Influence of the saturation degree and mix proportions on the behavior of concrete under high level of stresses

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ABSTRACT: The aim of the present study is to identify the concrete behavior under severe dynamical loading (explosions or ballistic impacts). This paper presents the effect of both the saturation degree and the water-cement ratio on the concrete behavior under static triaxial loading. The tests are done using a press with high capacities: confining pressure up to 650MPa and axial stress up to 2.3GPa. The test results show that the saturation degree has a major influence on the concrete deviatoric behavior. The strength of dried concrete strongly increases with the confining pressure whereas it is a constant for saturated samples beyond a confining pressure of 100MPa. The results also show that the concrete behaves like a granular stacking under high confinement without any influence of the cement paste strength.

1 INTRODUCTION

Right after the cement setting, an ordinary concrete is a quasi-saturated material. Most of the time, it is then submitted to a lower environmental relative humidity, so that a drying process occurs in the concrete. As the pore network of the cement matrix is very thin, this moisture transport is a very slow process which can be described using a diffusion-like equation (Baroghel-Bouny et al. 1999). The time required to reach the moisture equilibrium varies with the square of the built structure thickness. As most of concrete sensitive infrastructures such as dams or nuclear reactors are very massive, they might remain quasi-saturated in core most of their life-time whereas their facing dries very fast.

The concrete drying effect on its shrinkage or cracking has been intensely studied. It is well known that the saturation degree of the hardened concrete has a significant effect on its static uniaxial behavior (Burlion et al. 2005). On the other hand, there are very few results about the effect of the water on the behavior of concrete when it is subjected to extreme dynamical loadings (explosions or ballistic impacts). This lack of knowledge is due to the difficulty of reproducing such loadings experimentally with a simultaneous control of the concrete moisture content. If we consider for example the impact of a missile on a concrete structure, we observe three phases of triaxial behavior, each one associated with different damages but sometimes occurring simultaneously (Zukas, 1992). The validation of concrete behavior models taking into account simultaneously the phenomena of brittle damage and irreversible strain such as compaction thus needs new test results reproducing the complex loading paths described previously. The majority of the available experimental results in literature only relate to triaxial loadings with moderate confinement pressure. They notably allowed us to understand the transition of brittle-ductile behavior which is a characteristic of floating cohesive materials (Li et al. 1970). Numerous studies show that dynamic tests performed on concrete, for example by means of split pressure Hopkinson bars (Zhao et al., 1996), are difficult to realize essentially because of the brittle feature of material that leads to a rupture in the transient stage of loading. The inhomogeneous character of the stress state in the sample, the very limited control of the load path and relatively poor instrumentation lead to a delicate test result exploitation.

We present in this paper an experimental study on the concrete mechanical behavior under high confinement pressure, using a static triaxial press, called "GIGA". This press allows us to attain homogeneous, static and well controlled stress levels of the order of one Giga Pascal. The static characterization of a behavior model with a view to predicting dynamic behavior is not a new practice in the study of geomaterials. The rheological behavior of concrete under compression seems to slightly depend on the deformation rate for dry specimens (Bischoff et al., 1991). The very strong dependence on the loading rate in traction can be mainly explained by the influence of defects (Hild et al., 2003). Similar experimental studies were carried out previously. They were limited to small mortar samples (Burlion et al., 2001). The aim of the present study is to extend this practice to the study of "true" concretes (centimetric aggregate size). This paper presents the effect of both the saturation degree and the water-cement ratio on the concrete behavior under extreme static triaxial loading.

2 EXPERIMENTAL DEVICE

GIGA press is a large capacity triaxial press which has been specifically designed and developed for this study (Thiot, 2004). With this press, cylindrical concrete specimens of 7 cm in diameter and 14 cm in length with a confining pressure of up to 0.85 Gpa and with a 2.3 GPa maximum axial stress can be tested. Figure 1 shows a general scheme of the press (see Vu et al. 2006, Gabet et al. 2006, for more details).

The concrete specimen, surrounded by a membrane impermeable to the confinement fluid, is positioned between caps made of tungsten carbide. The specimen is also instrumented with a axial displacement sensor of type Linear Variable Differential Transformers (LVDT), one axial gauge and two orthoradial gauges (Figure 2). The axial stress applied to the specimen and the pressure inside the cell can be determined by means of a force sensor and a pressure one.

The porous feature of the concrete required the development of a protective multilayer membrane surrounding the specimen, preventing the confining fluid from infiltrating through the specimen (VU X. H. et al, 2006).

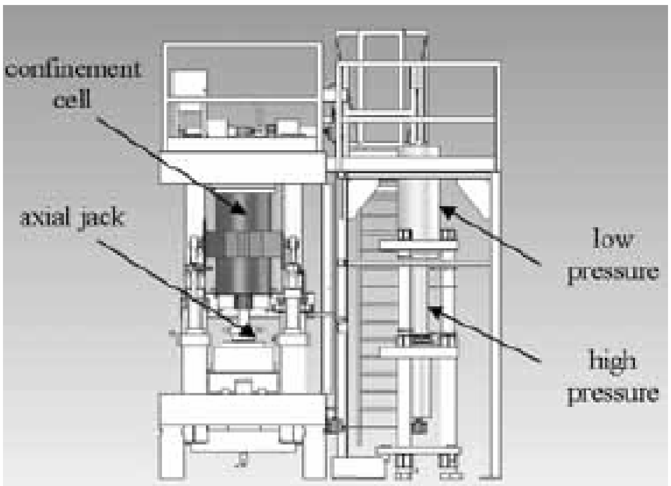

Figure 1. General scheme of the press

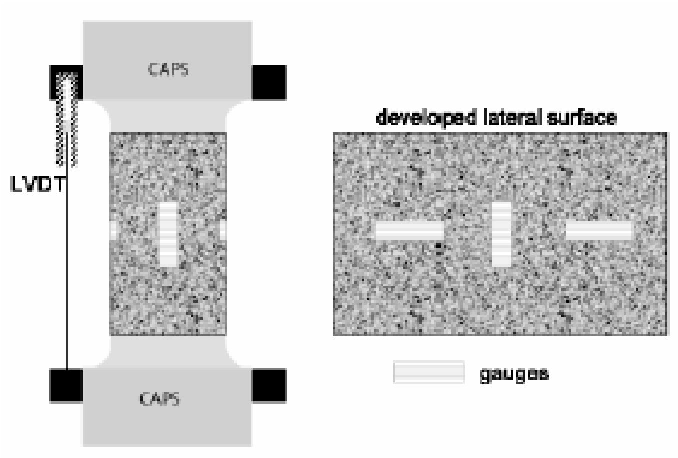

Figure 2. Scheme of strain measurement

3 MATERIAL DESCRIPTION

3.1 *Standard concrete R30A7 (dried, partially or "completely" saturated state)*

The standard R30A7 concrete is formulated for a resistance in simple compression at age of 28 days (fc28) and a slump of 30 MPa (± 2 MPa) and of 7cm (± 1cm) respectively. The aggregate size of the concrete is such that it must pass through the 8mm sieve when sieving. The composition and the mechanical properties of the concrete R30A7 are presented in table 1.

The concrete is preserved during 28 days in saturated surroundings inside waterproof bags immersed in water to insulate the concrete both physically and thermally. The specimens are then conserved in a drying oven at 50 °C for the dry specimens, or in water for the saturated specimens. A concrete sample is considered "100% dried" or "100% saturated" when the difference in its mass between two consecutive weighing during 24h is less than 1%. The partially saturated samples are conserved in water and then a few days in air. The saturation degree of these samples is determined by regular weighing and a drying kinetic of the saturated sample during preparation.

Table 1. Concretes mix proportion and mechanical properties

Mix proportion (kg/m^3)	**R30A7**	**EC08**	**EC04**
Aggregate D 0,5/8	1007	1007	1007
Sand D0/2	838	838	838
Cement CEMI52,5	263	226	352
Water	169	181	137
Water reducing admixture	0	0	4.57
Mix proportion (kg/m3)	**R30A7**	**EC08**	**EC04**
Fresh concrete properties	**R30A7**	**EC08**	**EC04**
Slump test (cm)	7	15	7
Entrapped air volume (%)	3.4	5.0	4.1
Water-cement ratio W/C	0.64	0.8	0.4
Cement paste volume Vp (%)	0.286	0.286	0.286

3.2 *Two other concretes (EC04 and EC08)*

In the composition of a concrete, the water-cement ratio (E/C) plays a very important role as it represents the cement paste strength. In the aim of studying of the water-cement ratio effect, two other concretes (EC04 and EC08) have been formulated at water-cement ratios of 0,4 and 0,8 respectively. Both concretes EC04 and EC08 have the same cement paste volume (total volume of water and cement) and the same aggregate composition as the standard concrete R30A7 (E/C=0.64). The composition and the mechanical properties of the concrete EC04 and EC08 are also presented in table 1. The procedure of specimen fabrication for these concretes is similar that of the dried concrete R30A7.

4 INFLUENCE OF SATURATION DEGREE

In this paper, compressive stresses and strains are assumed to be positive, some following symbols are used: σ_x is the principal stress, p is the pressure inside the cell $\sigma_m = \sigma_x + 2p$ is the mean stress, $q = \sigma_x - p$ is the principal stress difference (deviator), ε_x is the axial strain measured by LVDT (or axial strain gauge), ε_θ is the orthoraxial strain measured by orthoradial strain gauge and $\varepsilon_v = \varepsilon_x + 2\varepsilon_\theta$ is the volumetric strain.

A series of triaxial tests on dried and saturated concrete R30A7 samples have been carried out to study the influence of saturation degree. There are also a few tests which concern intermediate saturation degree. Because the drying kinetic of a saturated sample during its preparation occurs quickly, a saturated sample loses in general 20% of the water mass in its volume after 24h of exposure to air. Because of the complex sample instrumentation procedure before a test, the preparation of a concrete sample with strain gauges glued on its surfaces requires at least 24 hours, so that the majority of the “completely” saturated samples become partially saturated samples with a saturation degree of approximately 80% at the beginning of the test. Some triaxial tests have been carried out on “completely” saturated samples without strain gauges.

The results of triaxial tests carried out on dried and partially saturated concrete samples at confining pressure of 0 (simple compression), 50, 100, 200, 400, 650 MPa are presented as principal stress versus strains (Figures 4a and 4b) and as mean stress versus volumetric strains (Figure 6).

In the figures 4a and 4b, the hydrostatic part of each test shows a reproducible and isotropic behaviour because the two components of strain (ε_x, ε_θ) are very close. For the dried sample, the load-carrying capacity increases significantly with the increase of confining pressure. Whereas the saturated samples seem to have a perfectly plastic behaviour regardless of the confining pressure.

Figure 6 shows a similar compaction behaviour between saturated and dried samples during the hydrostatic phase. For saturated samples after a significant compaction phase, an abrupt dilatancy appears when the maximal axial stress is reached. This is also the case for dried samples at low confining pressure, but at higher confining pressure, the stress level continues to increase after the appearance of the dilatancy.

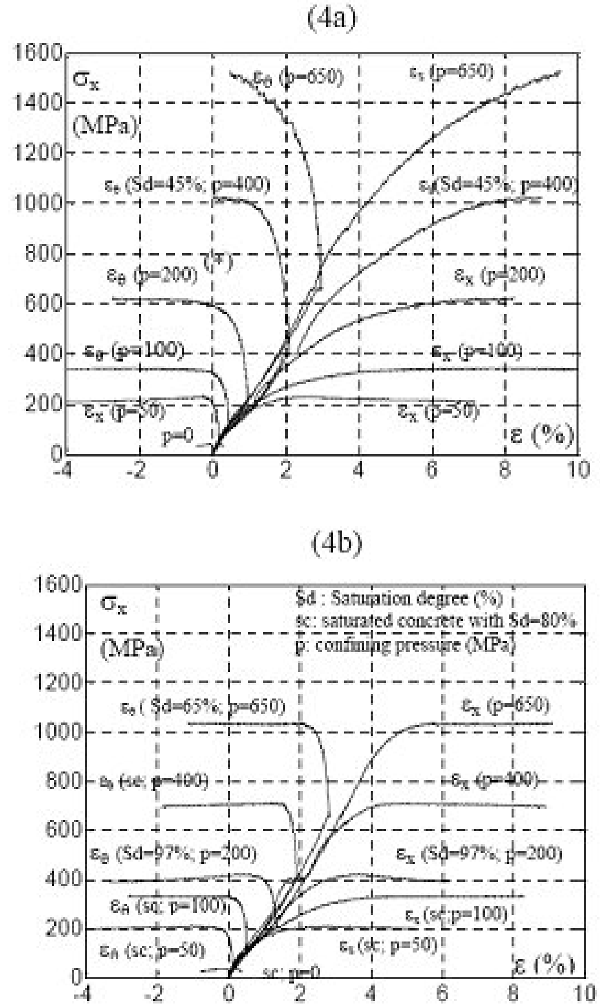

Figure 4. Triaxial tests on the dried concrete R30A7 (4a) and the partially saturated concrete R30A7 (4b) : stress/strain curves Sd: Saturation degree (Sd=0% for “completely” dried concrete and Sd=100% for “completely” saturated concrete); sc: saturated concrete with Sd=80%; p: confining pressure in the triaxial test (MPa).

Figures 5a and 5b show the deviatoric behaviour of both dried and saturated concrete. For confining pressure of 0 MPa, 50 MPa (Figure 5a), the dried concrete is stiffer than the saturated one. At 100 MPa confining pressure, the response of the saturated or dried samples are almost identical. This response may be associated with the response of granular stacking because the cement paste of both concretes may be almost destroyed at this confining pressure and the saturation degree of the saturated concrete is less than 100%. At a confining pressure of 200 MPa and above (Figure 5b), the strength of the dried samples strongly increases with confining pressure. This phenomenon may be explained by the increase of the material density with confining pressure. For saturated samples, the maximum deviatoric stress increases only slightly under high confining pressure.

Figure 7 shows the maximum deviatoric stress versus the mean stress of all triaxial tests on dried and saturated concrete. The maximum deviatoric stress is associated with the dilatancy in most the cases except for the dried samples at higher pressure level. Some triaxial tests at a confining pressure of 200 MPa and above has been carried out on "completely" saturated concrete with only LVDT measurement, and the results do not show in increase in the maximum deviatoric stress. This phenomenon may be explained by a pore pressure effect in "completely" saturated concrete. The tests with intermediate saturation degrees show a limit stress state which is between the dried and the saturated samples, indicating that the limit state curve may be a function of the saturation ratio. At low pressure level, if there is still air in the concrete, the limit state of the partially saturated concrete is the same as that of dried concrete, whereas at higher pressure level if all the dried porosity has been closed, it will behave as a saturated sample. This is an hypothesis which need to be confirm with more tests.

5 INFLUENCE OF WATER-CEMENT RATIO

To determine the influence of the water-cement ratio, a series of uniaxial compression tests (triaxial tests without confining pressure) and triaxial tests with confining pressures of 100 MPa and 650 MPa on concretes EC08 (E/C=0,8), R30A7 (E/C=0,64), EC04 (E/C=0,4) have been performed. Results from the uniaxial compression tests are shown as stress/strain curves in Figure 8. Age of the concretes EC08, R30A7, EC04 are 203, 197, 197 days respectively. The uniaxial compression test results show that the higher the ratio, the more weak and porous the concrete.

Results from the triaxial tests with confining pressure of 650 MPa are also shown as stress/strain curves in figure 10a and as principal stress difference/strain curves in figure 10b. The hydrostatic part of figure 10a shows that the higher the ratio, the more the concrete compacts under hydrostatic stress. But what is more surprising is that the deviatoric responses ot the three different concretes (Figure 10b) seem to be very close for each component (ε_x and ε_θ).

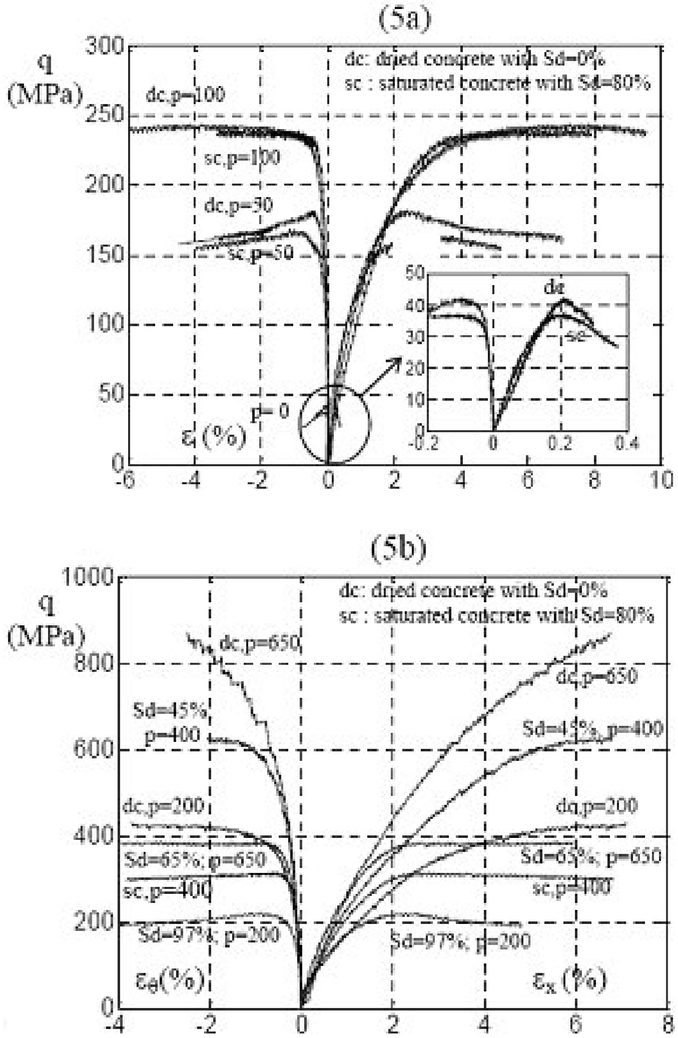

Figure 5. Triaxial tests on the dried and partially saturated concrete R30A7: principal stress difference versus strain curves with a confining pressure from 0 MPa to 100 MPa (5a) , and from 200 MPa to 650 MPa (5b)

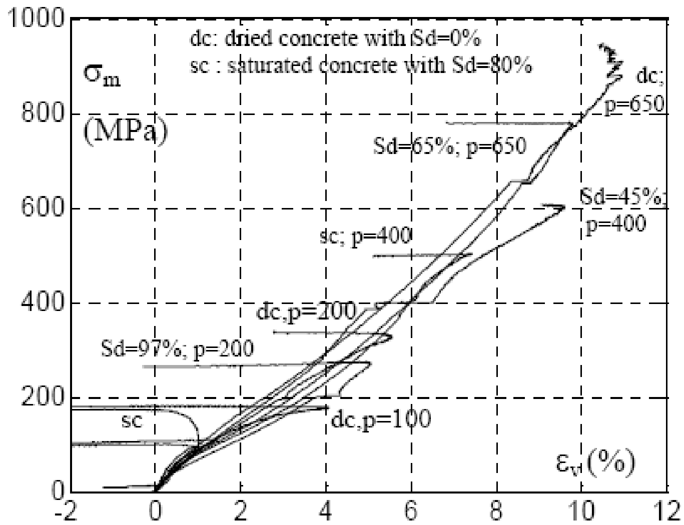

Figure 6. Triaxial tests on the dried and partially saturated concretes R30A7: volumetric behaviour

At the confining pressure of 100 MPa, Figure 9 also shows that the deviatoric responses of the concretes EC08 and R30A7 are also very close, as for the confining pressure of 650 MPa. This can be explained by the quasi-destruction of the cement paste matrix under high confinement (100 MPa and more), resulting a deviatoric response of both concretes similar to that of granular stacking. On the other hand, Figure 9 shows the concrete EC04 is harder than the others during both hydrostatic and deviatoric loading. This can be explained by the a good quality of cement paste which means that the cement paste matrix is not yet completely destroyed at the confining pressure of 100 MPa and therefore the concrete behaves as a matrix of cement paste and granular. These results confirm that the concrete behaviour at low confining pressure is strongly linked to the cement paste strength, whereas the behaviour is more like a granular stacking under high confinement.

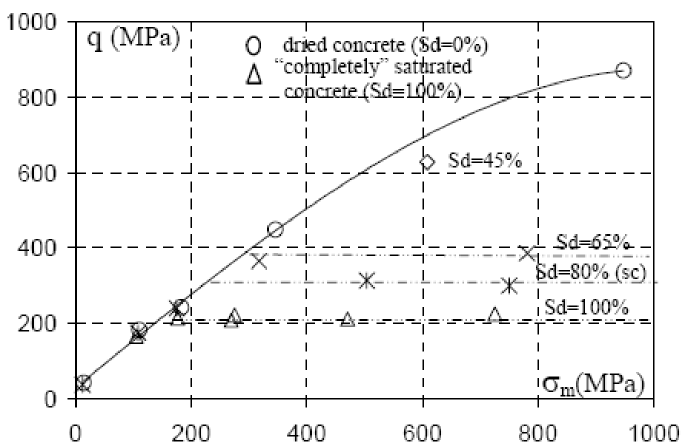

Figure 7: Limit states of the dried and saturated concrete in the stress invariant space (σ_m , q_{max}).

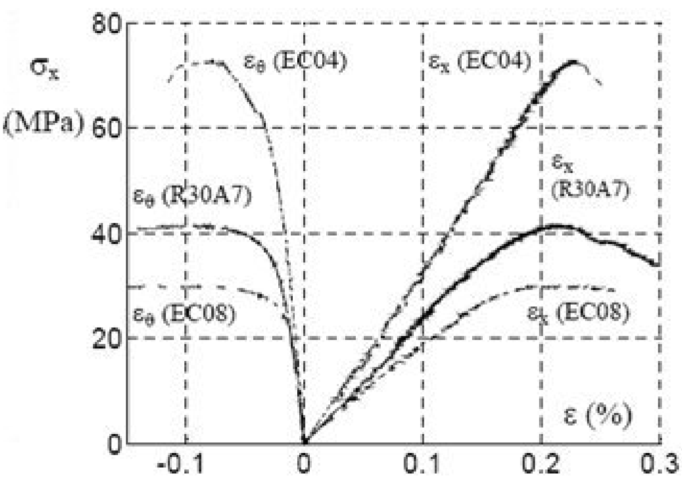

Figure 8: Uniaxial compression tests

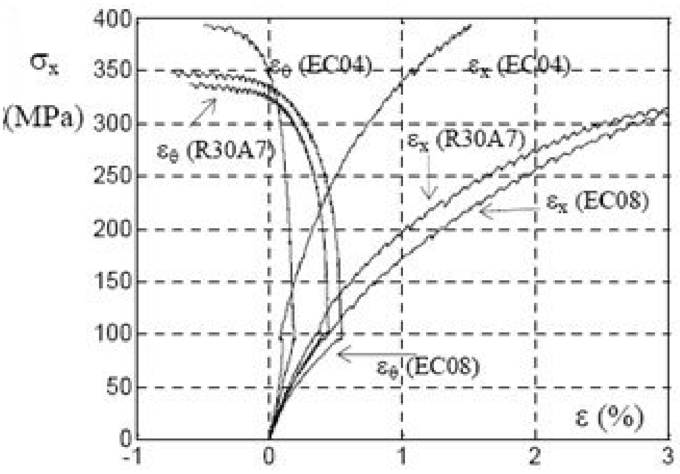

Figure 9: Triaxial tests with p=100 MPa

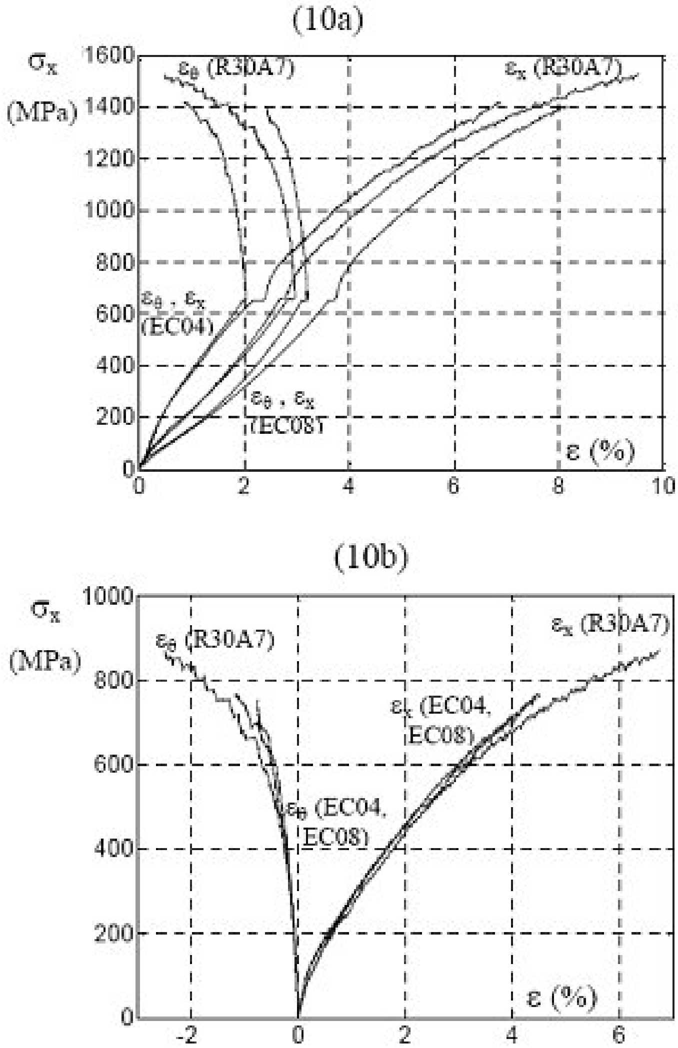

Figure 10: Triaxial tests on the concretes EC08, R30A7, EC04 with p= 650 MPa: stress/strain curves (a), principal stress difference/strain curves (b)

6 CONCLUSION

The test results show that the saturation degree has a major influence on the concrete deviatoric behavior of concrete. The strength of dried concrete strongly increases with the confining pressure whereas it is limited for saturated samples. Some supplementary tests on partially saturated concrete will be carried out to confirm that a limit state curve may be a function of the saturation ratio.

In addition, the results concerning the water-cement ratio of the concrete mixture confirm that the concrete behavior at low confining pressure is strongly linked to the cement paste strength whereas it behaves more like a granular stacking under high confinement.

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