INTERSTITIAL PORE PRESSURE IN CONCRETE UNDER HIGH CONFINEMENT PRESSURE: MEASUREMENT AND MODELLING

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Abstract. Application of concrete material in the design of protective structures requires the knowledge of its mechanical behavior when subjected to extreme loading conditions (i.e. ballistic impacts). Under such kind of loading, the material is subjected to high triaxial compressive stresses. Generally, protective concrete structures are massive and thus their drying process is very slow. Hence, the water saturation ratio may reach 100% at their core whereas their skin dries very quickly. In the last decade, a large number of studies have been conducted on this topic. Researchers studied the role of the concrete saturation ratio and initial matrix porosity on the response of concrete material under high confinement. Results have shown that the pore pressure developing in the material becomes considerable and increases the volumetric stiffness of concrete while restraining its strength capacity. This paper reports interstitial pore pressure measurement, conducted on a very wet reference concrete, under hydrostatic tests at high confinement. Experimental results show the volumetric behavior of concrete and the evolution of the pore pressure with respect to the applied confinement pressure. Then, analytical modeling, within the poromechanical framework based on the effective stress concept, is developed to estimate the interstitial pore pressure evolution under high confinement. The model shows promising results while comparing it to the experimental values.

1 INTRODUCTION

Concrete and cementitious like materials are widely used in the construction field. Sensitive concrete structures tend to be massive, and they remain quasi saturated in their core most of their life time while their face dries very fast [3]. These structures can be subjected to multi-axial mechanical loading (i.e. impact, detonation) leading to high triaxial compression stresses onside the component materials. Expanding the knowledge on the behavior of these structures under such loading conditions is of vital importance for people's safety and environmental damage prevention. Thus, numerous studies were conducted to quantify the effect of water content on concrete behavior when subjected to high stress levels. Skoczylas et al. [12] stud-

ied the drying effect on normalized mortar behavior under triaxial loading up to 50 MPa of confinement. He found that when the mortar is saturated, the failure strength decreases when compared to the dried mortar. This observation can be due to a local interstitial over-pressure and to a capillary suctions as stated by the author. Many researchers have extended the previous result by investigating the effect of free water on concrete materials under high confining pressure. Triaxial tests at 600 MPa of confinement were performed by [15], [8], [7] on concrete samples having different composition and saturation ratios. Results have shown that when the water content increases, a decrease of the axial strength and a hardening of the volumetric behavior are observed. According to these

authors, this phenomenon is due to the presence of free water inside pores which induces an increase of the interstitial pore pressure. In parallel to the experimental work, several constitutive models were developed to predict and reproduce the concrete behavior within this loading range (high triaxial stresses and high strain rates) [9]. In this paper, an experimental campaign is devoted to measure the interstitial pore pressure of the R30A7 concrete subjected to high hydrostatic compressive stress (up to 500 MPa) using two kinds of pressure sensors previously designed [1], [2]. Then, a numerical model, issued from the PRM one [9], is developed to simulate the increase of concrete interstitial pore pressure due to the porosity closure mechanism observed experimentally under high confinement [10]. The presented model uses the poromechanical approach and estimates the evolution of pore pressure by taking into account the effect of saturation ratio and initial porosity of concrete. Model results will be compared to the experimental one at the end.

2 TESTING PROCEDURE

2.1 Experimental device

The pore pressure measurement tests are conducted using the GIGA press installed at the 3SR laboratory (Figure 1: left). The press is constructed by THIOT engineering company with the financial support of the CEA and DGA in 2004. It is capable to generate a confining pressure up to 850 MPa and an axial stress reaching 2.3 GPa on a specimen with 7 cm in diameter allowing to perform a triaxial test at high confining pressure. Figure 1: right, describes in detail the inner part of the press. Concrete or rock samples (5 by 10.5 cm or 7 by 14 cm in diameter and length consecutively) are sandwiched between two main caps made of Tungsten material. The press is equipped with two sensors, a pressure and a force sensor. Both monitor the amount of confinement pressure and axial force during tests [14]. However, the press does not provide any information on the interstitial pore pressure since all the tests are performed under undrained conditions.
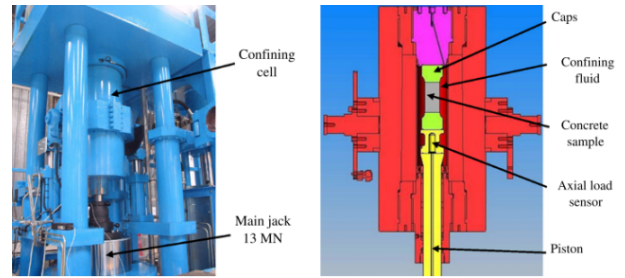

Figure 1: Giga press: (left) general view (right) cross-sectional view of the confinement cell

2.2 Set up for pore pressure test

A new experimental set up, already developed [1], consists in shortening the sample initial length (from 14 cm to 8 cm in height) and introducing a water collecting cap (6 cm in height) made of steel as shown in (Figure 2). The suggested device proposes to measure the interstitial pore pressure indirectly by means of a deformable sensor equipped with a strain gage (see [1] and [2] for more details).
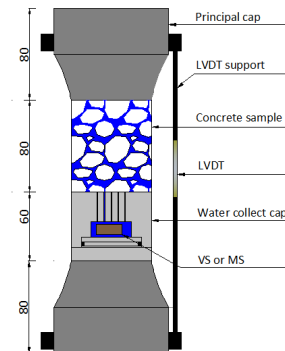

Figure 2: New design of the movable device

2.3 Concrete properties

Since this study is part of a larger project (launched in 2004) aiming to understand concrete triaxial behavior under high confinement, it is obvious to choose the same reference concrete named R30A7 (unconfined compressive strength of 37 MPa, w/c = 0.64, 12% porosity accessible to water). This concrete is deeply investigated before for different saturation ratios and states (dry or very wet). The formulation, preparation and processing of samples are inspired by [14]. For tests under high confinements such as those carried on the GIGA press,

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the imposed size of the specimens is 7 cm in diameter and 14 cm in height with a maximum size of the aggregates equal to 8 mm. We assume that, although with 8 cm specimen height, the granular skeleton still has a homogeneous distribution. Finally, each concrete sample is immersed into water for more than five months before performing pore pressure measurement tests so that the saturation of concrete is guaranteed.

3 EXPERIMENTAL RESULTS

3.1 Pore pressure measurement

Interstitial pore pressure tests have been performed on wet concrete under hydrostatic loading up to 500 MPa of confining pressure (p_c). Each test consists of applying homogeneous pressure around the specimen thanks to a non-compressible fluid at a rate of 1.7MPa/s until the target value is reached. In this phase, the mean stress (σ_m) is considered equal to the confinement pressure (p_c). Table 1 summarizes the experimental tests including the name of each test, the used sensor, the applied confinement and the maximum reached pore pressure.

Table 1: Summary of the pore pressure measurement tests

Test Name	Sensor type	σ_m (MPa)	p (MPa)
p1	HS	600	120
p2	HS	500	360
p3	HS	500	360
p4	HS	500	355
p5	HS	500	425
p6	HS	500	200
p7	HS	500	210
p8	HS	500	250
p9	MS	300	196

3.2 Concrete volumetric behavior

Figure 3 shows the results of concrete volumetric behavior during pore pressure tests compared with the results obtained by [7] on dry and very wet R30A7 samples. The volumetric strain ($\epsilon_v = \epsilon_x + 2\epsilon_\theta$) is estimated from the

axial strain ϵ_x using the LVDT and by considering that the concrete behavior is completely isotropic ($\epsilon_x = \epsilon_\theta$). In general, concrete volumetric behavior passes through three phases, an elastic phase until 40 MPa of confinement a compaction phase until 300 MPa associated with matrix damage, porosity closure and a hardening phase where the behavior of saturated concrete is stiffer than the dry one since the free water inside the saturated concrete is being compressed. It is observed that almost all of the tests have a small elastic phase followed by a compaction phase less stiff than both references concrete. Beyond 300 MPa of confinement, all the curves retrieve the same shape and slope as the saturated reference sample.
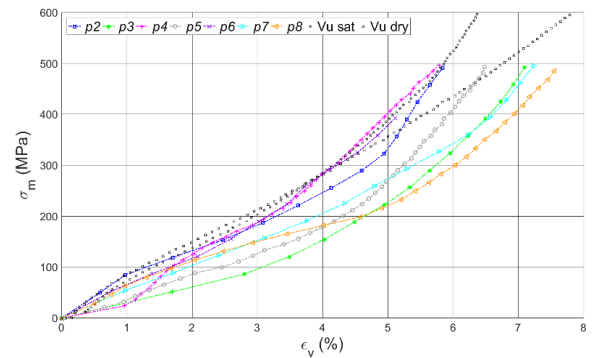

Figure 3: Concrete volumetric behavior during pore pressure test. Comparison with the reference concrete behavior for the dry and very wet states: σ_m vs. ϵ_v

4 NUMERICAL MODELLING

This section pertains to simulate the increase of concrete interstitial pore pressure due to the porosity closure mechanism observed experimentally under high confining pressure. The model presented herein is inspired from the coupled PRM model and takes into account the influence of the saturation ratio and the initial porosity of concrete ([9] and [13]).

4.1 PRM model: effective stress concept

The coupled PRM model was developed by Pontiroli, Rouquand and Mazars [9], in order to simulate concrete structures behavior when subjected to impacts. It is the resultant of two coupled models, a damageable model allowing

the description of concrete degradation mechanism at low stress and an elasto-plastic model called (KST). The latter is developed to reproduce the irreversible mechanism of the porosity closure during compaction, as well as the deviatory threshold depending on the average stress of the concrete under strong confinement [6] and [11]. The effective stress concept has been introduced into the PRM model so that the effect of water on the material behavior is considered. To do so, two approaches have been proposed. The first is the mixing law, serial or parallel model, while the second approach is the poro-mechanical theory. Both approaches make possible to simulate the volumetric behavior of the partially saturated material and permit to relate the volumetric deformation to the mean stress and water pressure. Therefore, the material is decomposed into a solid phase. Some voids filled with air while others are filled with water [5]. As long as the porosity filled with air has not been completely closed, the material is not consolidated and the water does not intervene in the behavior of the material. Beyond the point of consolidation, the presence of water is taken into account for both the volumetric behavior and the limit state curve (Figure 4). The mixing law approach showed a defect as stated by [13] since the behavior of the material became elastic after reaching the consolidation point (closure of all free pores) which is not observed experimentally.
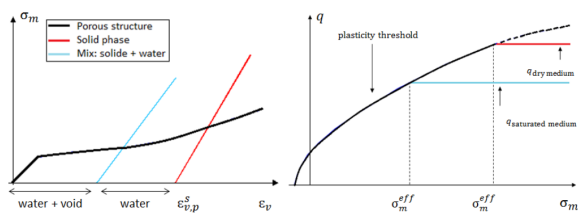

Figure 4: PRM coupled model with saturation ratio effect on the concrete volumetric and deviatoric behavior

4.2 Poromechanical approach

In this paper, the poromechanical theory is adapted to account for the effect of free water [5]. The concept of the effective stress is introduced to separate the fluid pressure in the total stress (σ_{tot}). This latter is supposed to be the sum of the mean stress transmitted by the skeleton at the macroscopic scale (σ_m) and the water pore pressure (p) corrected by the Biot's coefficient (b) [4], (eq. 1).

$$\sigma_{tot} = \sigma_m + bp \qquad (1)$$

4.3 Model parametric study

The described model is validated analytically under hydrostatic loading using a Matlab code for a saturation ratios and initial porosities range equal to [S_r = 100, 95, 85, 11%] and [ϕ_0 = 12, 15%] respectively. Figure 5 shows a comparison between the analytical mean stress and the experimental results obtained for both dry and saturated reference concrete [7]. The model gives very good results for saturation degrees between 85 and 95% where the consolidation point as well as the progressive increase of stiffness are well reproduced. The model significantly underestimates the deformations when the concrete is fully saturated which is explained by the high sensitivity of the model to the saturation ratio. It is also observed that the effect of the initial porosity decreases when the saturation ratio decreases. It is worth recalling that the analytical dry curve coincides with the experimental one since this latter is considered as an input parameter in the model.
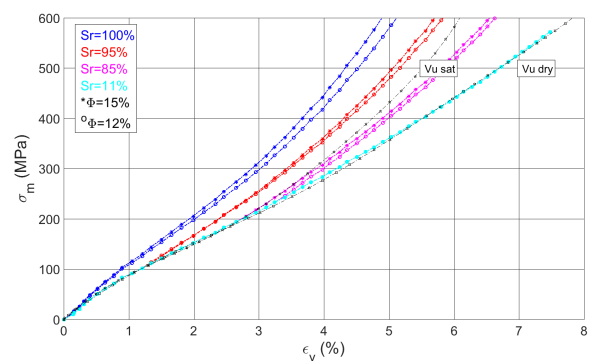

Figure 5: Model validation for different S_r-ϕ_0 compared with the dry and saturated R30A7 [7]: σ_m vs. ϵ_v

Figure 6 displays the pore pressure evolution with respect to the applied mean stress. It is clear that the increase of the saturation ratio induces an increase in the pore pressure since the

pores are filled by more water (i.e. 200 MPa of confinement is required to close all the pores for S_r equal to 85% against 100 MPa for S_r equal to 95%). The results also reveal that for the same saturation ratio and for a given mean stress, the higher the initial porosity is the lower the pore pressure is obtained.
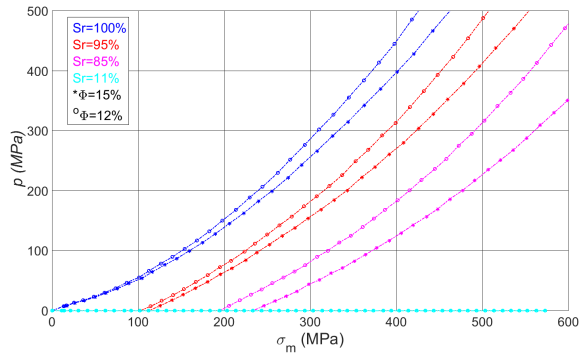

Figure 6: Model validation for different S_r-ϕ_0: p vs. σ_m

4.4 Comparison with experimental results

Figure 7 depicts the mean and envelop curves of the experimental evolution of the pore pressure with respect to the mean stress, compared to the numerical results for higher saturation ratios [S_r=100, 98, 95%]. The numerical model displays a great capability to cover experimental results. On the one hand, the maximum range of the experimental curve lies very close to the analytical one with a saturation ratio as high as 95%. Moreover, it is clear that a better estimation of the pore pressure occurs at high initial porosity.
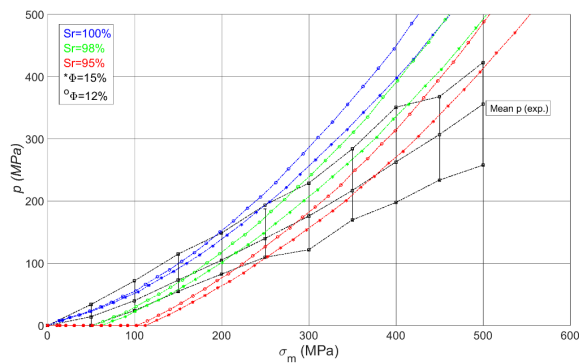

Figure 7: Comparison between the experimental measurement and the numerical results: p vs. σ_m

A closer look at the results is exposed in (Figure 8). The analytical curve with S_r equal to 98% estimates perfectly the experimental result where a very low pore pressure is recorded at low confinement. This result reveals the capability of the model to reproduce the behavior of a non-saturated sample where the pore pressure is not measured until the pores are all closed.
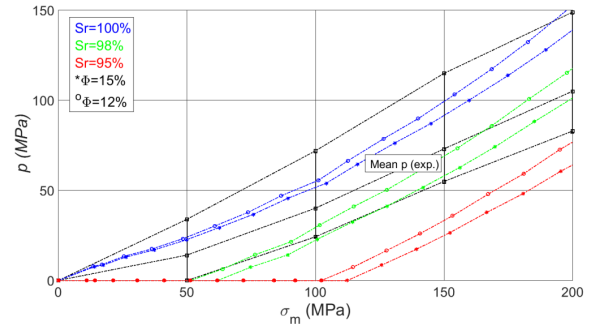

Figure 8: Zoom on the first part of figure 7: p vs. σ_m

5 CONCLUSION

Thanks to a novel experimental set up, interstitial pore pressure tests have been performed under hydrostatic condition at high confinement (up to 500 MPa) on an saturated R30A7 concrete using the Giga press. Experimental results show a significant effect of the cap/specimen initial saturation states on the response of concrete. Under low confinement, a quasi-null pore pressure is recorded for some tests. However, as long as the specimen is compressed, the pore pressure evolutions become stiffer and may reach high values. In addition, concrete volumetric behavior is evaluated during pore pressure tests due to LVDT facility. Three important stages are highlighted. A shorter elastic behavior, a less stiff compaction phase followed by a consolidation phase beyond 300 MPa of confinement. This paper has also presented the development of numerical model issued from the PRM coupled one. A poromechanical approach has been used in which the effective stress concept is considered. The model is dedicated to evaluate the porosity closure and the evolution of the pore pressure at a high confinement level. Finally, results obtained experimen-

tally have been compared with the numerical one by varying only two main parameters (the saturation ratio S_r and the initial porosity ϕ_0). The model showed a good capability to reproduce the evolution of the interstitial pore pressure with respect to the applied confinement.

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