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Influence of cement matrix porosity on the triaxial behaviour of concrete

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ABSTRACT

This article focuses on the influence of the cement matrix porosity on the triaxial behaviour of concrete in the presence of high confining pressures. It offers new experimental results on two concretes, respectively a high performance concrete (HPC) and a low performance concrete (LPC). These results complement recent studies on ordinary concrete (OC), in using the same large-capacity triaxial press. This paper serves to better characterise the behaviour of these 3 concretes, whose porosities are very different in terms of volume and size; moreover, it emphasises that the contribution of cement matrix strength (mainly linked to its porosity) decreases at high confining pressures and that concrete behaviour is governed by the granular skeleton, even when the capillary porosity is low or the entrapped air porosity is high. To reach this level of residual behaviour, higher confining pressures are needed for HPC, even if the amount of porosity compacted is smaller.

1. Introduction

When a concrete structure is subjected to an impact or a blast loading, the component material may be subjected to high triaxial compression stresses as well as tensile stresses due to the reflection of compressive waves on free surfaces [1–4]. For dynamic compressive loadings, the strain rate effect is mainly due to the inertial effect [2, 5–9]. The triaxial behaviour of concrete can therefore be identified under quasi-static conditions using a triaxial press with a high loading capacity [10–14]. Such tests are complementary to dynamic tests, which are unable to reproduce complex loading paths with a homogeneous stress state at the material scale.

Using the GIGA press, several studies have been conducted on specimens made of the same reference concrete [11,15]. This ordinary concrete, called R30A7 and denoted OC in this paper, displays a 28-day compressive strength fc28 of approx. 30 MPa and a slump of 7 cm. These studies (on specimens 7 cm in diameter and 14 cm high) show that the confined concrete behaviour is influenced by variations in both the water/cement ratio [16] and saturation ratio [17]. The influence of the water/cement ratio was also studied by Burlion et al. [10] on specimens 5 cm in diameter and 10 cm high, with water/cement ratio higher than 0.5 up to a confining pressure of 600 MPa. The effect of coarse aggregate and cement paste volume on concrete behaviour has also been investigated [18,19] showing in particular that coarse aggregate shape exerts no influence on the concrete response at high confinement whereas a lower aggregate strength serves to weaken the shear strength of concrete. All these triaxial compression tests have led to the conclusion that unconfined compressive strength is a poor indicator of the high-pressure mechanical response of concrete [16,18,20]. These results reveal that under high confinement, concrete behaves like a non-cohesive granular stacking, on which the cement matrix strength of the sound concrete no longer exerts any influence. The concrete becomes insensitive to fc28, whereas the saturation ratio exerts a major influence, particularly on both the concrete strength capacity and the volumetric stiffness. It would appear necessary therefore to evaluate and take into account the saturation ratio in order to accurately determine the vulnerability under the impact of massive concrete infrastructure.

Up until now, only ordinary concretes have been studied using GIGA press, with concrete porosity only varying by a small amount. Schmidt et al. [13] have conducted experimental studies on specimens of 5 cm in diameter and 11 cm high, with fc28 = 46 MPa up to a confining pressure of 500 MPa, but the porosity effect has not been studied. During severe triaxial loading, significant volumetric strains are observed; obviously, both the compaction and saturation ratio effect are expected to be correlated with concrete porosity. Hence, an investigation into the effects of varying porosity on the behaviour of concretes under high confinement is undertaken to complete previous findings. As an example, studies by Kearsley and Wainwright investigated the relationship between porosity and strength of foamed concretes, up to unconfined compressive strengths of about 100 MPa [21–23].

Concrete porosity extends to a very wide range of scales. Fig. 1 illustrates the porosity scale associated with concrete components. Concrete pores can be found from the nanoscale to the millimetre scale, with four pore types ultimately being identified. At the nanoscale, porosity occurs

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between CSH sheets; from the nanoscale to the microscale, a capillary network becomes observable due to the excess free water in concrete (the network is usually divided into gel pores from 0.5 nm to 10 nm and capillary pores from 10 nm to 10 μm [24]); between 50 μm and 1 mm, the porosity is mainly due to entrained air during the mixing process; and lastly, the millimetre scale features trapped air voids that are assumed to be expelled by a correct concrete vibration dependent upon the workability of fresh concrete.

The aim of this experimental campaign is to study the influence of concrete porosity on the triaxial behaviour of concrete, in addition to highlighting the influence of both capillary porosity and entrained air porosity. Previous results obtained on ordinary concrete (fc28 of approx. 30 MPa and a slump of 7 cm) are compared with concretes containing lower and higher porosities, in paying attention to modify just one porosity at a time. The first section below will describe the experimental device and compositions of used concretes, respectively a designed high performance concrete (HPC), which presents a capillary porosity much lower and low performance concrete (LPC), with a higher macroscopic porosity. Section 2 will provide a summary of these new experimental results in terms of axial, volumetric and deviatoric behaviour. The third and last section will analyse the results derived.

Notations

Variables

E	Young's modulus
p	confining pressure
ε	strain
σ_x	principal axial stress
σ_{mref}	reference mean stress
$\sigma_m = (\sigma_x + 2p) / 3$	mean stress
$q = \sigma x - p$	deviatoric stress
q_{max}	maximum deviatoric stress

Abbreviations

LVDT	linear variable differential transformer
REV	representative elementary volume
HPC	high performance concrete
LPC	low performance concrete
OC	ordinary concrete

Sign conventions

$\varepsilon > 0$	during contraction
$\sigma > 0$	during compression

2. Experimental program

This section will briefly present the experimental device, as detailed in [26], and provide information regarding concrete composition and concrete samples.

2.1. General description of the triaxial GIGA press and the experimental set-up

The GIGA press was designed to study the behaviour of concrete under high confinement within the framework of a partnership between the 3SR laboratory and the CEA Gramat Centre. It serves to load cylindrical concrete specimens 7 cm in diameter and 14 cm high to a confining pressure of up to 0.85 GPa and an axial stress of 2.3 GPa. This large specimen size makes it possible to test real concrete samples with a largest aggregate size capable of reaching 8 mm.

In the following discussion, σ_x denotes the principal axial stress, p the pressure inside the confining cell, $\sigma_m = (\sigma_x + 2p) / 3$ the mean stress, and $q = \sigma_x - p$ the deviatoric stress (principal stress difference). Compression stresses and contraction strains are all assumed to be positive.

All tests have been conducted by following the same type of loading path. The triaxial compression test begins with a hydrostatic test and, once the desired confinement has been reached, the specimen is loaded axially while holding the confining pressure constant. Concrete strains are measured by means of a LVDT sensor and by one axial and two circumferential gauges. The LVDT sensor gives the length variation of the specimen. Each part of the LVDT is fixed on a cap, which leads to a global measurement of the axial strain. Detail about the used gauges, glue and gauges protection could be found in Vu et al. [26].

2.2. Specimen production

Concrete specimens were cast in parallelepiped moulds with batch volumes of 13.5 l (27 × 27 × 18.5 cm^3). Concrete placement entails 30 s of vibration on a vibrating table. The concrete block, upon removal from the mould 24 h after casting, was stored for 28 days in a saturated environment within plastic bags immersed in water, so as to insulate the concrete both physically and thermally.

The specimens used were 70 mm in diameter and 140 mm high (i.e. for a sample size compatible with the press and a size ratio = 2). The maximum aggregate size contained in the concrete mix was 8 mm. For triaxial tests, such dimensions yield an REV (representative elementary volume; minimal dimension = 3 to 5 times the largest aggregate) and help protect against significant variability in results due to the presence of large aggregates. All samples were cored and rectified with water, in order to prevent edge effects due to their geometrical defects [26].

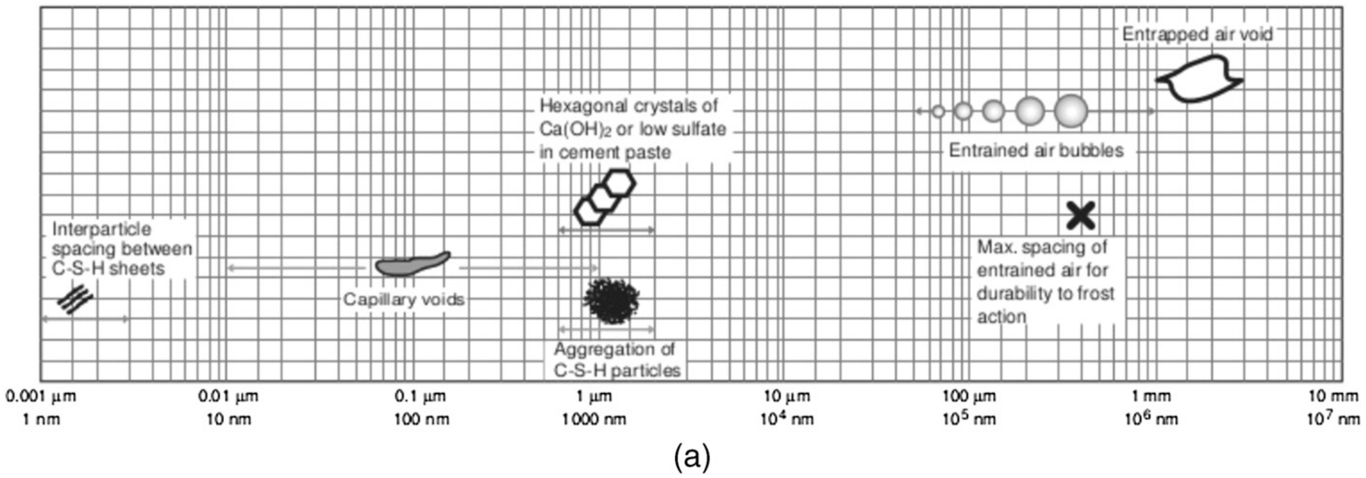

Fig. 1. Solid scales and pore voids in concrete [26].