the pressure drop curve. We observe, near the hygrometric equilibrium at 92% R.H., a good agreement between pulse measurements and weighing. At the start, larger difference can be explained by the relative saturation of the area close to sensor, whereas the specimen is already dried on the edge. During the drying step at 72% R.H., the gap between experimental and numerical points increases with the dessaturation process. As presented figure 4, the value of the influence radius may reach the border of the sample within the measurement period. The size of the investigated zone may vary according to the length of the measurement period and with the liquid saturation of the sample. For a given measurement time, the lower is the liquid saturation, the higher is the permeability and the bigger is the investigated radius. As a consequence, the heterogeneity of the casted material may affect the liquid saturation measurement. This effect should not be sensitive in the case of in situ testing of a massive concrete piece. We also have to consider a possible development of cracks around the “pulse sensor” due to drying shrinkage and incompatibility of elastic moduli between sintered stainless steel and high W/C mortar. Finally, the mortar casted in the 11x22 mould may be slightly different from the mortar used for the definition of the $K_{rg}(S_w)$ curve. This underlines an important point of this measurement method: the characteristic curve has to be defined for the investigated material, and if the material used for the characterization is not representative of the in situ material, the measurement may not be accurate. The quality of the preliminary characterization study is of major importance.

![Figure 3: comparison between liquid saturation measured by weighing and pulse interpretation.](image-url)
5 IN SITU EXPERIMENT

5.1 Context

In the context of nuclear waste storage, the long term durability of structures is particularly important. The moisture state influences elastic modulus, shrinkage, long term creeping, gas and liquid permeability. It is then a necessary entry parameter for a model simulating the behavior of structure over the storage period. The C.S.F.M.A., located in the Aube district, in the North-East of France, is a surface nuclear waste storage, managed by the French National Radioactive Waste Management Agency (ANDRA). Figure 5 present a global view of the disposal facility. This site is dedicated to the disposal of low and intermediate level short life wastes. The concept of this storage is stated, as follows. The waste, mainly coming from maintenance activities and operation of nuclear installations, is compacted or solidified, and it is placed in metal or concrete containers. The waste package is disposed in reinforced concrete cells (25 meters square by 8 meter height) (see figure 6) in successive layers (see figure 7). For each layer, the space between containers is filled with concrete in order to obtain a plane surface to place the next containers layer (see figure 8). The cells are then sealed with a slab of concrete, and a final several-meters-thick clay cap is placed over the cell for long-term protection. The pulse sensor is fixed in a reinforced steel cage and placed between the waste packages before concrete filling of the cell (see figures 9 and 10).
The objective of the “pulse sensor” installation consists in measuring the moisture content of concrete between waste containers in the center of a disposal cell. This implies that several meters of concrete separate the “sensor” from the operator who performs the moisture content measurement.

5.2 First results

The concrete used to fill the layers has been characterized in order to obtain the \( K_{rg}(S_w) \) curve necessary to deduce moisture content from gas permeability tests. Six pulse sensors have been installed in two different layers of a waste disposal cell, demonstrating the feasibility of the implantation. In addition, two 16x32 reference samples, made of the same concrete, have been equipped and placed beside the disposal cell. They can be weighed regularly to measure their liquid saturation and compared with in-situ measurement. Sensors have been connected to the measurement device and the first pressure drop curves have been obtained. The installation of the sensor has necessitated an important tube length (up to 50 meters) to link the sensor to the measurement device (gas holder and computer). This tube acts as an additional buffer tank. As the importance of the drop of pressure is directly linked to the size of the gas buffer tank (see 2.1.1), the amplitude of the pressure drop is lowered and reduces the accuracy of the measurement. External temperature variations are also a source of error. Figure 9 presents the pressure drops obtained for different pulse devices. The drop of pressure which appears at the beginning of the test is due to temperature effect. Indeed, due to gas compression, temperature is slightly increased and the observed variation of pressure is due to the return to ambient temperature. This variation is reproducible and can then be corrected. Concrete permeability appears close to zero, indicating a liquid saturation of 100%. Considering the size of the structure and the fact that the concrete has been casted for less than two years, this result is logical.
CONCLUSION

This study aims at testing the feasibility of using relative gas permeability to determine the moisture content of cementitious materials. Preliminary study has allowed characterizing the reference material used for the laboratory validation study. The laboratory experiment has underlined a good correlation between saturation measured by weighing and pulse measurement, at least above 70% of moisture content. The two measurements are diverging for lower saturation. Micro cracking around the device may explain this. The accuracy of this measurement method is linked to the quality of the preliminary characterization study. Differences of microstructure, due to changes in the casting methodology, between the material tested by the pulse method and the one used for the characterization study, may affect the quality of the results. The reliability of this measurement method proved by the laboratory study has led to place those sensors in a nuclear waste disposal facility, and, in a close future, in a 1.8m thick wall of the French EPR. The feasibility of pulse sensor installation in a nuclear facility environment and of pulse test completion have been demonstrated.

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References


