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Investigation of the Interstitial Pore Pressure of Saturated Concrete under High Confinement †

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Abstract: The objective of this study is to measure the interstitial pore pressure into saturated concrete under hundreds of megapascals of confinement. This study is carried out within a more general context aiming to understand the behavior of concrete structures under impact. It is well known that the water saturation in massive concrete structures evolves from quasi-dry state at the surface to reach a quasi-saturated state at the core. Since the response of these structures under impact is highly linked to the state of saturation into the material, it is suspected that the pore pressure plays a major effect. This paper presents a new testing technique developed to measure the concrete pore pressure at high confining pressure. This latter is generated by means of a high capacity GIGA press. The new concept consists in implementing a pressure sensor into a water collecting cap. This cap is designed specially to collect water from concrete subjected to mechanical confinement pressure. Experimental results show that concrete pore pressure can reach values of the order of the confining pressure.

Keywords: wet concrete; high confinement; pore pressure; hydrostatic pressure sensor

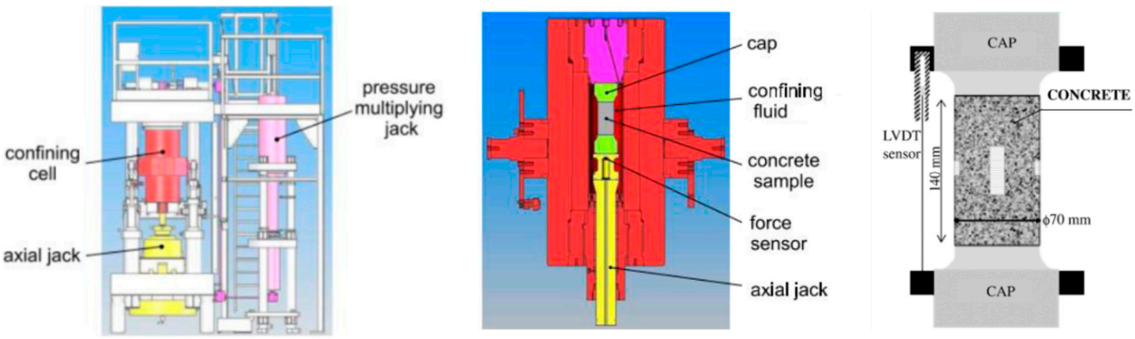
1. Introduction

When a projectile penetrates a concrete structure during an impact, a state of triaxial stresses with very high confinement level occurs into the material [1,2]. Besides, massive concrete structures keep a saturation ratio strongly depth dependent almost all their life time (from a quasi-saturated state into the core to an almost dry state near its faces) [3]. The effect of saturation ratio, water over cement ration, concrete initial porosity and aggregate shapes and nature were deeply investigated under static and dynamic conditions at high confinement [4–7]. These tests have demonstrated that concrete saturation ratio influences strongly its behavior. The presence of water in pores generates a hardening of the bulk modulus and, in the same time, a strong reduction of the shear strength under high confinement. It was also shown that the quantity of free water contained in concrete pores has a preponderant role on its behavior under high confinement compared to other material parameters like the water/cement ratio and the concrete porosity [8]. While all these experimental observations may be attributed to an increase of the interstitial pore pressure due to the porosity closure during the mechanical loading, such a pressure was never measured. To measure the interstitial pore pressure into the R30A7 reference concrete, a new testing technique has been developed using the GIGA press of 3SR Laboratory. The technique consists in replacing the 14 cm concrete sample by a smaller one (8 cm in height) and a water collecting cap (6 cm in height). A deformable sensor, equipped with a strain gage, is placed into the free space of the water collecting cap. This setup is used to conduct hydrostatic tests up to 500 MPa of confinement on concrete samples. The experimental procedure adapted for the calibration test is clearly shown. Pore pressure measurement tests and results on a fully saturated concrete sample are discussed at the end.

2. Experimental Procedure

2.1. Experimental Device and Concrete Samples

The main machine used to achieve the experimental campaign is called the GIGA press [9]. It is a large capacity press designed specifically to study the triaxial behavior of geo-material under high confining pressure, (Figure 1a). A cross section of the press is shown in (Figure 1b) where a concrete specimen is placed inside the confining cell. To generate the hydrostatic confinement, a specific confining fluid called DOZ is injected into the cell through an upper opening. This test is called hydrostatic in which a pressure is applied all around the specimen. Once the sample is confined, an axial force is generated by means of a 10 MN jack located under the cell. The GIGA press allows loading a cylindrical concrete specimen having 7 cm in diameter and 14 cm in length to a confining pressure up to 0.85 GPa and a maximal axial stress of 2.3 GPa. The large sample size of 14 cm in length (compared to the high stress level) allows testing real concrete samples with an aggregate size able to reach 8 mm [10] (Figure 1c).



(**a**) (**b**) (**c**)

Figure 1. GIGA press (**a**) general view (**b**) section of the confining cell (**c**) sample instrumentation.

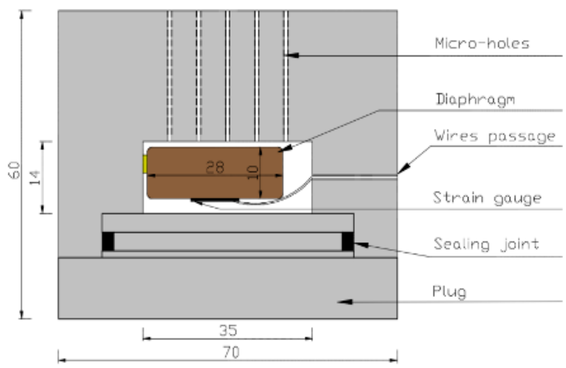
Since this study is part of a larger project that aims to characterize the triaxial behavior of cementitious material, the same reference concrete (R30A7) already studied before is used herein [11,12]. Its composition and mechanical properties are summarized in Table 1. Sample fabrication, conservation and preparation have to be accomplished very carefully in order to guarantee a good reproducibility, so that the same procedure of [5] has been followed. First, the concrete block is cast in a parallelepiped mold. Once the block is cured (after 24 h) it is removed from the mold, covered within plastic bags and conserved in a saturated environment for 28 days. This technique permits to insulate the concrete both physically and thermally. Second, the block is cored cylindrically at 7 cm in diameter and cut at 8 cm of length. Finally, all the concrete samples are immersed in the water for approximately five months until their masses stabilization before being tested.

Table 1. Compositions and mechanical properties of the R30A7 ordinary concrete.

Concrete Mix Properties	Kg/m^3	Mechanical Properties	Values
Cement CEM I 52.5 N	263	Compressive strength (MPa)	30
Sand 'D' 1.8 mm	838	Porosity accessible to water (%)	12
Gravel 'D' 0.5–8 mm	1007	Slump (cm)	7
Water	169	W/C	0.64

2.2. Water Collecting Cap and Sensor Design

The GIGA press is not equipped by a drainage system for pore pressure measurement, so that a water collecting cap is created and place below the concrete sample, (Figure 2a). The collecting cap is made of steel material and has 7 cm in diameter and 6 cm in length. The concrete sample's initial length is shortened to 8 cm so that the overall length of the new system remains equal to 14 cm. The collecting cap has 24 micro-holes of 1 mm each driven on its upper surface. Thanks to those micro-holes the water pressure can be transmitted from the concrete sample to the cap cavity once the hydrostatic loading is applied. The water collecting cap lower part consists of a movable plug permitting an easy access into the cavity. The plug itself is equipped by an O-ring sealing joint so that no mixing between the acting confining fluid and the water inside the cap could occur. In its current state, the water collecting cap is not able to measure any pressure, thus a deformable sensor is fabricated. The sensor is made of an aluminum material (Young modulus E equal to 80 GPa and Poisson ratio ν equal to 0.35) and has a dimensions of 28 cm in length and 10 cm in thickness which are lower than the cap free space. A gage is glued on the sensor upper face and it is protected from water conductivity with specific mastic. A single hole is done on the cap lateral surface serving to pass the connection wires from the cap inner space to the press acquisition system. This sensor (hydrostatic type) is loaded in all directions once placed into the cap cavity so that it deforms homogeneously under pressure. The water collecting cap, the upper plug, the O-ring joint and the sensor supplied by the gage-connection wires are illustrated in (Figure 2b).



(**a**)

(**b**)

Figure 2. Water collecting cap with the sensor of hydrostatic type (**a**) design and (**b**) real concept.

3. Interstitial Pore Pressure Tests

Once the design is set a calibration test of the hydrostatic sensor is required. This test aims to establish a relation between the applied known pressure and the sensor strain. An aluminum sample having two connected holes of 4 mm in diameter each driven transversally and longitudinally is used. The concrete sample is then replaced by the aluminum specimen placed above the water collecting cap. The applied known confinement pressure is then transmitted from the aluminum specimen holes to the sensor placed inside the cap through the cap micro-holes, (Figure 3a). Therefore, the sensor bulk modulus K can be deduced from the applied pressure and the strain gage volumetric response under hydrostatic loading (K = p_c/ε_v). Referring to the calibration test results K is set equal to 90 GPa. After sensor calibration two interstitial pore pressure measurement tests are performed on very wet concrete samples under hydrostatic pressure at 400 and 500 MPa of confinement. The aluminum sample is replaced by a saturated R30A7 concrete one. The interstitial pore pressure is quantified by multiplying the sensor bulk modulus by the strain evolution (p_i = K ε_v). Tests preparation, wires protection and membranes application require rapidity to minimize the surface water evaporation phenomenon. A wet sponge is attached on the concrete side surface during the preparation phase. Before each test, the water collecting cap is saturated by water, (Figure 3b).

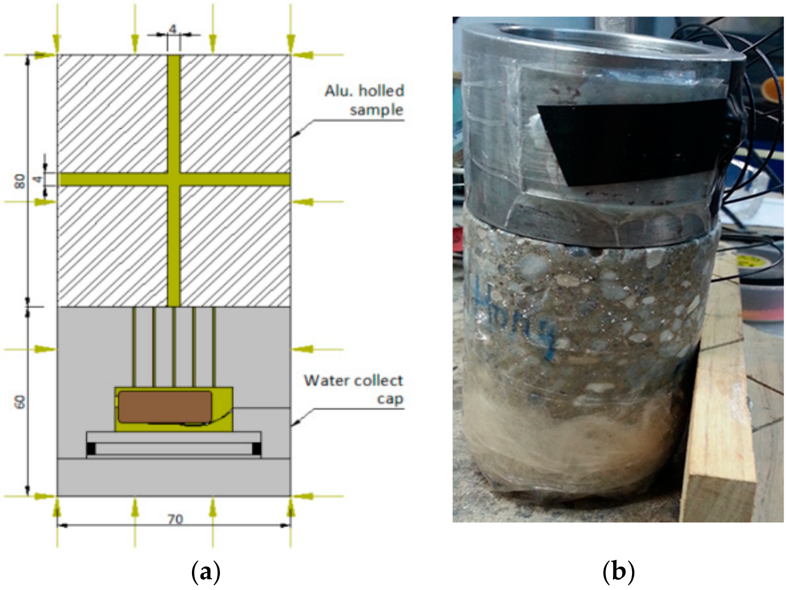


Figure 3. Experimental set up: (**a**) calibration test concept (**b**) pore pressure test preparation.

Figure 4 presents the result of two interstitial pore pressure measurement tests under hydrostatic confinement conducted on saturated concrete. The concrete pore pressure, p_i is plotted versus the applied confining pressure p_c. The evolution of pore pressure for both tests at the beginning is different. An instantaneous increase of pore pressure against a quasi-null one for both tests is noticed. Two reasons can explain this behavior: the first one is linked to the experimental set up. For instance, it may come from either a late response of the sensor or a slight default in the saturation process while saturating the water collecting cap. The second reason could be linked to the concrete itself where it may conserve a small void filled by air and not by water during the saturation period (S_r lower than 100%). Thus, the pore pressure for test (HYDR 400 MPa) starts to increases when all pores are totally closed. For both tests, the pore pressure increases linearly at the beginning then a change in slope which becomes stiffer is noticed since the concrete skeleton undergoes the compaction as the sample is more confined.

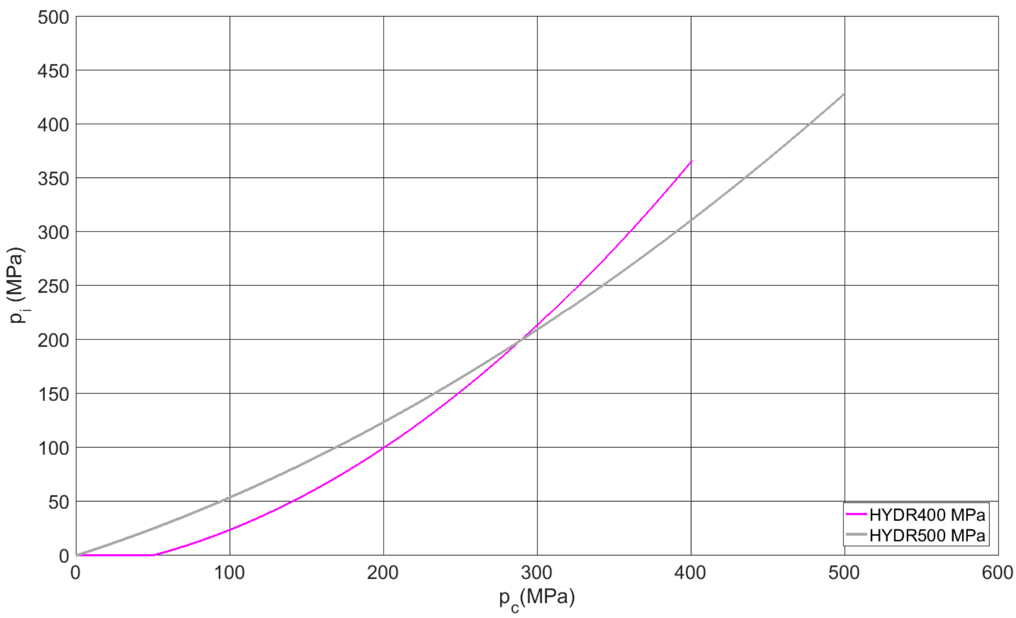


Figure 4. Pore pressure tests result: pore pressure p_i vs. confining pressure p_c.

4. Conclusions

A new testing technique aiming to measure the interstitial pore pressure into concrete has been presented in this paper. The technique consists in creating a water collecting cap equipped with a deformable sensor of type hydrostatic. The experimental study has been accomplished thanks to the GIGA press at the 3SR laboratory. Two kinds of test, where each one has a different purpose, have been discussed. The first one is the calibration test in which a relation between the known confining pressure and the sensor strain is established. The second one is the pore pressure measurement test on a reference ordinary saturated concrete. Results show that pore pressure could reach very high level up to 400 MPa under 500 MPa of confinement.

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