Ultimate strength of plain concrete under extreme combined stresses: triaxial and proportional stress paths

Thomas GABET*, Yann MALECOT, Laurent DAUDEVILLE

Laboratoire Sols, Solides, Structures
B.P. 53 - 38041 Grenoble Cedex 9, France
**Corresponding author, e-mail: gabet@geo.hmg.inpg.fr*

ABSTRACT. *Concrete is a building material used for sensitive infrastructures (dams, nuclear reactors), however its behaviour under extreme dynamical loading (rock falls, explosions, ballistic impacts) remains poorly known. This is due both to the difficulty of experimentally reproducing such a loading and to the intrinsic complexity of concrete behaviour. In order to predict its response under dynamic loading the experimental characterization of its static behaviour in compression under very high confinement is needed. In this paper a new large capacity triaxial press and the manufacturing and testing procedures developed to perform the tests are presented. Low strength plain concrete specimens were subjected to triaxial and proportional loading paths up to an ultimate state associated to failure. The influence of the loading path on the observed limit state of concrete subjected to multiaxial stress states will then be discussed.*

RÉSUMÉ. *Le béton est un matériau de construction utilisé pour les infrastructures sensibles (barrages, centrales nucléaires), cependant son comportement sous chargement dynamique extrême (chutes de blocs, explosions, impacts balistiques) reste encore mal connu. Ceci est à la fois dû à la complexité intrinsèque du matériau et aux difficultés à reproduire de tels chargements. La prédiction de la réponse dynamique du béton nécessite préalablement la caractérisation de son comportement sous sollicitation statique en compression sous fort confinement. Cet article présente le dispositif expérimental constitué d'une presse triaxiale de grande capacité ainsi que les procédures de fabrication et de tests des échantillons de béton. On présente les premiers résultats d'essais triaxiaux et proportionnels menés sur un béton standard jusqu'à un état limite que l'on associe à de l'endommagement. Ils permettent de mettre en évidence l'influence du trajet de chargement sur la surface seuil du matériau.*

KEYWORDS: *compression, high confinement, plain concrete, limit state, loading path.*

MOTS-CLÉS : *compression, fort confinement, béton, état limite, trajet de chargement.*

1. INTRODUCTION

Concrete material may be submitted to severe triaxial stress states. Under quasi-static loading, such a situation may occur in concrete for punching problems or in the vicinity of steel-concrete connections. High triaxial stress states in concrete structures may also be due to impacts. During the impact of a missile on a concrete target, three phases of triaxial behaviour can be observed. Each of these is associated with different damage modes which can sometimes occur simultaneously (Zukas *et al.,* 1992); (Li *et al.,* 2005). On the proximal face of the target, spalling occurs which, from a mechanical point of view, is associated with extensions. The penetration of the missile in the core of the target then generates a triaxial compression, while the inertia of the surrounding material creates a passive confinement in front of the missile. With a thick target the projectile tunnels into the target: this is due to the important shear stresses. Finally, during the last phase of penetration, simple tensile stresses occur on the distal face of the target which means scabbing is taking place.

Thus, in order to validate models of concrete behaviour, which take into account the phenomena of brittle damage and irreversible strain such as compaction, new test results which reproduce the complex loading paths described previously are needed. Most of the available experimental results in literature only relates to triaxial loadings with moderate confining pressure (Li *et al.,* 1970). With them the transition from a brittle to a ductile behaviour which is characteristic of cohesive materials was understood. Numerous studies show that dynamic tests performed on concrete, for example by means of split Hopkinson pressure bars (Hopkinson, 1914); (Zhao *et al.,* 1996), are difficult to carry out essentially because of the brittle aspect of the material that leads to rupture in the transient stage of loading. The inhomogeneous character of the stress state in the sample, the very limited control of the loading path and the relatively poor instrumentation lead to a difficult test result analysis. In dynamics, methods using the plate/plate experiment allow to characterize the material equation of state. These testing methods, however, remain quite difficult to implement since each experimental point on the Hugoniot curve refers to a single experiment. Furthermore, this type of experiments yields very high pressures which are larger than the stresses obtained in classical impact problems on a concrete structure.

In this paper tests done on a low strength plain concrete, using the "GIGA" press which is a large capacity triaxial press are shown. This press allows to attain stress levels on the order of one GigaPascal with homogeneous, static and well controlled load paths. The static characterization of a constitutive model to predict the dynamic behaviour is not a new practice in the study of geomaterials. The rheological behaviour of concrete under compression seems to depend slightly on the strain rate for dried specimens (Bischoff *et al.,* 1991); (Toutlemonde, 1995). The very strong loading rate dependence in tension can mainly be explained by the influence of propagation velocity of defects (Hild *et al.,* 2003).

Similar experimental studies were carried out previously but they were limited to small mortar samples (Bazant *et al.,* 1986); (Burlion *et al.,* 2001). The aim of the present study is to extend this practice to "real" concretes, with aggregate dimensions on the order of one centimeter. The influence of the loading path on the behaviour of a given concrete is presented in this paper; constitutive materials and mix proportions influences (aggregate size, water/cement ratio ...) are being studied in another experimental program (Vu *et al.*, 2006). A particular procedure of experimentation and instrumentation was defined which takes into account the very high stress level and the macro-porous feature of the concrete under study. It is presented in the following paragraphs. The first test results obtained with triaxial and proportional loading paths are then shown. They display a good consistency with the available results in literature and the limit state seems to be independent of the loading path. The main perspectives for this study are finally presented.

2. EXPERIMENTAL DEVICE

2.1. *The triaxial press "GIGA"*

GIGA 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. The concrete specimen is placed in the confining cell. The confining fluid, diethylhexyl azelate, a non-volatile organic liquid, is injected in the cell through the upper opening. It is then put under pressure by means of a multiplying jack. The axial force is generated by means of a 10 MN jack which is located under the cell. It is transmitted to the specimen by a piston which passes through the lower plug of the cell. The confining pressure and the axial jack displacement are controlled independently giving five possible loading paths: hydrostatic, triaxial, proportional, extensional and oedometric. A hydrostatic test consists of applying a pressure all around the specimen; this pressure increases linearly. In a triaxial test, the specimen is loaded axially (constant rate of displacement) while keeping the confining pressure constant. A proportional test consists of loading the specimen axially (by imposing a constant displacement rate) while keeping the pressure proportional to the axial stress ($p = k \times \sigma_x$ with $0 < k < 1$). An extension test begins like a proportional test with k=1 (in order to simulate a hydrostatic test). This allows to maintain a contact between the jack and the specimen. Then the axial stress on the specimen is relaxed by imposing a constant displacement rate to the axial jack, while keeping the confining pressure constant. During an oedometric test, the specimen is placed inside a thick steel pipe to prevent orthoradial strains. A constant rate displacement is imposed to the axial jack. By means of a control of orthoradial strains of the tube (performed by an orthoradial gauge), pressure all around the tube increases so that this one can not deform.

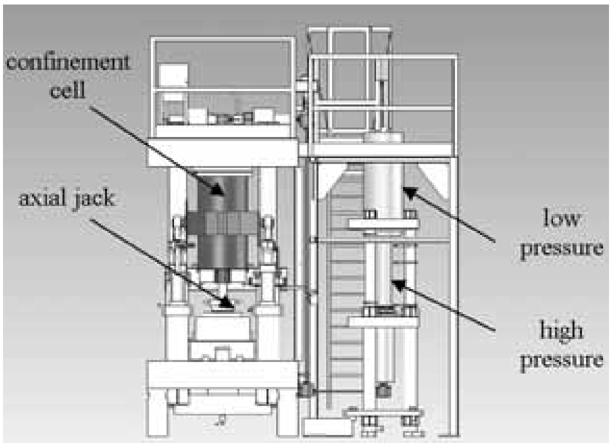


Figure 1. *General scheme of the "GIGA" press*

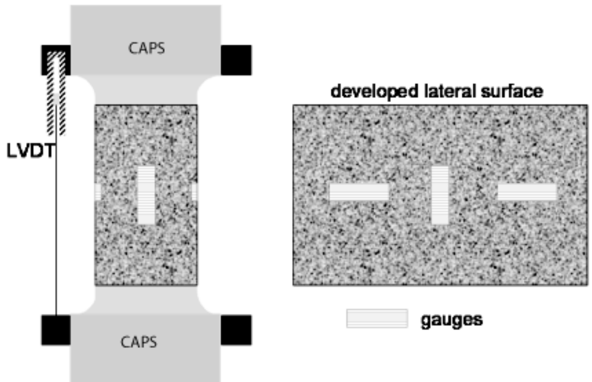


Figure 2. *Scheme of strain measurement*

2.2. *Measurement*

The strain measurement is performed by means of a LVDT sensor, one axial gauge and two circumferential gauges (Figure 2); gauge measurement on concrete is completely original for such levels of confinement. The LVDT sensor gives the length variation of the specimen. Each end of the LVDT is positioned on one of the two caps, and thus leads to a measure of the global strain. The axial gauge allows to check the consistency of the signals by giving an additional and local measure of the strain [1]. We have to notice that all the axial measures presented in this paper are given by LVDT. An axial displacement sensor located on the machine is used to pilot the axial jack displacement. It approximates the axial strains correctly but includes the strains of all the machine. The circumferential strain, which will also be named orthoradial, is measured by means of two gauges. These two gauges are necessary because of a high variability of signals obtained in that direction and because these gauges are more fragile. With a force sensor and a pressure one, the axial stress applied to the specimen and the pressure inside the cell can be determined.

2.3. *Material and specimens*

The concrete tested has a strength of 30 MPa in compression and a 7 cm slump. The composition and the mechanical properties of this concrete are presented in Table 1. The manufacturing procedure of the concrete specimens was chosen so as to ensure a minimal variability in their mechanical properties for those made at different times. The concrete is cast in a 13.5 litre wooden mould, whose base is a square of side 27 cm. The concrete block is removed 24 hours after casting. The block is then preserved during 28 days in a saturated environment inside waterproof bags immersed in water to insulate the concrete both physically and thermally. The concrete block is then cored, cut and ground. Specimens are then preserved in a drying oven until the stabilization of their weight. Weight is considered as stable when its daily variation doesn't exceed 0.1% ($\frac{\Delta m_{24h}}{m} \leq 0.1\%$). The influence of the saturation degree is studied in (Vu *et al.*, 2006). Note that the maximum aggregate size (8 mm) and the sample realization method (cores) were chosen with regards to specimen diameter (70 mm). According to Yip et al. (Yip *et al.*, 1995) and main standards there is no size effect on the compressive strength of concrete with the chosen dimensions for aggregates and samples. This conclusion is assumed to be also valid in triaxial compression.

3. TEST PROCEDURE DEVELOPMENT

A test procedure has been developed to get repeatable and reliable tests by protecting the specimen from "punching" ; punching is defined as the penetration of the confining fluid into the specimen after the perforation of all the membrane layers. Punching is both due to material porosity and high pressure all around the specimen. It has two consequences: it changes the material properties because of an infiltration of the confining fluid and leads to the loss of the gauge signals because of damaged gauges or because connection wires break.

1. Adding this axial strain makes the specimen preparation for testing more complicated; for these reasons, it hasn't been done systematically.

Concrete mix proportions	
Water	169 kg/m^3
Sand D(diameter)$_{\max}$ 1.8 mm	838 kg/m^3
Aggregate D 0.5 to 8 mm	1007 kg/m^3
Cement CEM I 52.5 N PM ES CP2 (Vicat)	263 kg/m^3
Characteristics	
Compression strength (average)	30 MPa
Maximum size aggregate	8 mm
Concrete measured porosity	11.6%
Degree of saturation	dried

Table 1. *Concrete mix proportions and characteristics*

After the concrete specimens machining, the surfaces of the specimens are prepared, gauges are glued and protection devices are set up.

3.1. *Concrete specimens machining*

Our specimens are cored, cut and grinded. Each step of machining is performed with a water cooling device in order to preserve the concrete specimens from bursting due to high local gradients of temperature. The parallelism of the faces is about 0.1 mm for 70 mm diameter. All the specimens are then kept in an oven at 50 °C during one month (at least) until the stabilization of their weight. The weight measurement is part of a procedure to determine the porosity of the concrete specimen (porosity accessible to water) (ISO-5017, 1998). The concrete porosity, based on a measure performed on two specimens of a same concrete block, is estimated to 11.6%.

3.2. *Surface preparation*

The surface preparation consists of opening the subjacent porosity by slightly striking the surface with a sharp object (a punch) and then filling in these opened pores with a mortar whose mechanical characteristics are close to those of concrete. Filling in pores increases membranes durability. The mortar is SIKATOP® SF 126. By opening subjacent porosity proper areas on the surface can be found where pores do not seem to be present at all. Then, the gauges should not fail due to punching hence they can be glued.

3.3. *PVC-shield and aqua-seal membrane*

A PVC-shield is locally set up on gauges as an additional protection. The shield is very useful during the specimen preparation and offers a plane support surface which

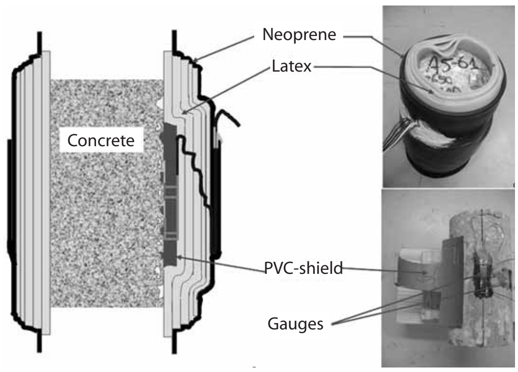


Figure 3. *Vertical cross-section of a ready to test specimen*

limits possible ruptures.
The specimen is then wrapped within a cylindrical membrane, which is essential to prevent the confining fluid from infiltrating the specimen. Membranes are longer than the specimen and recover a part of the caps (showed on Figure 2). After different attempts using various materials (nitril, rubber, neoprene, silicon, latex), a multilayer membrane has been developed. It is made up of 8 mm of latex, used for its shear strength and its high deformability, and it is surrounded by a 1 mm neoprene layer used for its chemical inertia in order to protect the latex which can be easily damaged by the confining fluid. A cross-section of a ready-to-test specimen is presented in Figure 3.

3.4. *Influence of the specimen preparation on measurement*

Hydrostatic tests at 700 MPa were carried out on polycarbonate specimens, by Mr X.H. VU. Results are presented on Figure 4. The behaviour of this homogeneous and isotropic material is well known. It is used here as a reference to validate the measuring channels. Three tests with the membrane and PVC-shield, without the membrane and without the PVC-shield respectively have been performed, and show that the protection device has no influence on the measurement (Vu *et al.,* 2005). These results confirm the ability to measure strains by means of gauges,thanks to additional protections, in spite of the high confining pressure.

4. TRIAXIAL TESTING PROGRAM

4.1. *Presentation*

During a triaxial test, the loading path first consists of applying a hydrostatic pressure (at 100 MPa/min) all around the specimen up to a given p value. A constant

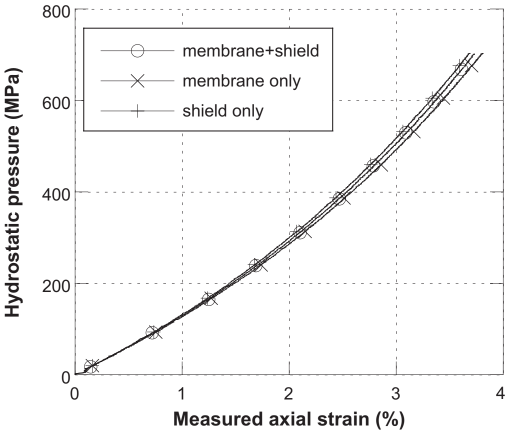


Figure 4. *Influence of the PVC-shield and the membrane on measurement*

displacement rate (5 μm/s) of the axial jack at a constant confining pressure p on the lateral face is then imposed.
Five triaxial tests have been performed with the following confining pressures: 50, 100, 200, 500 and 650 MPa. A uniaxial compression test (which is a triaxial test without confining pressure) is also presented to give an idea of the impressive stress level concerned by this study. Results are presented as stress/strain curves in Figure 5(a). For each confining pressure, the axial stress (σ_x) versus the axial strain (ϵ_x) and the axial stress versus the orthoradial strain (ϵ_θ) are plotted. In all the following figures, the axial compression stress and the corresponding compressive axial strains are considered as positive, whereas extensions are negative.

4.2. *Stress versus strain behaviour*

The load-carrying capacity of standard concrete increases significantly with the increase of the confining pressure. During the hydrostatic phase of the tests, a compaction process can be observed. It is similar to those found in the literature for mortar (Burlion, 1997); (Schmidt, 2003); (Warren *et al.*, 2004). This compaction curve can be characterized by a slope decrease which corresponds to damage of the cement paste followed by an increase of this slope which corresponds in turn to the porosity closure. In this hydrostatic phase and for each test, the axial and the orthoradial strains, obtained respectively with the LVDT sensor and a circumferential gauge, have approximately the same response. Hence it can be concluded that the material is isotropic (identical axial and orthoradial strains under hydrostatic loading), that the stress state is homogeneous (identical global and local signals) and that the material is repro-

ducible (the specimens come from different concrete blocks).
This phase is followed by the deviatoric phase. During this second phase, the slope decreases in a monotonous way with the increase of the deviatoric stress. For the 50 MPa confinement test, a peak load is reached at 200 MPa and the response is similar to the one observed with a simple compression test. For the 100 MPa and 200 MPa confinement tests, the slope seems to tend toward a plateau. The other two tests do not exhibit any limit state. By comparing the slopes of each test during the deviatoric phase, a stiffening can be observed with an increase of slope with confining pressure. This phenomenon may be explained by an increase of the material density with the confining pressure.

4.3. *Volumetric strain versus mean stress behaviour*

The volumetric behaviour of all five triaxial tests is presented in Figure 5(b). Results are presented as mean stress (σ_m) / volumetric strain (ϵ_v) curves. Note that all the test results follow the same volumetric strain versus hydrostatic stress curve during the hydrostatic phase. Once the deviatoric phase has begun, a deviation of the curves is observed for all the tests. For a given mean stress, the higher the deviatoric stress, the more compacted is the specimen. It can then be concluded that shear improves compaction.
For the 50, 100 and 200 MPa confinement tests, a limit state corresponding to an abrupt dilatancy is reached. For the other two tests with the 500 and 650 MPa confining pressures, at the end of the tests, at σ_m= 650 MPa and σ_m= 870 MPa respectively, a variation of the signal with a slope increase and a signal disturbance can be observed. This signal disturbance is associated with hard sounds like squeaking. As soon as these disturbances begin, they are often and quickly followed by a rupture of the signal given by the gauges. They may be associated with localization.

5. PROPORTIONAL TESTING PROGRAM

A proportional test consists of imposing the axial displacement at a constant rate (5 μm/s) while keeping the pressure proportional to the axial stress. k is the proportionality factor, with $p = k \times \sigma_x$. Four tests have been performed with k=0.5, 0.3, 0.35 and 0.2. The results of these four tests are compared with results obtained with a hydrostatic test (k=1) and a simple compressive one (k=0). For each test the axial stress is plotted on figure 6(a) as a function of the axial strain and as a function of the orthoradial strain.

5.1. *Stress versus strain behaviour*

Once again, the load-carrying capacity of the material increases significantly with k. For a given axial strain, both the axial stress reached and the slope increased with k.

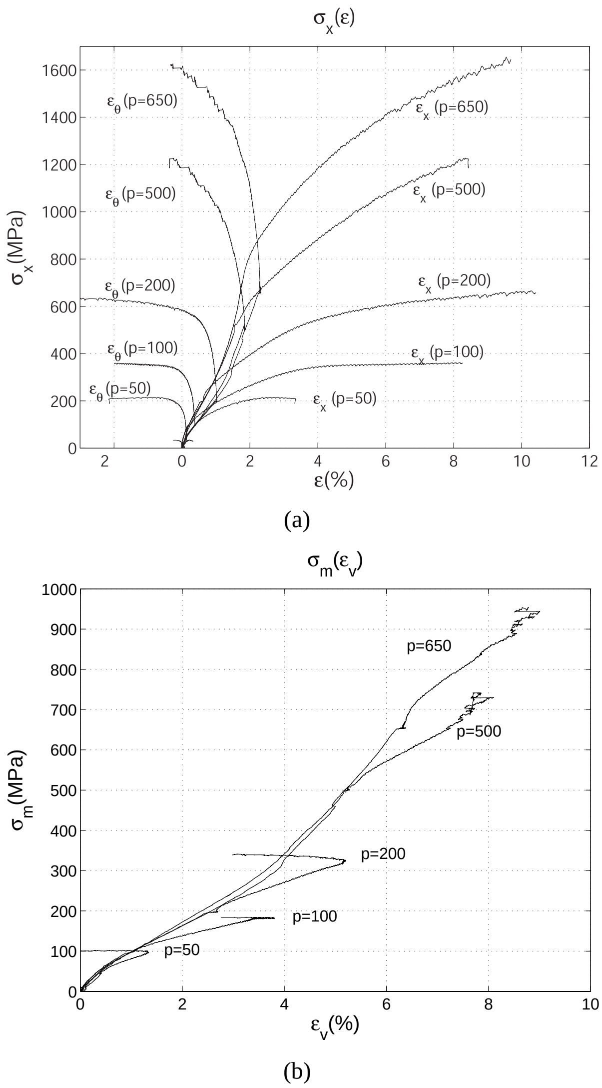


Figure 5. *Triaxial testing program : stress/strains curves (a) and volumetric behaviour (b).*

For the k=0.2 test, a peak load (180 MPa) is reached as in the simple compression test. For the k=0.3 test, a slope variation can be observed at approximately 350 MPa. The other two tests k=0.35 and k=0.5 do not seem to reach any limit state [2] as observed with a hydrostatic test. These tests clearly display a compaction process as seen previously on mortar (Bazant *et al.*, 1986); (Burlion *et al.*, 2001). After a small elastic regime, the material response is nonlinear. The evolution of the tangent modulus is due to the compaction process. As the pores are progressively crushed, the material becomes stiffer.

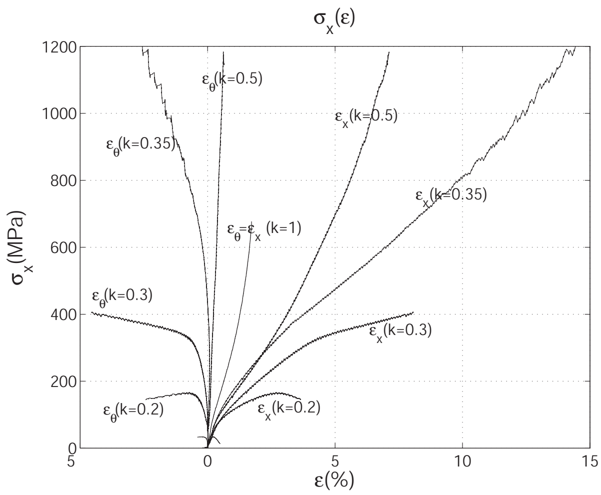
5.2. *Volumetric strain versus hydrostatic stress behaviour*

The volumetric behaviour of all four proportional tests is presented in Figure 6(b). The compaction increases with a decrease of k. For a given mean stress, a lower value of k corresponds to a more compacted specimen, since a lower k is associated with higher deviatoric stresses and higher shear stresses. Once again, as it was shown in the triaxial test results, a deviatoric stress influences strongly the volumetric strain versus hydrostatic stress behaviour of the material.
Let us focus on the limit states reached at the end of the tests. For the k=0.2 and k=0.3 tests, a limit state which corresponds to an abrupt dilatancy is reached. For the k=0.35 test, a variation of the signal can be observed at the end of the test: it corresponds to an increase of the slope and a tendance to dilatancy associated with a disturbance of the signal. Once this disturbance appears, hard sounds like squeaking are emitted from the cell and seem to correspond with a phase of structural rearrangement of the specimen. The k=0.5 test has not reached any limit state before reaching the loading capacity limit.

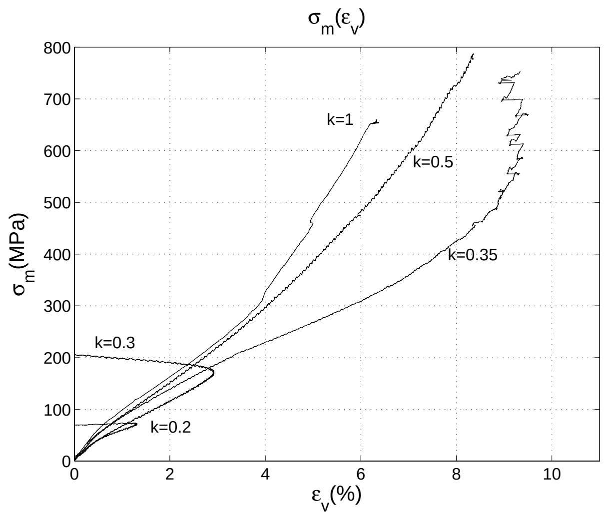
6. LIMIT STATES

Every limit state has been plotted in the (σ_m, q) space[3], where σ_m is the mean stress and q the principal stress difference. The results of 10 tests are presented in figure 7. The seven points in the lower space part represent the limit state associated to k=0/p=0, which is the simple compression test, k=0.2, p=50 MPa, k=0.3, p=100 MPa and p=200 MPa. For all these points, the limit state corresponds to abrupt dilatancy. The three upper points represent the maximum stress level reached in the specimen for k=0.35, p=500 MPa and p=650 MPa. Then, for these last three tests, it is not possible to say that a limit state has been reached. The limit surface characterized by these limit state points does not seem to depend on the loading path, and seems to display a linear evolution.

2. For the presented tests, the press GIGA couldn't develop a pressure higher than approximately 650 MPa which is a temporary technical limit. Thereby, the axial stress level is also limited because of the proportional feature of the test.
3. $\sigma_m = \frac{\sigma_{ii}}{3} = \frac{\sigma_x + 2p}{3}$, where p is the pressure inside the cell, and $q = \sigma_x - p$



(a)



(b)

Figure 6. *Proportional testing program : stress/strains curves (a) and volumetric behaviour (b).*

7. CONCLUSION

A protocol to manufacture concrete and to prepare the specimens has been defined, then high pressure and extreme loadings tests on low-strength concrete specimens can be performed. Strains are measured by means of gauges. A multilayer

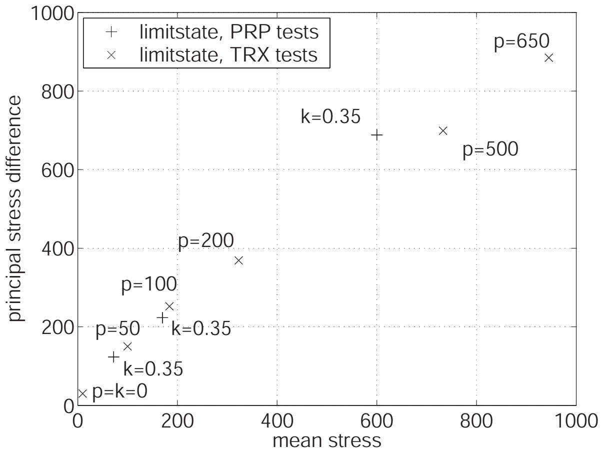


Figure 7. *Limit states of concrete in the stress invariant space*

membrane associated with a specific surface preparation protects both the specimens and the gauges from punching. Both triaxial and proportional testing programs have been performed on dried plain concrete samples. Results have exhibited a specimen isotropy, a stress homogeneity and a correct reproducibility, regarding their consistency during the hydrostatic phase of the triaxial tests. They have put in evidence an influence of the loading path on the compaction behaviour; deviatoric stresses, associated to shear stresses seem to improve compaction. Finally, plotting the limit states of a dried concrete in the (σ_m, q) space exhibits a curve which seems linear and independent from the loading path. Hence, even if the compaction behaviour depends on loading path, the limit state does not.

Test results confirm previous studies carried out on mortar specimens and clearly show the influence of the loading path on the compaction process. Hence, constitutive models should take into account the influences of both mean and deviatoric stresses for a proper description of the compaction process. From a microstructural point of view, this sensitivity to the deviatoric stress could be expected because the porosity of the material is crushed in different ways depending on the deviatoric stress. The behaviour of concrete under high confinement seems similar to those observed with other geomaterials ; the maximum deviatoric stress depends on the mean stress in a linear way, and could easily be modeled in the framework of the plasticity theory as a Drucker-Prager surface or a Willam-Warnke surface in case of influence of the Lode angle (Willam *et al.*, 1974).

An oedometric testing program is going to be performed to show the influence of the loading path on compaction curve and to confirm that the limit surface is independent from the loading path. Other tests such as extension tests will be soon carried out to show the possible influence of the Lode angle on the material behaviour. In this study, our purpose is to put in evidence the influence of loading path on concrete behaviour. Parallel studies are being carried out in order to show that water content of the specimens is a major element of the material response, tests at different saturation degrees are being performed (Vu *et al.*, 2006). They will soon be compared with the tests presented in this paper. In the same time, tests on different concretes are being performed to show the influence of mix proportions (water/cement ratio, paste/aggregate ratio) and maximum aggregate size on their response.

8. ACKNOWLEDGEMENTS

The GIGA press was implemented in Laboratoire 3S in the framework of a co-operation agreement with the French Délégation Générale pour l'Armement (DGA, French Ministry of Defence). This research has been developed with the financial support of the Centre d'Études Techniques de Gramat (CEG, DGA). We would like to thank Dr. Éric Buzaud (CEG) for giving technical and scientific advice.

9. REFERENCES

Bazant Z., Bishop F., Chang T., « Confined compression tests of cement paste and concrete up to 300 Ksi », *ACI Journal*, vol. 33, p. 553-560, 1986.

Bischoff P., Perry S., « Compressive bahaviour of concrete at high strain rates », *Materials and Structures*, vol. 24, p. 425-450, 1991.

Burlion N., Compaction des bétons : éléments de modélisation et caractérisation expérimentale, PhD thesis, ENS Cachan, France, 1997.

Burlion N., Pijaudier-Cabot G., Dahan N., « Experimental analysis of compaction of concrete and mortar », *Int. J. for Numerical and Analytical Methods in Geomechanics*, vol. 25, p. 1467-1486, 2001.

Hild F., Denoual C., Forquin P., Brajer X., « On the probabilistic-deterministic transition involved in a fragmentation process of brittle materials strains », *Computers and Structures*, vol. 81, n° 12, p. 1241-1254, 2003.

Hopkinson B., « A method of measuring the pressure in the deformation of high explosives or by the impact of bullets », *Philosophic Transactions of the Royal Society*, vol. A213, p. 437-452, 1914.

ISO-5017, « Dense shaped refractory products - Determination of bulk density, apparent porosity and true porosity », 1998.

Li H., Pugh D., « Mechanical behaviour of materials under pressure », *Elsevier*, 1970.

Li Q., Reid S., Wen H., Telford A., « Local impact effects of hard missiles on concrete targets », *Journal of Impact Engineering*, 2005.

Schmidt J. M., High pressure and high strain rate behaviour of cementitious materials : experiments and elastic/vicoplastic modeling, PhD thesis, University of Florida, USA, 2003.

Thiot P., « Thiot-Ingénierie », 2004. la Croix Blanche 46130 Saint Michel Loubejou, France. Website: www.thiot-ingenierie.com.

Toutlemonde F., Résistance au choc des structures en béton; du comportement du matériau au calcul des ouvrages, PhD thesis, ENPC, 1995.

Vu X., Gabet T., Malécot Y., Daudeville L., « Experimental analysis of concrete behavior under severe triaxial loading », *The 2005 Joint ASCE/ASME/SES Conference on Mechanics and Materials*, McMat 2005 Mechanics and Materials Conference Baton Rouge, Louisiana, 1-5 June , 2005.

Vu X., Malécot Y., Daudeville L., « A First analysis of concrete behaviour under high confinement: influence of moisture content », *First Euro Mediterranean Symposium in Advances on Geomaterials and Structures*, Tunisia., 3-5 May , 2006.

Warren T., Fossum A., Frew D., « Penetration into low-strength (23 Mpa) concrete : target characterization and simulations », *Int. J. of Impact Engineering*, vol. 30, p. 477-503, 2004.

Willam K. J., Warnke E. P., Constitutive Models for the Triaxial Behavior of Concrete, Report n˚ 19 Section III, Proc. Intl. Assoc. Bridge Struct. Engrg., Zurich, 1974. 1-30.

Yip W. K., Tam C. T., « Concrete strength evaluation through the use of small diameter cores. », *Magazine of Concrete Research*, vol. 40, n˚ 143, p. 99-105, 1995.

Zhao H., Gary G., « On the use of SHPB techniques to determine the dynamic behavior of materials in the range of small strains », *Int. J. Solids Structures*, vol. 33, n˚ 23, p. 3363-3375(13), September, 1996.

Zukas J. A., Nicholas T., Swift H. F., Greszczuk L., Curran D. R., « Penetration and perforation of solids », *Impact Dynamics*,p. 155-183, 1992.