Neutron imaging of hydraulic flow within structural concrete

M. YEHYA[a,b], E. ANDÒ[a], F. DUFOUR[a,c], A. TENGATTINI[a]

a. Univ. Grenoble Alpes, CNRS, Grenoble INP[1], 3SR, F-38000 Grenoble, France
b. Grenoble INP Partnership Foundation, Chair PERENITI - EDF, Grenoble, France
c. Chairholder, Chair PERENITI (EDF SEPTEN/DTG/CIH), Grenoble, France
Email: mohamad.yehya@3sr-grenoble.fr, edward.ando@3sr-grenoble.fr,
frederic.dufour@3sr-grenoble.fr, alessandro.tengattini@3sr-grenoble.fr

Résumé :

La quantification et l'analyse de la distribution spatiale des flux et la compétition entre diverses porosités est à ce jour un verrou scientifique majeur ne permettant pas d'alimenter proprement des modèles de perméabilités si ce n'est par le biais de la perméabilité moyenne. Le but de cette étude est de développer une nouvelle méthodologie et de valider le dispositif experimental par imagerie neutronique à la ligne de faisceaux D50 à l'Institut Laue Langevin. Le test consiste à injecter de l'eau normale (H_2O) sous haute pression dans un échantillon de béton coulé et saturé avec de l'eau lourde (D_2O) afin de suivre la progression d'un front d'eau dans le temps par différence d'atténuation des deux eaux. Un test préléminaire a été mené et les premiers résultats sont présentés.

Abstract :

Quantification and analysis of the spatial distribution of fluid flows in concrete, translating the complex interconnections between various porosities is to this day a major scientific challenge that hinders the development of complex permeability models since practically all experiments measure some sort of average permeability. The purpose of this article is to develop a methodology and to validate an experimental setup using neutron imaging at the NeXT instrument on the D50 beamline in the Institute Laue Langevin (Grenoble), by injecting normal water (H_2O) into a concrete sample casted and saturated with heavy water (D_2O) at high pressure. A preliminary test was conducted and the initial results of neutron imaging showing the moving water front are here presented.

Key-words : Neutron imaging, Permeability, Concrete, Heavy water, Normal water

[1]Institute of Engineering Univ. Grenoble Alpes

1 Introduction

The durability of reinforced concrete structures is mainly governed by the transfer properties of the material. Service life of reinforced concrete structures is often limited by the penetration of chemical compounds dissolved in water into the porous cement-based material. Most of, not to say all, physical and chemical reactions are delayed in time if the material has a low permeability. Furthermore, for specific structures such as confinement vessels of nuclear power plants, gas reservoirs, *etc.*, a tightness criterion is imposed. In concrete structures, fluids may migrate through different paths: in the bulk of the material due to porosity and microcracking, along macrocracks [2] if any, or along geometrical discontinuities (*e.g.*, rebar interface [3], construction joints). Therefore, the analysis of relative influence of the different propagation modes is a key issue for the characterization and the modeling of the concrete structure durability.

Neutron radiography has shown in previous studies that the hydrogen (in water for example) highly attenuates neutrons [4, 5], thus its presence in the sample has high contrast in the resulting radiograms, allowing the detection of the hydraulic front. This technique is considered as a very powerful tool in determination of hydraulic behavior in geomaterials and concrete compared to x-ray radiography (which itself is better suited to following the solid skeleton [1]). With this technique, it is also sometimes possible to distinguish different isotopes of the same element. A good contrast between normal (H_2O, density 1.00 g/cm^3) and heavy (D_2O, density 1.11 g/cm3) water can be obtained, since D_2O attenuates neutrons 7 times less than H_2O [4] , allowing neutrons to penetrate further into the sample.

The main objective of this paper was to develop a technique capable of determining the water permeability by applying a pressure gradient allowing normal water to percolate into the concrete sample that has been casted and saturated with heavy water. An external confining pressure will be applied to seal the specimen in order to prevent leakage around the sides, also to prevent the internal damage of the material due to the occurred internal pressurization.

Quantitative estimates of the front's velocity between both waters and connected porosity of the concrete can be made by analyzing the neutron-attenuation images when applying a pressure-driven flow into the saturated concrete sample. An inverse analysis will be required to estimate the local permeability in the sense of Darcy.

2 Experimental method

The visualization of fluid flow and characterization of porous media in concrete, by means of neutron scans, have been tested at the NeXT imaging instrument (institute Laue Langevin ILL in Grenoble). The flow-experiment set-up (see fig.1) was prepared and a preliminary test was performed.

As the quality of concrete increases, measuring water permeability with high accuracy has become more difficult. High pressure driven flow should be selected for the purpose of accelerating the test and in order to increase the water flow available, thereby reducing the error of the measurement. A Titanium hassler cell was designed in order to handle the high pressure and to be transparent to neutrons. De Beer and Middleton [6] were the first to use two-phase fluid flow through oil bearing rock inside a Hassler high-pressure apparatus in order to reproduce deep reservoir pressure conditions . A standard concrete sample (7cm x 7cm) was selected to contain sufficient aggregates to be representative, and was prepared with heavy water (and thereafter kept saturated) in order to start with a relatively low neutron attenuation. A first campaign of tests on mortar cubes in compression shows that the resistance is not affected by the hydration in heavy water. Two similar cubic mortars of edge 4.3 cm were poured, one with normal water and the other with heavy water. A simple compression test up to the peak was carried out. The compression peak for the D_2O mortar was 68.4 kN significantly greater than the one with H_2O that was 50.9 kN. This means that using heavy water to cast our samples in the future will not have a negative impact on the strength of our concretes but perhaps even increases their mechanical strength. Repeatability tests are of course necessary.

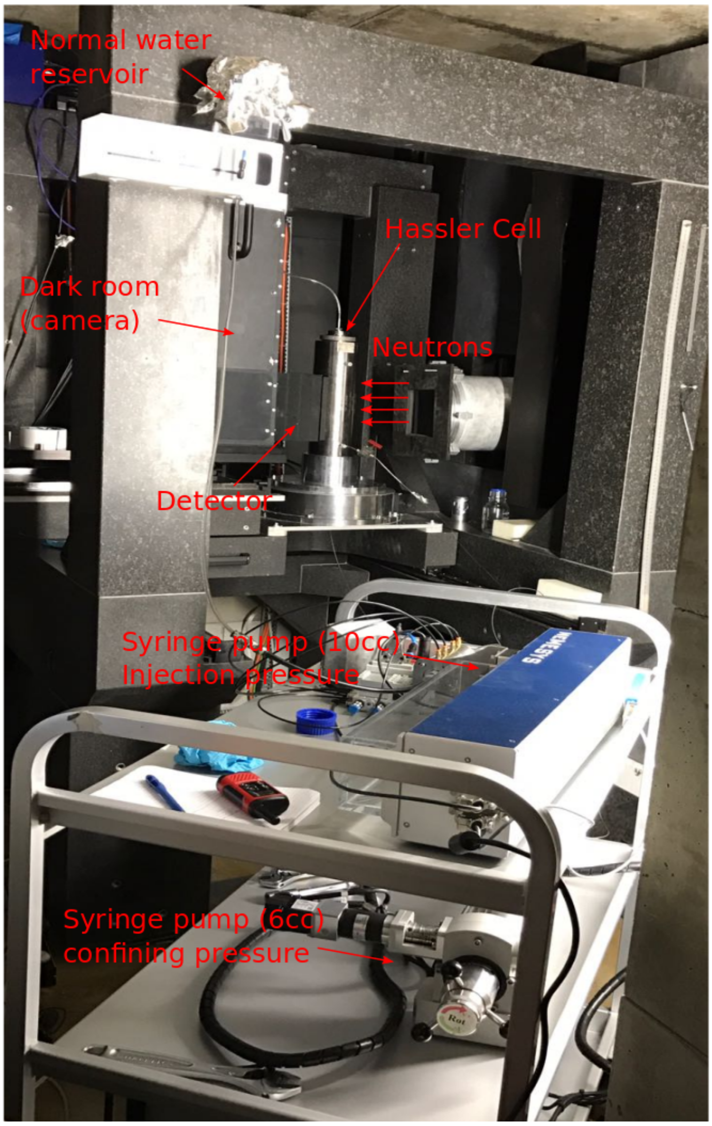

Figure 1: Experimental set-up at the beamline D50 at the ILL.

On the other hand, a 2 mm thick Teflon membrane was used to seal the sample preventing the confining water to penetrate. Fig.2 shows the attenuation of the saturated D_2O concrete sample inside the membrane. As we can see the sample was not fully saturated (some black zone corresponding to air-filled pores) since the sample has being poured kept under in heavy water for only one month. The membrane/concrete interface appears to attenuate many neutrons since there was heavy water added during the tomography to avoid evaporation and to keep the sample saturated.

The aim of the water injection test is to detect and follow a rising front between both waters over time. The difference in attenuation between H_2O and D_2O will allow us to estimate the flow velocity at any point. Once found, a local Darcy-permeability field can be obtained by inverse analysis; *i.e.,* matching the velocity field with a numerical model with the same conditions. During the test, two syringe pumps were used. One with a small reservoir of 6 cm^3 was used to maintain a confining pressure of 30 MPa with D_2O to minimise attenuation of the beam. The second pump with 10 cm^3 capacity, was saturated with H_2O and refilled remotely during the experiment thanks to an H_2O reservoir.

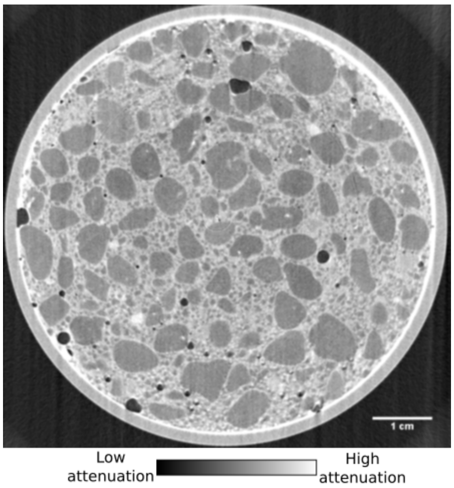

Figure 2: 3D reconstructed horizontal slice of the heavy water concrete sample inside the Teflon membrane before starting the experiment.

After a stable confinement was achieved, H_2O was injected at 20 MPa. This pressure was chosen in order to have a reasonable percolation time and to have an acceptable cost for this experiment. During the water percolation process, continuous neutron radiographies were acquired in order to follow the raise of the H_2O front in the sample. A series of radiographies with an exposure time of 10 seconds were acquired through the injection phase, which lasted 1hr30mins. Periodically the injection was paused to acquire longer neutron-tomographies in order to characterize the H_2O front in 3D. The fluid injection was paused after 13 mins and a 2-hour tomography was launched. 720 projections were acquired, each the result of the average of 3 projections, over an 180 degrees rotation. The exposure time was 10 secs and the images were acquired with 2x2 binning. It should be noted that the normal water front in the sample appears stable when the injection pressure is maintained at zero.

3 Results

Fig.3 shows the neutron radiography images for normal water (blue) into the concrete sample saturated with heavy water (green) during the injection test. It should be noted that the images were normalized by the dark and the flat images, and the outliers values removed (the very-low and very-high pixel values, corresponding to ineffective detector pixels the noise caused by secondary gamma radiation).

A series of horizontal sections of the 3D sample after 13 min of H_2O injection is shown in fig.4, the distance between two slices being of about 1 cm in the sample. There was more normal water flowing in the left part of the sample that was more porous as we can see in the reconstruction. Fig.3 shows that the water percolates directly in the porous zone of the concrete especially in a large pore visible at 1cm from the bottom which was filled rapidly.

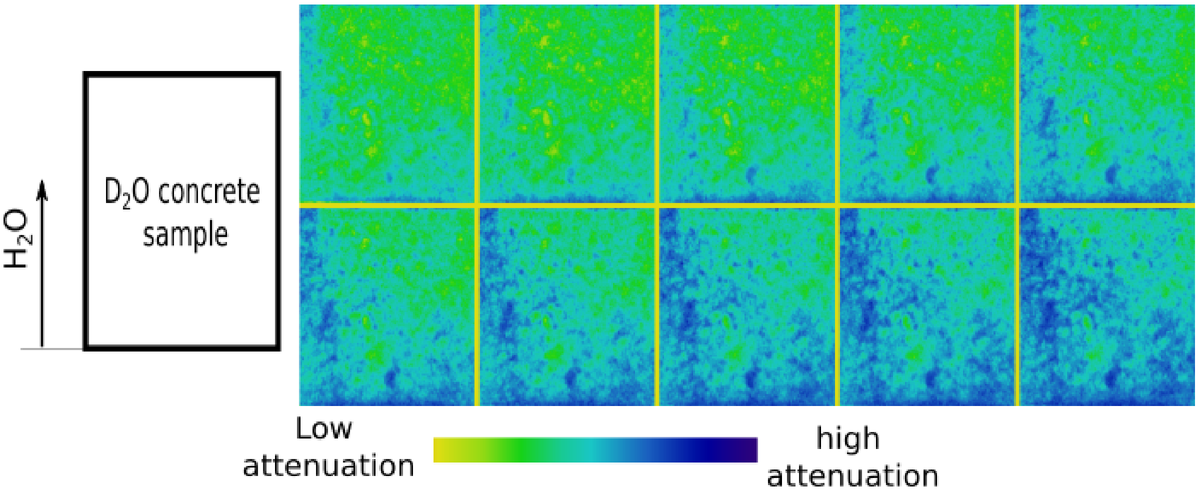

Figure 3: Time-lapse neutron radiography images of normal water injection into heavy water concrete sample. The time intervals between each image are about 8 minutes.

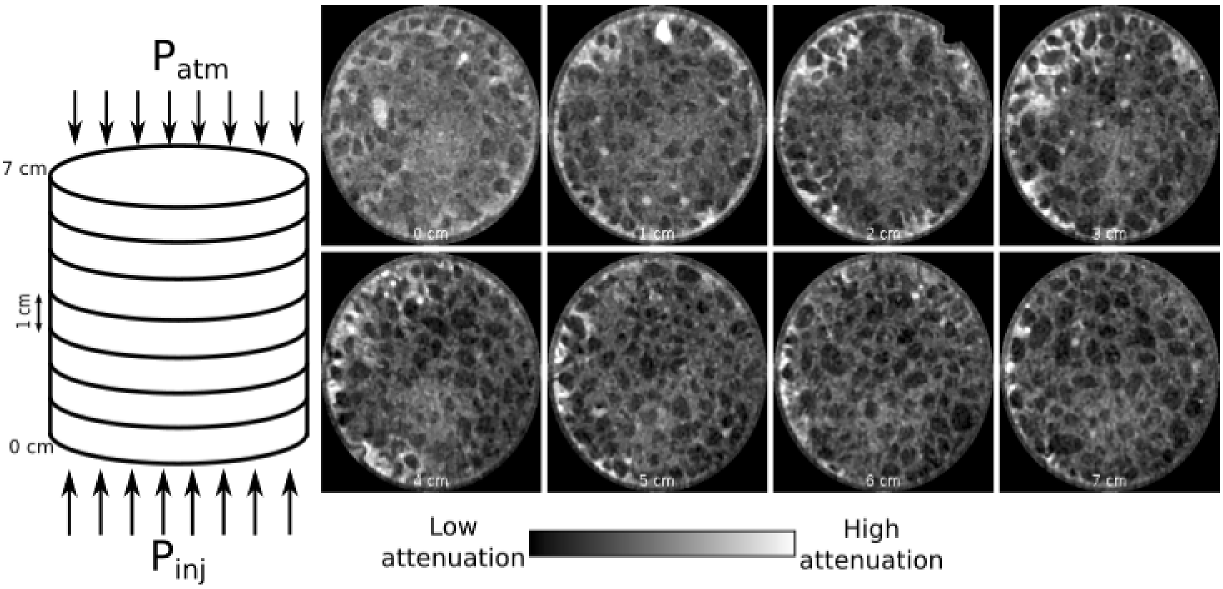

Figure 4: Series of horizontal slices showing the distribution of the water in the different positions of the sample after 13 min of injection.

4 Conclusion and outlook

This contribution presents preliminary results of neutron imaging used to follow fluid flow under high confinement, taking advantage of the high contrast between the normal water flushed in the sample and the heavy water used to cast it. The key aim of the work was to follow a rising front in the saturated specimen under high pressure, which provides the possibility to acquire a velocity field and therefore to estimate a local permeability field by inverse analysis.

In this paper we presented the methodology and the experimental setup used to study the local permeability in a concrete sample using the neutron radiography technique. Further experimental works will focus on the study of cracked and reinforced concrete by injection as well as on the visualization the water percolation under high pressure, in order to validate the existing numerical models of the permeability.

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References

[1] E. Andò, G. Viggiani, S. A. Hall, & J. Desrues, Experimental micro-mechanics of granular media studied by x-ray tomography: recent results and challenges, Géotechnique Letters, 3, 142–146, 2013.

[2] M . Ezzedine El Dandachy, M. Briffaut , F. Dufour & S. Dal Pont. An original semi discrete approach to assess gas conductivity of concrete structures, International Journal for Numerical and Analytical Methods in Geomechanics, DOI: 10.1002/nag.2655 , 2016.

[3] M. Briffaut, M. Ezzedine El Dandachy, S. Dal Pont & F. Dufour. Permeability analysis of the interface between concrete and rebars during push in test,Strategies for Sustainable Concrete Structures, Rio De Janeiro, 14-16 December, 2015.

[4] E. Perfect, C.-L. Cheng, M.Kang, H.Z. Bilheux, J.M. Lamanna, M.J. Gragg & D.M. Wright. Neutron imaging of hydrogen-rich fluids in geomaterials and engineered porous media: A review, Earth-Science Reviews, 129, 120–135, 2014.

[5] P. Zhang, F.H. Wittman, T.Zhao & E.H.Lehmann. Neutron imaging of water penetration into cracked steel reinforced concrete, Nuclear Engineering and Design, 241, 4758–4766, 2011.

[6] F.C. de Beer & M.F.Middleton. Neutron radiography, porosity and permeability in porous rocks, South African Journal of Geology, 109, 541–550, 2006.