Meeting on concrete order multiaxial conditions
Toulouse (France) 22-24 May 1984
CEA-CONF--7303

FR8402538

TRIAXIAL BEHAVIOUR OF A MICRO-CONCRETE COMPLETE STRESS-STRAIN CURVE FOR CONFINING PRESSURES RANGING FROM 0 TO 100 MPa

COMPORTEMENT TRI-AXIAL D'UN MICRO-BETON - DETERMINATION DE COURBES COMPLETES POUR DES PRESSIONS DE CONFINEMENT COMPRISES ENTRE 0 ET 100 MPa

P. JAMET - Chef de Laboratoire - CEA-CEN/SACLAY - DEMT/SMTS/LAMS
91191 GIF SUR YVETTE CEDEX (France)
A. MILLARD - Ingénieur - CEA-CEN/SACLAY - DEMT/SMTS/LAMS
91191 GIF SUR YVETTE CEDEX (Cedex)
G. NAHAS - Stagiaire Universitaire - CEA-CEN/SACLAY - DEMT/SMTS/LAMS
91191 GIF SUR YVETTE CEDEX (France)

A series of triaxial tests has been performed on micro-concrete cylinders. The specimens have been strained with a constant displacement rate, up to a deformation of about 10 %. Two different domains were distinguished. For low confining pressures strain softening is observed, the behaviour of the material becomes ductile for high confining pressures. Continuous measurement of the volume of fluid which had to be injected or withdrawn from the cell, to keep the confining pressure constant during the test, allowed to obtain data, concerning the overall lateral deformations of the specimens. Some specimens were also subjected to successive loadings with different confining pressures, in order to study the influence of stress path.

Une série d'essais triaxiaux a été effectuée sur des cylindres de micro-béton. Les éprouvettes ont été chargées à vitesse de déplacement imposée, jusqu'à une déformation axiale voisine de 10 %. Deux domaines ont été mis en évidence : à basse pression de confinement les courbes obtenus ont une branche descendante, le comportement du matériau devient ductile pour des pressions de confinement élevées. La mesure de la quantité de fluide qu'il était nécessaire de retirer, ou d'injecter, dans la cellule, pour maintenir la pression de confinement constante, à fourni une mesure globale des déformations latérales des éprouvettes Des chargements successifs à des pressions de confinement différentes ont permis d'étudier l'influence de certaines trajets de chargement.

1. INTRODUCTION

Under accidental circumstances, concrete structures can be subjected to important multiaxial stresses, while the material undergoes very hight deformations. One typical example is the perforation of a reinforced slab by a rigid missile : while penetrations occurs, high shear stresses appear in the vicinity of the lateral boundary of the missile, while all the principal stresses are compressive. From a safety point of view, it is necessary to perform mechanical analysis of such cases. One of the main problems associated with such an analysis is that after fracture occured, concrete is not continuous anymore. An equivalent homogeneous material has then to be defined in order to stay within the frame of continuous mechanics.

The constitutive relations for this material have then to be representative of the overall behaviour of actual concrete, when subjected to high strains eventually leading to fracture.

Extensive experimental studies have already been carried out in order characterize triaxial behaviour of concrete (References 1 to 9). However, most of the tests have been stoped after the maximum load bearing capacity of the specimen was reached. At low confining pressures, it was then impossible to observe strain softening. On the other hand, constitutive relations for an equivalent material have to represent accurately the overall deformations of fractured concrete. In a conventional triaxial test, where a cylindrical specimen is axially strained under constant lateral stress, it is then necessary to measure the axial and lateral overall deformations of the sample, even if fracture and strain softening occurs. This problem has been solved in the field of rock mechanics (10), (11). A similar experimental set up was developped for concrete testing.

Complete stress-strain curves were obtained in the case of micro-concrete. lateral strain-longitudinal strain cruves were also recorded.

2. EXPERIMENTAL PROCEDURE

2.1 - Specimen preparation

The admixture, for 1 m^3 of cast micro-concrete, was the following :

- sand 2.5 mm/5 mm : 1180 kg
- sand 0.8 mm/2.5 mm : 275 kg
- sand 0.2 mm/0.8 mm : 415 kg
- cement CPA 55 : 340 kg
- water : 180 l

The specimens were cast in cylindrical molds Ø 11 cm, H 22 cm, and vibrated. The molds where then sealed and stored at 20°C. After 48 hours the specimens were removed from the molds, and stored for 30 days at 20°C and 65 % relative humidity. Grinding was then performed, so that the parallelism defect between the two faces of the specimens was less than 0.02 mm. The cylinders were finaly stored in the same conditions than above, for 180 more days before testing. Some samples were equiped with two strain gages of 70 mm active length. One strain gauge was in the axial direction, the other one in the transverse direction.

2.2 - Experimental device

The experimental device was a classical one : A 2500 kN hydraulic, servo-controlled testing machine was used to apply the axial load. The specimens were jacketed in rubber sleeves which had been specially studied in order to avoid any leakage, even if the sample was severely fractured. The steel spacers used to apply the load were directly in contact with the faces of the specimen. The axial force F transmited to the sample was measured externally, by use of the load cell of the testing machine. The axial displacement S of the actuator was measured by means of an LVDT transducer. An analogical device, using the force signal as in input, was calibrated in order to record continuously the elastic displacement due to the deformation of the loading frame and spacers. This

quantity was substracted from the signal S, in order to directly obtain the relative displacement between the two faces of the micro-concrete cylinder. The piston of the pressure generator connected to the cell was also equiped with an LVDT transducer, in order to record the volume variation ΔV necessary to keep the confining pressure P constant. The pressure P was servo-controlled, with an independant system.
The error associated with all the measurements was ± 1 %.

2.3 - Load path

The specimen were first loaded hydrostatically, at a constant rate of 1 MPa/s up to the selected confining pressure. The confining pressure was then kept constant. After this initial loading, the sample were strained axially at a constant actuator displacement rate of 0.11 mm/s. Unloading occured after a total displacement of 2 cm.

2.4 - Presentation of results

In order to present the results in terms of nominal stress and nominal strains, it was assumed that throughout the tests, the shape of the samples remainded cylindrical. This assumption can only be accepted as a first approximation, since friction between the loading spacers and the specimen results in a complicated state of stresses and strains within the sample.
Let σ_1 and ε_1 be the nominal axial stress and axial strain of the specimen, $\sigma_2 = \sigma_3$ and $\varepsilon_2 = \varepsilon_3$, the nominal lateral stresses and strains. The above assumption then leads to the following expressions.

$$\sigma_1 - \sigma_3 = \frac{F}{S + \dfrac{\Delta V}{H - \delta}}$$

$$\sigma_2 = \sigma_3 = P$$

$$\varepsilon_1 = \log\left(1 + \frac{\delta}{H}\right)$$

$$\varepsilon_2 = \varepsilon_3 = \frac{1}{2}\log\left[1 + \frac{\Delta V}{S\,(H - \delta)}\right]$$

with : F = axial load
P = confining pressure
S = crors section of the specimen after hydrostatic loading
H = Heigth of the specimen after hydrostatic loading
δ = relative displacement between the two faces of the specimen
ΔV = fluid volume variation necessary to keep the confining pressure constant

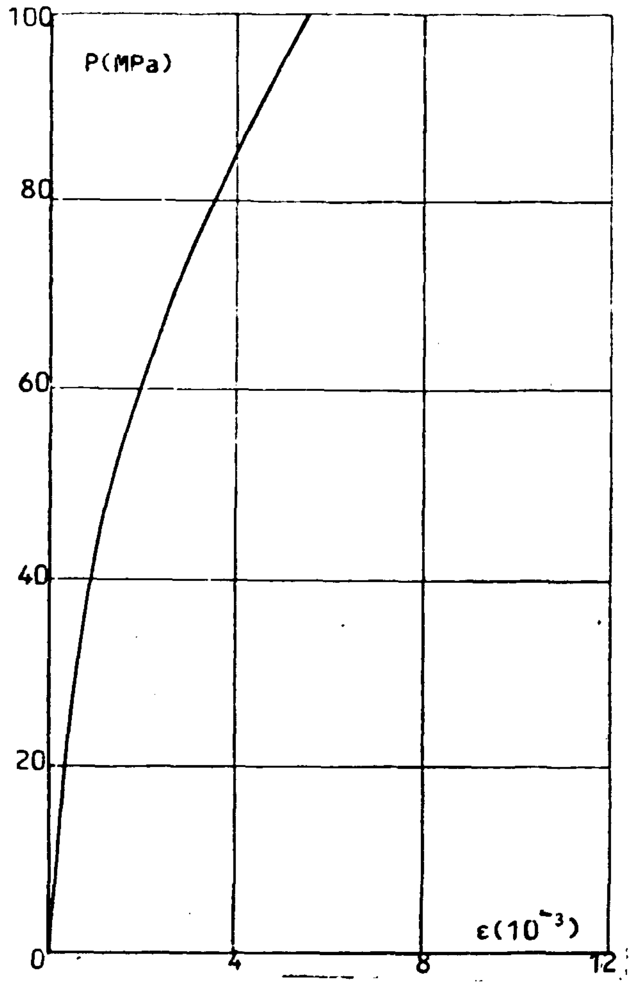
3. EXPERIMENTAL RESULTS FOR CONVENTIONAL TRIAXIAL TESTS

3.1 - Hydrostatic loading

A series of 3 tests was first performed in order to characterize the behaviour of the material under hydrostatic loading. For these tests, the specimens were equiped with strain gauges. The error associated with the strain measurements is ± 4 %. Figure 1 presents the mean curve obtained after averaging all the experimental values. The scatter is relatively important, since some differences between the measured and mean values of the strain was 20 %. However, there is no significant difference between the output from the longitudinal and transverse strain gauges. After testing, no visible sign of damage could be observed on the specimens.

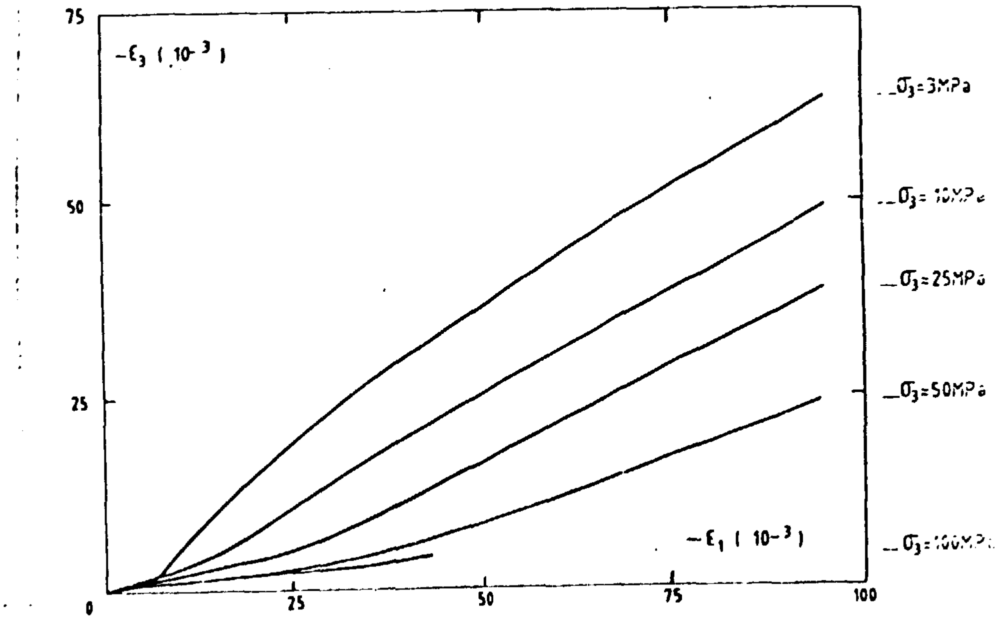
3.2 - Triaxial loading

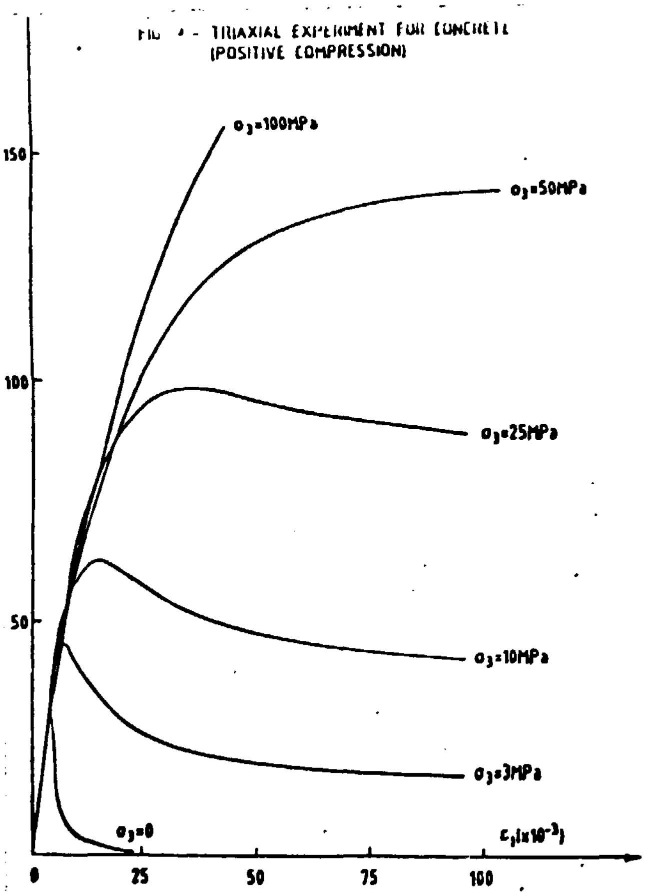
Triaxial loading of 3 specimens was performed for each of the following confining pressures : 0,3 MPa, 10 MPa, 25 MPa, 50 MPa, 100 MPa. Figures 2 and 3 present the obtained results. Each curve represents the mean values obtained out of the 3 tests, for a specific confining pressure. The experimental scatter is relatively low. The difference between measured and mean values never exceeds 10 %.



← **FIGURE 1** : Compressibility of the micro-concrete

FIGURE 2 : Nominal lateral strain - Nominal axial strain curves for the micro-concrete →





← FIGURE 3 : Nominal Stress
Nominal strain curves
for the micro-concrete

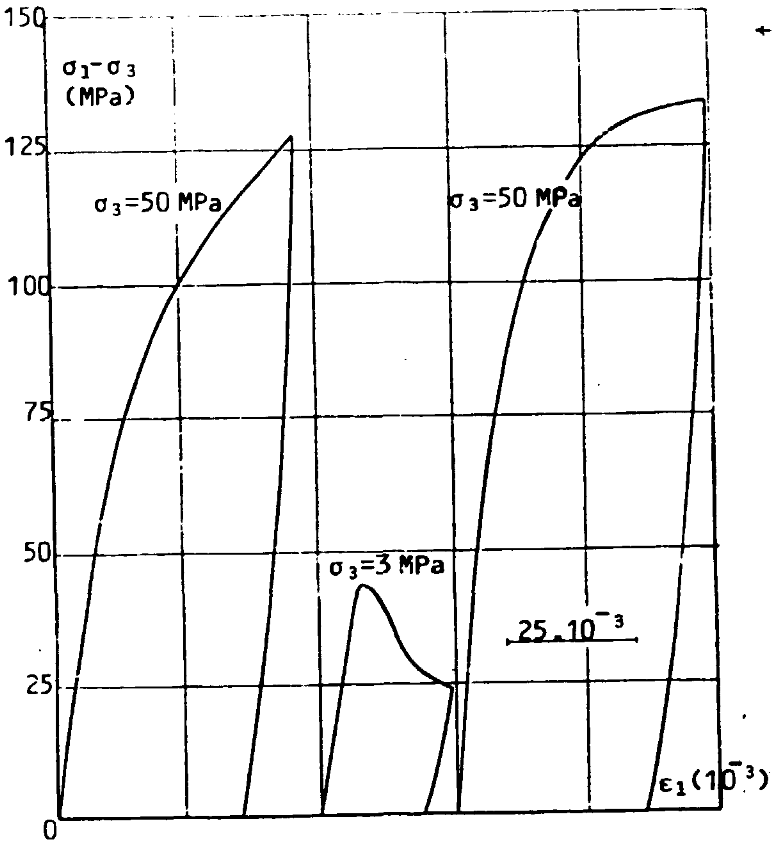
Up to a confining pressure of 25 MPa strain softening is observed. The slope of the descending branch of the curves increases with the confining pressure. The obtained results suggest that after strain softening, the behaviour of the material becomes assymptotically perfectly plastic.
For confining pressures of 50 MPa and 100 MPa, the behaviour of the micro-concrete is plastic. However, the test performed at a 100 MPa confining pressure had to be stopped for a relatively low axial strain, since the maximum load capability of the testing machine was reached.
For confining pressures of 3 MPa, and 10 MPa, the curves on figure 3, show that before the maximum stress is reached, dilatance causes a significant relative increase of lateral strains. After most of the strain softening has occured, the slope of the curves tends to decrease towards a constant value. At 25 MPa confining pressure, the slope of the curve increases before the maximum stress has been reached, it directly tends towards a constant value.
For confining pressures of 50 MPa and 100 MPa, the initial slope of the curves is comparable to the values obtained in the previous tests. After a very short strain, the slope decreases to a low value, and increases again while the specimen is strained.
The aspect of the specimens after testing depended upen the confining pressure : for confining pressures less than or equal to 10 MPa, well individualized, open fractures could be observed. Their inclination with respect to the cylinder axis was about 25°. For 25 MPa confining pressure, the fractures tended to be smeared within the sample. They were less open, their inclination was about 30°. For confining pressures of 50 MPa and 100 MPa, no visible sign of mechanical damage could be observed on the cylinders.

4. SUCCESSIVE LOADINGS AT DIFFERENT CONFINING PRESSURES

4.1 - High and low confining pressures

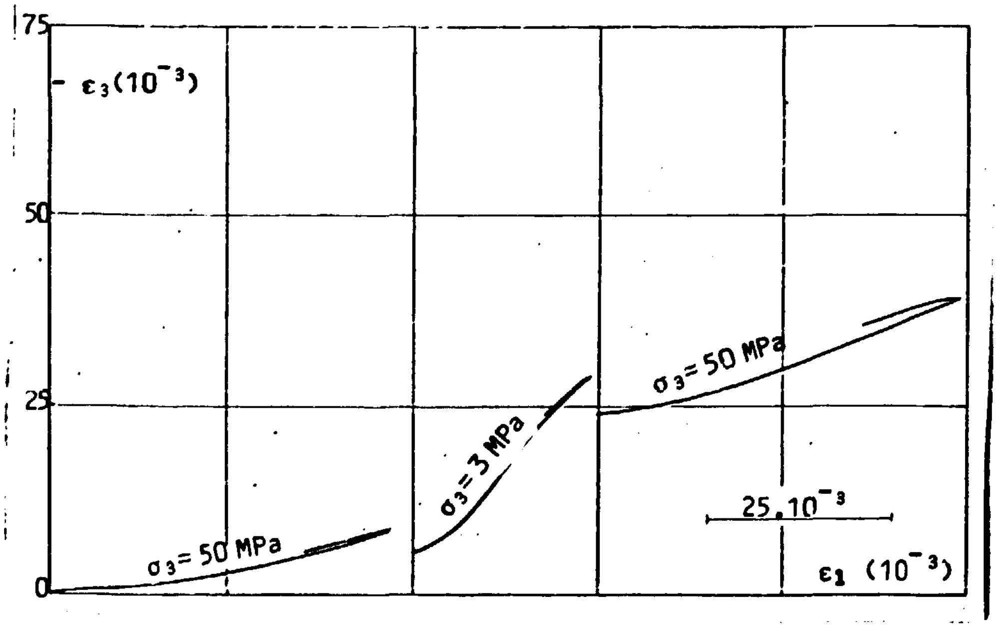
The following loading sequence was performed on 3 cylinders :
- Hydrostatic loading up to 50 MPa, axial loading up to a strain of $50\ 10^{-3}$, axial unloading,
- Reduction of the confining pressure down to 3 MPa, axial loading up to a strain of $25\ 10^{-3}$, axial unloading,
- Hydrostatic loading up to 50 MPa, axial loading up to a strain of 50 MPa, final unloading.

Figures 4 and 5 show the obtained results.



← FIGURE 4 : Axial nominal stress-axial nominal strain for successive loadings at 50 MPa and 3 MPa confining pressures

FIGURE 5 : Lateral nominal strain-axial nominal strain for successive loadings at 50 MPa and 3 MPa confining pressures



When compared to the curves on figures 2 and 3, the obtained results show that :

- strain softening performed at low confining pressure has a slight influence upon the axial behaviour of a specimen, when loaded again at high confining pressure.
- axial straining at high confining pressure has a great influence upon the lateral behaviour of a specimen, when subsequently strained at low confining pressure.

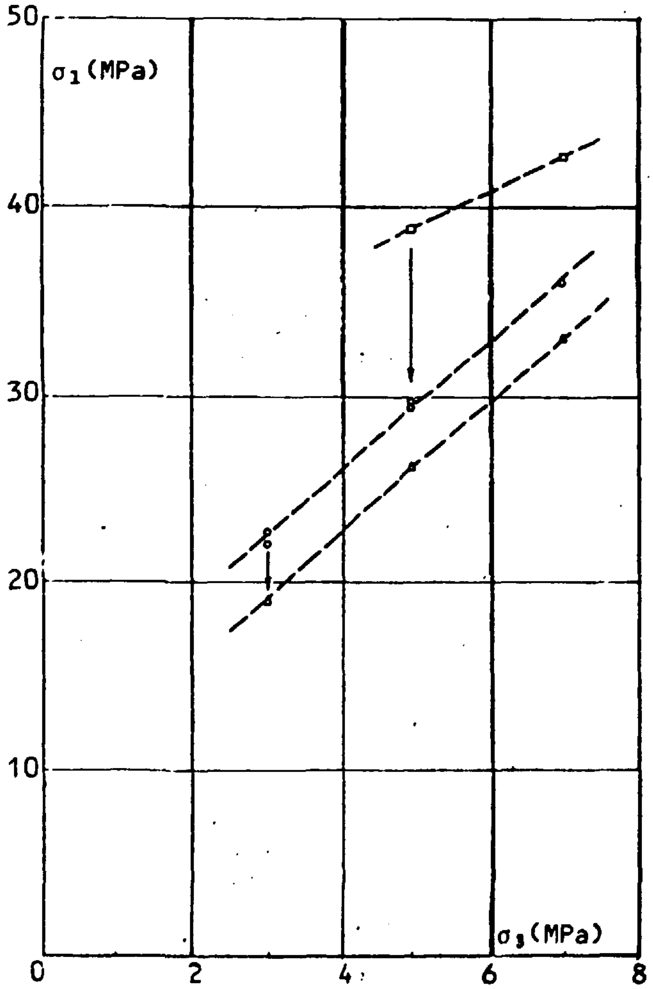
4.2 - Low confining pressures

In order to get some informations about the evolution of the loading surface when strain softening occurs, successive loadings were performed on a series of specimen for 3 MPa, 5 MPa, and 7 MPa confining pressures. Unfortunalely, the cement used to cast these last samples was slighly different from the previous one, and the experimental results are self concistent, but not directly comparable to the one presented before :
It was assumed that the loading surface was reached in the two following situations :

- when the maximum stress was reached, in a strain softening case,
- at the begining of linear plastic deformation in case of ductile behaviour.

The specimens were first strained until the loading surface was reached and instantaneously unloaded. This was done for different confining pressures. Strain softening was then achieved, and the same method was applied again, in order to obtain the new loading surface. The obtained results are presented on figure 6.

FIGURE 6 : Evolution of the loading surface in the $\sigma_1 - \sigma_2$ plane



It can be seen that when initial strain softening occurs, the trace of the loacing curve in the $\sigma_1 - \sigma_3$ plane first undergoes translation and rotation. When subsequent strain softening is performed, translation only is observed.

5. CONCLUSION

The triaxial tests performed on micro-concrete specimens showed that when the confining pressures increases, the behaviour of the material evoluates gradually from drastic strain-softening to classical ductility. Lateral strains of the samples were also measured in all cases. It was found that the overall transverse deformations of the micro-concrete are also strongly dependent upon the confining pressure.
Some informations were finally obtained, about the effect of different loading histories, upon the subsequent behaviour of the material.

BIBLIOGRAPHY

1. BALMER G.G., Shearing strength of concrete under high triaxial stress. Computation of Mohr's envelope as a curve. Structural Research Laboratory N° SP 23 - Structural Research Laboratory, Denver, Colorado, Oct. 1949.

2. GARDNER J.J., Triaxial behaviour of concrete. ACI Journal, Tittle n° 66-15, Feb. 69, pp. 136-146.

3. GREEN S.J. and SWANSON S.R., Static constitutive relations for concrete Technical Report n° AFWC-72-2. Terra Tek Inc., Salt Lake City, Utah, Apr. 73

4. KUPFER H.B., HILSDORF H.K. and RÜSCH H., Behaviour of concrete under triaxial stresses. American Concrete Institute Journal, Vol. 66, Aug. 69, pp. 656-666

5. LAUNAY P. and GACHON H.
   Strain and ultimate strength of concrete under triaxial stress. First International Conference on Structure Mechanics in Reactor Technology, Berlin, Germany, Paper H 1/5, Sept. 71.

6. MASURE P., Cisaillement des mortiers de ciment et comparaison avec l'essai triaxial. Revue des Matériaux de Construction n° 659-660. Sept. 70 pp.229-241.

7. MILLS L.L. and ZIMMERMAN R.M., Compressive strength of plain concrete under multiaxial loading conditions. Proceedings, American Concrete Institute, Vol. 57, n° 10, Oct. 70, pp. 802-807.

8. PALANISWAWY R. and SHAH S.P., Fracture and Stress-strain relationship of concrete under triaxial compression, Journal of Structural Division, ASCE, n° ST 5, Proc. Paper 10 547, May 74, pp. 901-916.

9. RICHART F.E., BRANDTZAEG A. and BROWN R.L., A study of the failure of concrete under combined compressive stresses, Engineering Experiment Station, University of Illinois, Bulletin n° 185, 1928.

10. CROUCH S.L., Experimental determination of volumetric strains in failed rock, International Journal of Rock Mechanics and Mining Science, n° 7, pp. 589-603, 1970

11. CROUCH S.L., The influence of failed rock on the mechanical behaviour of underground excavations, Ph.D.Thesis, University of Minnesota, 1970.

TEXT

Start text on page 2, at the top of the frame.

Type with one line space.

Titles and sub-titles on the margin limit, underlined forthe sub-titles, in capital letters for the principal titles and small letters for the sub-titles.

FIGURES

They include drawings, curves, graphs and exclude photographs. Lines should be drawn in China black ink on tracing paper or white paper.

They should be numbered in sequence according to their order of insertion in the text.

All figures should be inserted by the author(s) as close possible to their first reference in the text, the caption should be typed on the bottom of the space provided for the insertion of the figure, and its text should preferably be centred.

A three line space should be left between the bottom of the caption and the following text.

Authors are reminded that all lines of diagrams and all letters may undergo a standard reduction equal to about 0,7. Consequently original letters and figures should have a minimum size so as to insure after reduction a good legibility.

The drawings, curves, graphs should not be glued in place by the author(s). They will be referenced properly by the author(s) (number of the figure, name(s) of the author(s), title of the paper on the back of the figure).

TABLES

All tables should be framed and meet the same **requirements** as figures.

They should be numbered in Roman figures and set in the text as close as possible to the first reference of them.

EQUATIONS AND FORMULAE

They should be typed if possible. If hand written, use black China ink.

UNITS AND SYMBOLS

Use SI units and symbols. International notations as those proposed by CEB and FIP are recommended.

BIBLIOGRAPHY

Here is an example of presentation :

1. BAZANT Z., Prediction of Concrete Creep Effects using Age Adjusted Effective Modulus Method. ACI Journal, April 1972.
2. CEB-FIP Model Code for concrete structures. Bulletin d'Information CEB n° 124-125/1978.
3. HARTSON H.R., HSIAO D.K., Systems for large data bases, North-Holland, Amsterdam, 1977, pp 27-42.
4. CHOMSKY N., Essays on form and interpretation, North-Holland, Amsterdam, 1977.

INTERNATIONAL CONFERENCE

CONCRETE UNDER MULTIAXIAL CONDITIONS

TOULOUSE (France), MAY 22-23-24, 1984

EDITION OF PAPERS - PRACTICAL RULES FOR AUTHOR(S)

Reports will be offset printed and distributed to the participants before the Congress.

These texts should be sent typed. They will be reproduced without any correction.

All typing mistakes should be properly erased so that no traces may be seen. They should be typed, on an electric golfball type writer if possible, with neat letters and a black carbon ribbon of good quality.

PRESENTATION OF REPORTS

The reports could not exceed 10 pages, including the summaries the name(s) and addresse(s) of the author(s) etc... and will be presented on format A4, white paper inside a 170 x 250 mm guidelines, drawn in blue pencil,

* typed on one face only of the sheets,
* the sheets will be numbered in blue pencil with Arabic numerals 1, 2, 3..., in the rigth hand corner at the top of the page,
* the name(s) of the author(s) will appear on the left top of every page, in blue pencil.

FIRST PAGE

The first page should only include the title of the paper in English and in French, the author(s) name(s), position and professional address, and the English and French summaries.

Title - Author(s)

On full width of sheet, starting from the margin limit, at the top of the frame

* English title of report in capital letters, underlined
* Leave 3 lines space between the two titles
* French title of report in italic capital letters, underlined
* Leave 4 lines space between the last title and the name of the author(s)
* Name(s) of author(s) preceded by initials (capital letters) and followed by the position (small letters), the name of the firm or University (capital letters) and the country (small letters). Give professional address at the bottom of the page.

SUMMARIES

Will be typed on full width of sheet, in both languages. They should occupy the first page only.

Type with one line space.

Begin the first summary just under the dotted line.

A space will be reserved between the two summaries according to their importance.