J. Phys. IV France **134** (2006) 635–640

DOI: 10.1051/jp4:2006134098

A new experimental technique for the analysis of concrete under high triaxial loading

T. Gabet[1], X.H. Vu[1], Y. Malecot[1] and L. Daudeville[1]

[1] *Laboratoire Sols Solides Structures, BP. 53, 38041 Grenoble Cedex 9, France*
e-mail: Laurent.Daudeville@inpg.fr

Abstract. Concrete is a building material used for sensitive infrastructures like dams or nuclear power reactors; however its behaviour remains badly known under extreme dynamical loading like rock falls, explosions or ballistic impacts. It is due both to the difficulty of reproducing experimentally such a loading and to the intrinsic complexity of concrete behaviour. Predicting its response under dynamic loading needs the experimental characterization of its static behaviour in compression under very high confinement. This paper first presents a new large capacity triaxial press and the manufacturing and testing procedures developed to perform the tests. Plain concrete specimens (centimetric aggregate dimension) were submitted to different loading paths up to an ultimate state associated to failure.

1. INTRODUCTION

Although it is the most used construction material, notably for sensitive infrastructures such as dams or nuclear reactors, the behaviour of concrete is still not well known when subjected to extreme loadings due to natural or anthropic hazards (rock falls, explosion or ballistic impacts) [1]. This lack of knowledge comes as much from the difficulty of reproducing these loads in laboratory as from the intrinsic complexity of the material behaviour. Considering the impact of a missile on a concrete structure, three phases of triaxial behaviour can be observed; each of these is associated with different damages which can sometimes occur simultaneously [2]. On the proximal face of the target, a spalling occurs associated, from a mechanical point of view, 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 the front zone of the missile. In case of a thick target the penetration phenomenon is a tunneling into the target by the projectile associated to a important shear stresses. Finally, during the last phase of penetration, simple traction stresses occur on the distal face of the target (scabbing).

Thus the validation of concrete behaviour models, which take into account simultaneously the phenomena of brittle damage and irreversible strain such as compaction, needs new test results reproducing the complex loading paths described previously. The majority of the available experimental results in literature only relates to triaxial loadings with moderate confining pressure. They notably allowed understanding the transition of brittle-ductile behaviour which is a characteristic of cohesive materials [3].

Numerous studies show that dynamic tests performed on concrete, for example by means of split pressure Hopkinson bars [4-5], 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 analysis. There are methods in dynamics which can be used in order to characterize the equation of state such as the plate/plate experiment. These testing methods, however, remain quite difficult to implement since each experimental point on the hydrostatic response refers to a single experiment. Furthermore, this type of experiments yields very high pressures, larger than the stresses obtained in classical impact problems on a concrete structure.

This paper presents the development of a test procedure and first triaxial results of tests carried out on a standard concrete, using the large capacity triaxial press "GIGA". This press allows us to attain stress levels of the order of the Giga Pascal with homogeneous, static and well controlled different load paths. The static characterization of a behaviour model with a view to predicting 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 deformation rate for dried specimens [6]. The very strong dependence on the loading rate in traction can mainly be explained by the influence of defects [7].

Similar experimental studies were carried out previously. They were limited to small mortar samples [8-9]. The aim of that study is to extend this practice to the study of "real" concretes with aggregate dimensions on the order of one centimetre.

Taking into account the very high stress level and the macro-porous feature of the studied concrete, a particular procedure of experimentation and instrumentation was defined. It is presented in the following paragraphs. The first test results obtained with triaxial and proportional loading paths are then shown. They reveal a good coherence with the available results in literature.

2. EXPERIMENTAL SET-UP

2.1 The press and the measurements

GIGA is a triaxial press of large capacity specifically designed and developed for this study [10]. This press allows to test cylindrical 7 × 14 cm concrete specimens with a confining pressure up to 0.85 GPa and with a 2.3 GPa maximum axial stress (Figure 1). The concrete specimen is placed in a confining cell. The confining fluid, a non-volatile organic liquid diethylhexyl azelate, is injected in the cell and put under pressure by means of a multiplying jack. The axial force is generated by means of a 10 MN jack. 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 5 possible loading paths: hydrostatic,triaxial, proportional, extension and oedometric.

The strain measurement is performed by means of a LVDT sensor and gages; gage measurement on concrete is completely original for such levels of confinement. The LVDT sensor gives a global measure of the axial strain. One axial gage is added to check the coherence of the signals; it gives a local measure of the strain. The circumferential or orthoradial strain is measured by means of 2 gages. These 2 gages are necessary because of a higher variability of signals obtained in that direction and because these gages are more fragile. A force sensor and a pressure one give the axial stress and the lateral pressure respectively.

2.2 Material and specimens

The concrete is formulated for a 30 MPa strength in compression and a 7 cm slump. The composition and the mechanical properties of concrete are presented in table 1. The manufacturing procedure of

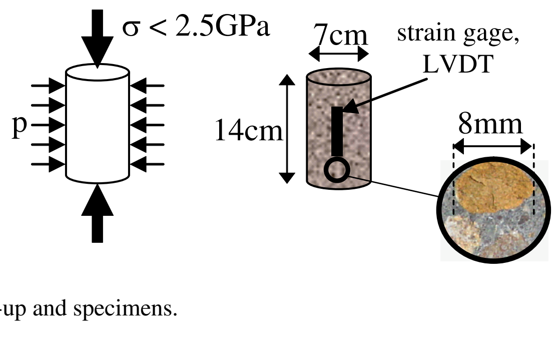

Figure 1. Experimental set-up and specimens.

concrete specimens was chosen with the intent to insure a minimal variability of mechanical properties of concrete specimens realized at different moments. Concrete specimens are cored, cut and ground after 28 days. Specimens are then conserved in a drying oven for the dried specimens or in water for the saturated specimens. Results presented in this paper only concern dried specimens.

Table 1. Normalized concrete mix proportions per m^3 and main characteristics.

Water	169 kg	Compressive strength	30 MPa
Aggregate D 0, 5/8	1007 kg	Aggregate maximum size	8 mm
Sand D1800μm	838 kg	Concrete measured porosity	11.6 %
Cement CEM I 52.5 N PM ES CP2	263 kg	Density	2277 kg/m^3

3. PROTECTION MEMBRANE SYSTEM

A test procedure development has been carried out 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 rupture of the gage signals.

After the concrete specimens machining, the surfaces of the specimens are prepared, gages are glued and protection devices are set up (Figure 2).

The surface preparation consists in opening the subjacent porosity by slightly striking surface with a sharp object (a punch) and then filling in these opened pores with a mortar whose mechanical characteristics are close to concrete's ones. Filling in pores increases membranes durability. This mortar is SIKATOP SF 126. By opening subjacent porosity also allows to find proper areas on the surface where it seems to have no pores at all. At these locations, gages are not expected to fail due to punching thus they can be glued.

A PVC shield is locally set up on gages as an additional protection. The specimen is then surrounded by a membrane, which is essential to prevent the confining fluid from infiltrating the specimen. After different attempts using various materials (nitril, rubber, neoprene, silicon, latex), a multilayer membrane has been developed made of 8 mm of latex, used for its shear strength and its high deformability, and surrounded by a 1 mm neoprene layer used for its chemical inertia in order to protect the latex easily damaged by the confining fluid (Figure 2).

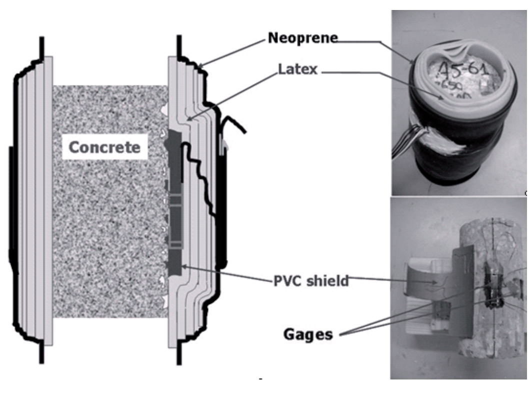

Figure 2. Protection membrane system.

The non influence of the specimen preparation on measurement was verified by means of hydrostatic tests at 700 MPa carried out on polycarbonate specimens. The behaviour of this homogeneous and isotropic material is well known, it is used here as a reference to validate the measuring channels. Different tests with or without the membrane, with or without the PVC-shield have been performed, and show that the protection device has no influence on measurement. All the results validate the measuring channels by strain gages.

4. FIRST RESULTS OF TESTS PERFORMED ON DRIED CONCRETE

4.1 Triaxial tests

During a triaxial test, the loading path consists first in a hydrostatic pressure up to a given p value. A constant displacement rate of the axial jack at a constant confining pressure p on the lateral face is then imposed.

5 triaxial tests are shown with the following confining pressures: 50, 100, 200, 500 and 650 MPa.

A simple compression test (no confining pressure) is also presented to give an idea of the impressive stress level concerned by this study. For each confining pressure results are presented as stress versus orthoradial and axial strain curves on figure 3a and volumetric strain versus hydrostatic stress on figure 3b. In all the following figures, the axial compression stress and its associated axial strain are considered as positive.

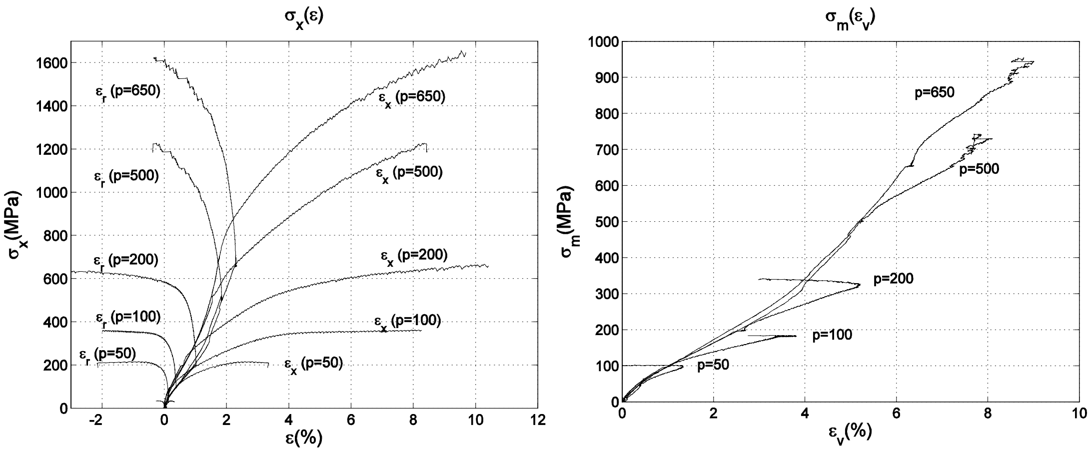

Figure 3. Triaxial testing program: stress/strains curves (a) and volumetric behaviour (b).

4.2 Proportional tests

A proportional test consists in imposing the axial displacement at a constant rate while keeping the pressure p proportional to the axial stress. k is the proportionality factor ($p = k\sigma_1$). The stress:strain curves of these tests are shown on figure 4.

4.3 Analysis of results

The load-carrying capacity of the standard concrete increases significantly with the increase of the confining pressure. During the hydrostatic phase of triaxial tests, a compaction curve can be observed. It is similar to the ones given in the literature for mortar [8-9] [1].

Note that all the triaxial test results follow the same volumetric strain versus hydrostatic stress curve during the hydrostatic phase. In this hydrostatic phase and for each test, the axial strain and

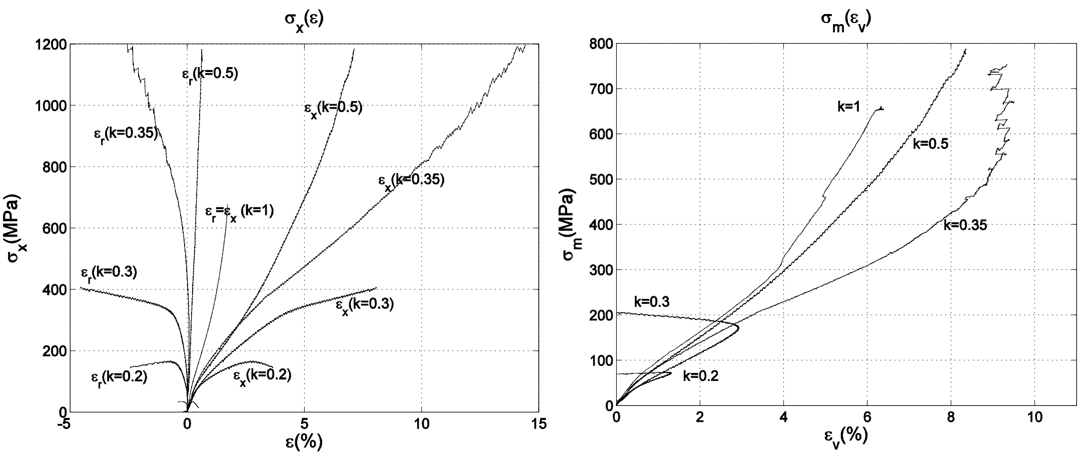

Figure 4. Proportional testing program: stress/strains curves (a) and volumetric behaviour (b).

the orthoradial one, respectively obtained with the LVDT sensor and a circumferential gage, give approximately the same response. This latter result allows to conclude the material is isotropic (identical axial and orthoradial strains under hydrostatic loading), the stress state is homogeneous (identical global and local signals) and the material is reproducible (the specimens come from different concrete blocks).

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.

4.4 Limit states

For each test, a limit state is defined when a peak load is reached or when a transition from a compaction to a dilatancy is observed. All the limit states have been plotted in the (I_1, $\sqrt{J_2}$) space. The results of 10 tests are presented on figure 5. The 7 points in the lower part of the space 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 an abrupt dilatancy. The 3 upper points represent the maximum stress level reached in the specimen for k=0.35, p=500 MPa

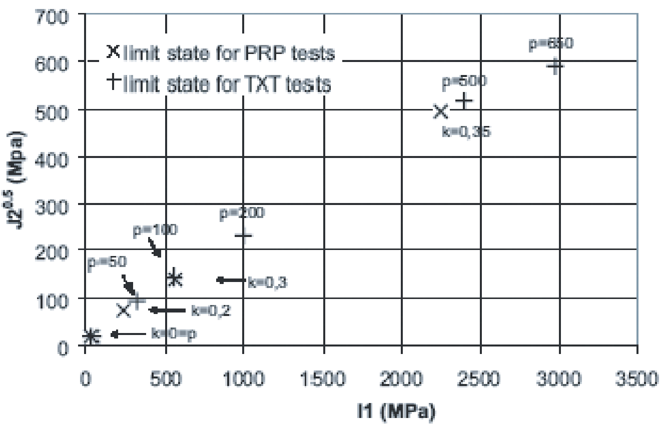

Figure 5. Limit states of concrete in the stress invariant space.

and p=650 MPa. The surface characterized by these limit-state points does not seem to depend on the loading path and seems to display a linear evolution.

5. CONCLUSION

By defining a protocol to manufacture concrete and to prepare the specimens, high pressure and extreme loadings tests on standard concrete specimens could be performed. Strains are measured by means of gages. An aqua-seal membrane associated with a specific surface preparation protects specimens and gages from punching. Both triaxial and proportional testing programs have been performed on dried plain concrete samples. Test results have exhibited a specimen isotropy, a stress homogeneity and a correct reproducibility. Test results confirm previous studies carried out on mortar specimens, they clearly show an influence of the loading path on the material behaviour. Hence, it is not possible in constitutive models to uncouple the hydrostatic and the deviatoric responses of concrete. 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 the one observed with other geomaterials, the maximum deviatoric stress depends on the mean stress.

The limit state reached depends on the confining pressure: an abrupt dilatancy appears for the lower confined tests whereas the higher confined tests just show a slope variation with a disturbance of the signal. Finally, plotting the limit states in the (I_1, $\sqrt{J_2}$) space shows that the loading surface of a dried concrete seems independent from the loading path and similar to a Druker-Prager yield surface. This latter result has to be confirmed with test results obtained with other loading paths.

Acknowledgements

The GIGA press was implemented in the Soils Solids Structures laboratory in the framework of a cooperation agreement with DGA, French Ministry of Defense. This research has been developed with the financial support of CEG (DGA). We would like to thank Dr. Éric Buzaud (CEG) for giving technical and scientific advice.

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[10] Thiot Ingénierie, la Croix Blanche, 46130 Saint Michel Loubejou, France.