Large triaxial - torsional testing machine with hygrothermal control

Z.P. Bažant, S. Prasannan, M. Hagen, S. Meiri
Center for Concrete and Geomaterials, Northwestern University, Evanston, Illinois 60201, USA.
R. Vaitys, R. Klima
GARD, Inc., 7449 North Natchez, Niles, Illinois 60648.
J.D. Hess
Structural Behavior Engineering Laboratories (SBEL), P.O. Box 23167, Phoenix, Arizona 85063.

A novel triaxial-torsional testing machine with temperature control has been designed, built, and rendered operational at the Center for Concrete and Geomaterials at Northwestern University. The technical features and capabilities of the machine are described. With a test cavity of diameter 216*mm* (8.5 *in.*), *the machine can handle large specimens. The maximum axial load is* 5 *MN* (1.13×10^6 *lb.*), *and the maximum torque is* 5.6 *kNm* (50,000 *in.-lb.*). *The temperature range is from room to* 600°*C* (1110°*F*). *The test chamber can be filled with gas or water with maximum pressure* 138 *MPa* (20,000 *psi*), *and the specimens can be either sealed or unsealed. The machine opens new horizons in testing the constitutive and fracture properties of concrete and rock.*

INTRODUCTION

Design of concrete structures against earthquake, blast or impact, as well as modern structural uses of concrete in nuclear reactor vessels and containments, radiactive waste storage, offshore oil platforms, undersea structures, etc., require a deeper knowledge of stress-strain relations, fracture properties, and hygro-thermal properties of concrete. Similar needs arise in various modern problems of geotechnical engineering as well as mining, petroleum engineering, earthquake forecasting and geology.

Concrete and rock are materials with highly heterogeneous microstructure which dictates the use of relatively large specimens for testing. At the same time, conventional types of tests, such as standard triaxial, true triaxial (cubical) and biaxial tests, are insufficient to determine the constitutive properties of the material which are needed in the analysis of the current problems. Especially needed is information on the material response at combinations of normal and shear stresses, dilatancy due to shear, as well as the variation of material response at loading histories with rotating principal stress directions or at states at which the principal directions of strain and stress do not coincide. Certain problems of radioactive waste disposal, nuclear

Certain problems of radioactive waste disposal, nuclear reactor safety, fire resistance or origination of earthquakes at great depths also require knowing the material properties at very high temperatures. For many applications, further knowledge is needed with regard to the effect of pore water and its pressure on material deformation. The material properties need to be established not only for the failure initiation regime, but all the way up to the final failure or fracture, which means that tests need to reach into softening regimes for which the load declines at increasing deformation.

To meet these needs, a novel large triaxial-torsional testing machine has been designed, built and put in operation at the Center for Concrete and geomaterials at Northwestern University. The basic initial design [1] was made in cooperation with Structural Behavior Engineering Laboratories, Phoenix, Arizona. This company also produced the major large pieces of hardware and the initial incomplete version of the hydraulic and electrical systems. The final redesign, completion and modification of hardware, hydraulic system and electrical system, as well as the design and production of the load cell, extensometer, and electronic controls, were carried out in cooperation with GARD, Inc., Niles, Illinois. In what follows, a brief report on the technical features and special capabilities of this machine is presented.

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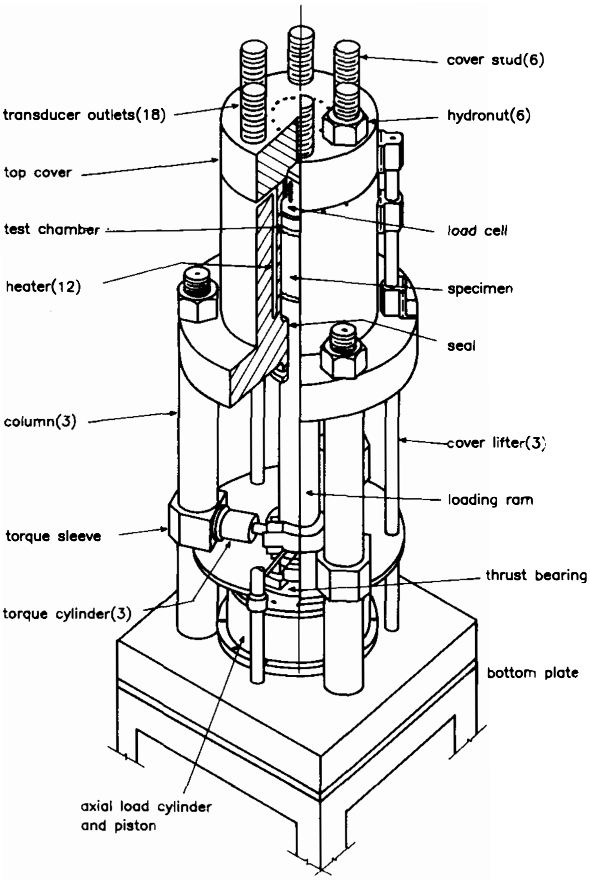


Fig. 1. – Top view of the testing machine.

DESCRIPTION AND TECHNICAL DATA

Test Chamber and Frame

The machine (*figs.* 1 and 2) can exert axial loads up to 5 MN (1.13×10^6 lbs.), confining pressures up to 138MPa (20,000 psi), and torque 5.6 kNm (50,000 in.-lb.). The temperature in the test chamber can be varied between room temperature and 600°C (1110°F). The specimen cavity in the test chamber has the diameter of 216 mm (8.5 in.) and is 686 mm (27 in.) long. The overall height of the machine is 4270 mm (14 ft.), its base dimensions are 1420×1420 mm (56×56 in.), and it weighs 80 kN (18,000 lbs). The test cavity can be pressurized either by water or by gas (usually air or nitrogen). The axial and torsional loads are servo-controlled with a closed-loop hydraulic system, and computer control of the loads or deformations, utilizing an IBM-PC-XT microcomputer, is possible. Under the top lid, as wells as on the piston shaft at the base, the test cavity is sealed with synthetic graphite rings (trade name Grafoil) which are pressurized before the test to double the pressure in the chamber. The high temperature parts of the test chamber are made of Inconel 718 steel, which has negligible creep within the design temperature range, and the remaining parts are made of steels No. 304 and 4340S.S.

Generally, the use of water as the pressurizing medium is more convenient because water stores much less energy than gas, due to its much smaller compressi-

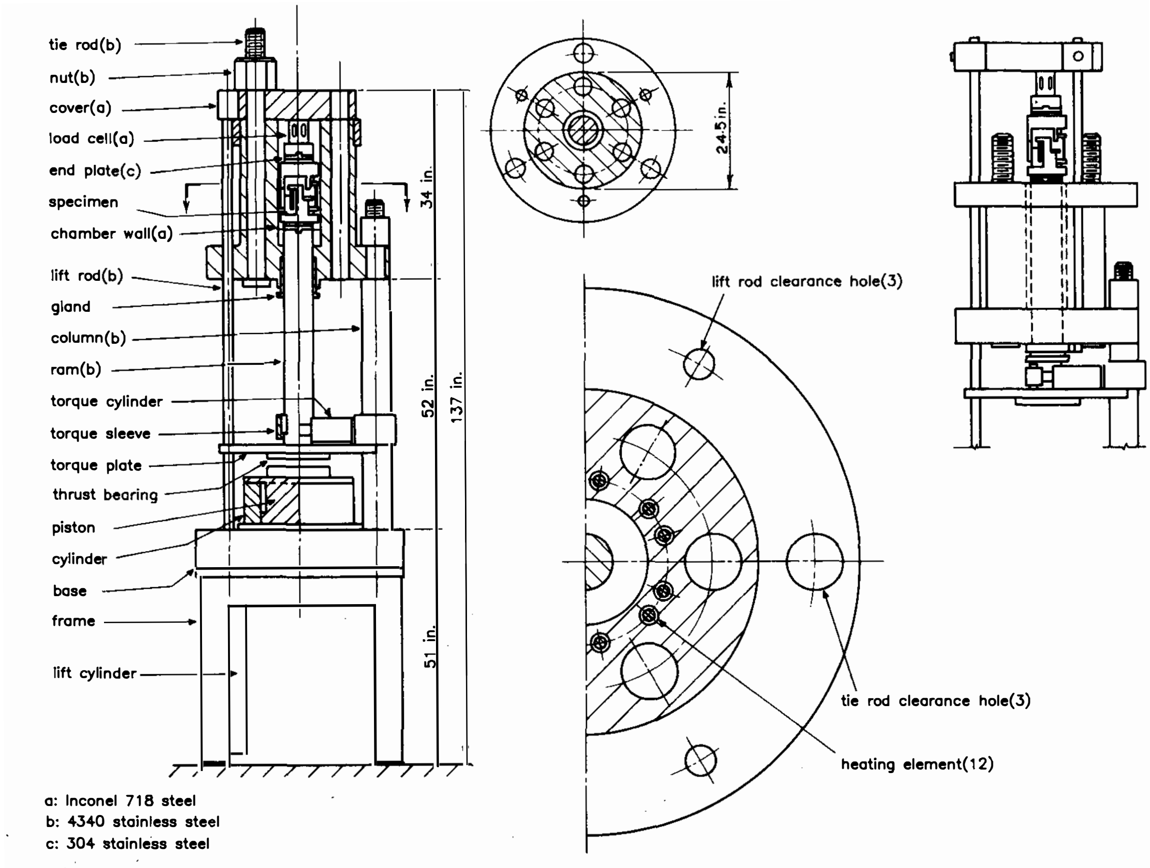


Fig. 2. – Vertical and horizontal cross sections of the machine.

bility, and because the leak rate at the loading shaft seals is smaller (in fact, undetectably small). On the other hand, the durability of the specimen sealing jackets in gas seems better than in water. The option of pressurizing with gas is required to make it possible to test specimens in a drying regime, and the option of pressurizing with water is required for testing the effect of water penetration into the specimen.

The top cover is tightened to the chamber by a set of six studs provided with hydranuts. To assure the correct value of the axial force in each stud, the closing operation consists of pretensioning each stud with a hydra-jack to the desired force, upon which the nut is tightened by hand before the jack is released.

The chamber is thermally insulated on the outside by a vacuum-formed high alumina ceramic fiber material. When the test chamber is operated at high temperature, it is cooled by an upward stream of air drawn from an intake below the chamber and collected in an exhaust hood above the chamber. The chamber safety has been evaluated by means of three-dimensional elastic finite element analysis as well as simplified plastic limit analysis. The axial stiffness of the machine has been measured to be 394 MN/m (2.25×10^6lb./in.). This is a relatively high stiffness value which, in combination with fast servocontrol, suffices to make the softening response of many types of specimens stable. The torsional stiffness of the machine has been measured to be 120 kNm/rad (1.1×10^6in. $\times$ lb./rad). When the compressibility of oil in the hydraulic system is taken into account, these stiffness values decrease by 13% and 5.5%, respectively.

Hydraulic System

The axial load is controlled by a high capacity pump with the power of 60 HP, oil flow of $0.95 \times 10^{-3}m^3/s$ (15 gallons per minute) and pressure 38.6 MPa (5600 psi) (*fig.* 3). The torque loading is realized by three symmetrically located pistons (*fig.* 1 and 2), controlled by a separate smaller pump of power 5 HP, oil flow $0.32 \times 10^{-3}m^3/s$ (5 gallons per minute), and pressure 20.7MPa (3000 psi). The torque pistons, the actions of which are reversible, apply their loads directly on the axial loading shaft through a common cam. The three cylinders are arranged symmetrically at 120°C spacing and always apply the same force so that there is no net horizontal resultant force applied on the vertical loading shaft. Such a force would increase friction for axial loads.

The machine is designed so as to allow a large displacement of the axial loading shaft such that the test specimen can be lifted above the barrel section of the test chamber (*fig.* 2). This facilitates setting up the experiment before the test as well as removal of the specimen after the test. The heavy top cover of the test chamber (*fig.* 1 and 2) can be lifted by three hydraulically operated rods to a height which permits easy access to the specimen during its installation. The lifting rods are driven by three independent pistons

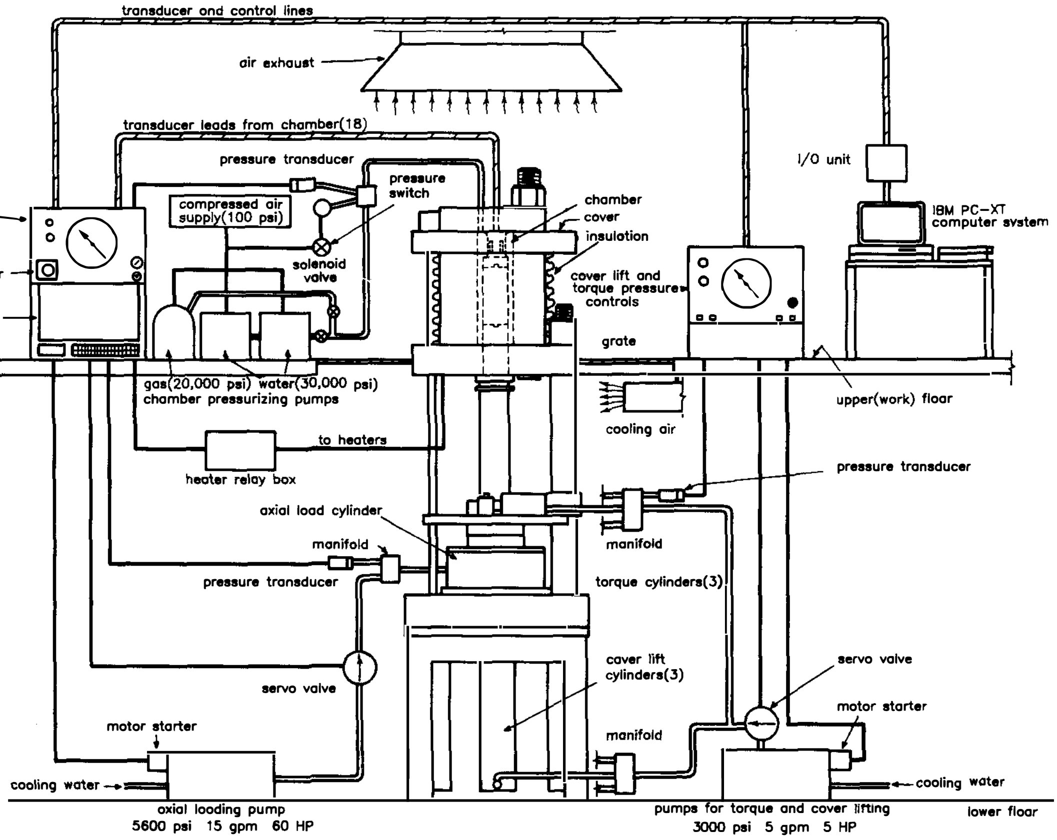


Fig. 3. – Schematic diagram of hydraulic, electric and thermal systems.

which are operated by the same pump as the torque cylinders.

Pressurization of the test chamber is effected by either two water pumps of 207 MPa (30,000 psi) capacity, or by two gas pumps consisting of one 41.4 MPa (6000 psi) pump cascaded with another pump to obtain the 138 MPa (20,000 psi) maximum pressure (*fig.* 3). The first of these pumps is directly fed either from a liquid pressurized nitrogen bottle or from an air compressor. All of these pumps are driven by compressed air from a central air compressor of the building.

Electrical System and Transducers

The chamber is heated by 12 electrical heaters of 5400 Watt power each, controlled by a thermocontroller. The heaters are arranged vertically along the circumference of the wall of the chamber (*fig.* 2).

The control circuits consist of hydraulic pump motor starters, oil flow control valves, and oil pressure servovalves. The chamber pressure is measured by a pressure transducer (manometer) outside the chamber. Pressure transducers also measure the pressures of the oil driving the axial load piston as well as the oil driving the torque pistons. The temperature in the chamber is measured by thermocouples at several locations.

To avoid the uncertainties due to friction on the axial loading piston and to the deformation of the axial loading piston and specimen end caps, the axial load and torque are measured inside the test chamber, and so are the deformations of the test specimen. The measurement systems have been designed to operate up to the full range of design pressures and temperatures within the chamber, and in gas as well as water environments. These were difficult conditions to meet, however, the design and production of the load cell and extensometer were eventually successful.

The axial load and torque are measured by a load cell which is made of Inconel and is located above the test specimen under the top cover of the chamber (*fig.* 4). The load cell is equipped with welded Ailtech encapsulated strain gages which operate in gas or water within the aforementioned range of temperatures and pressures. The top cover of the chamber is provided with a plug which allows interchange of the load cell (*fig.* 4). Load cells with three different ranges are necessary to cover the entire range of test conditions. The capability of measuring both the axial loads and torque with the same load cell is achieved by cutouts in the cylindrical body of the load cell (*fig.* 4). The strain gages are located and wired so as to separate the values of the axial load and the torque. The axial load and torque are controlled according to the signal from the load cell, and the chamber pressure according to the signal from the pressure transducer. The loads and temperatures are monitored and recorded by the Kaye Digistrip II Datalogger or a microcomputer, which converts the electric signals from the transducers to load and temperature values by means of a preprogrammed calibration data package.

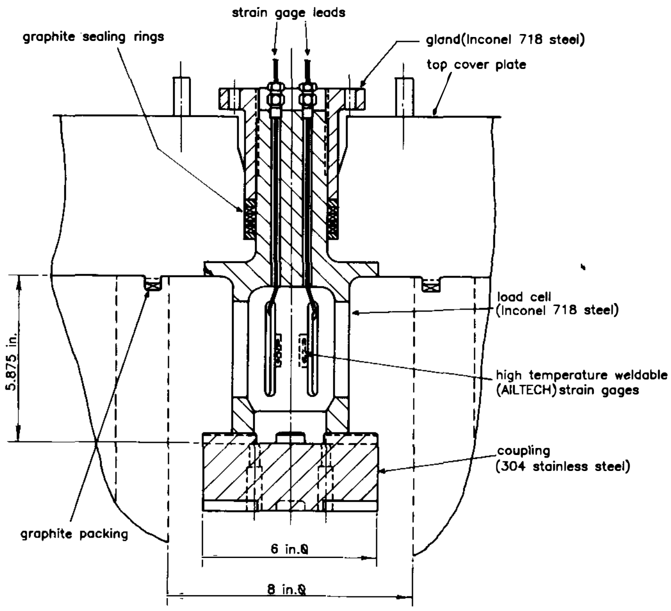


Fig. 4. — Cross section of the axial-torsional load cell and cover plug.

The axial, lateral and torsional deformations are measured by an attachable extensometer with welded encapsulted (Ailtech) high temperature strain gages. The extensometer, which is adjustable to fit three specimen sizes 152 mm, 102 mm, and 76 mm (diameters 6, 4 and 3 in.), measures the relative axial displacement on a 152 mm (6 in.) base or 76 mm (3 in.) base, the change of diameter of the specimen, and the relative rotation of the cross sections over the aforementioned base. The extensometer is designed and the strain gages are wired in such a manner that the average axial, torsional, and lateral strains over the measurement base can be read and controlled separately for axial and torsional strain measurements. The corresponding electric signals, obtained from four strain gages attached to the extensometer (*fig.* 5), two on either side of the specimen, are fed into the recorder and the computer. For lateral strains, signals from two strain gages are fed. With the help of a software package, the computer converts the electric signals into deformation readings (in inches) and then, depending on the size of the specimen, into strain readings. The average values of the strain readings are then plotted against time, for a preset frequency of data output. The extensometer is made of Inconel steel so it does not creep at high temperature. The load cell and extensometer have been accurately calibrated, at various temperatures and chamber pressures, to include the effects of temperature and pressure on the strain gage readings.

Since the extensometer frame is relatively heavy, the weight of the extensometer is supported by springs. The extensometer is attached to the specimen by small steel pins which fit into conical holes in 8 stainless steel buttons that are glued or cemented in a recess on the surface of the concrete specimen. If a sealing jacket is used, these buttons protrude through the jacket. The buttons are installed in precise locations with the help of a specially manufactured drilling jig made of steel.

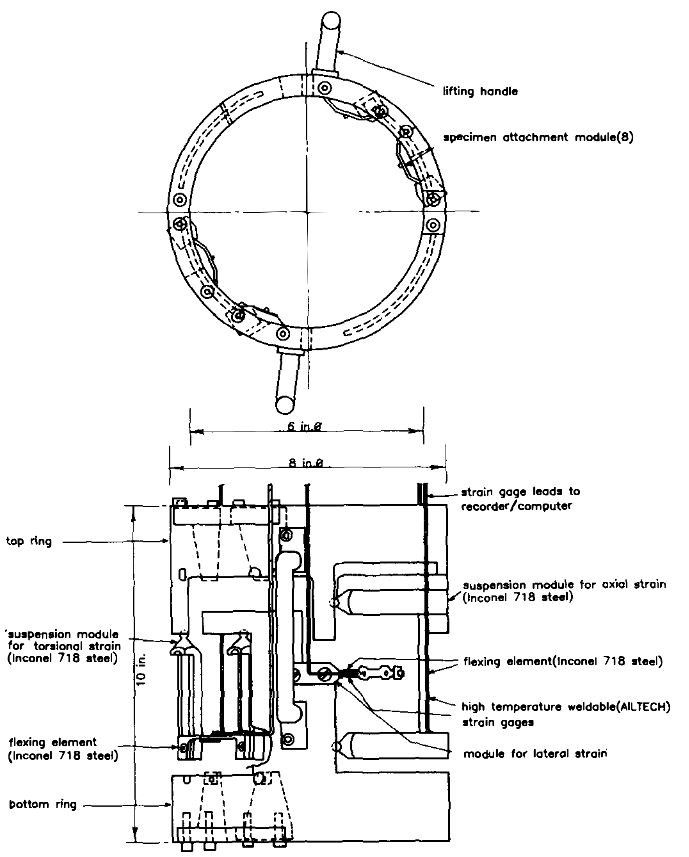


Fig. 5. – Vertical and horizontal views of the axial-torsional-lateral high temperature extensometer.

For a short time after a rapid change of chamber temperature, the extensometer as well as the load cell cannot give correct readings. This is because the surface layers of the extensometer frame are heated before the core layers are. It has been calculated that about two hours after a sudden temperature change are required for the material of the extensometer frame to approach a uniform temperature with variations not exceeding 2.5% of the initial sudden temperature change. During the initial two-hour period after rapid heating, neither the extensometer nor the load cell give correct readings for the strains, unless the output were mathematically processed in a special sophisticated manner.

The Kaye Digistrip II data logger or the IBM-PC-XT microcomputer is used as the data acquisition system. Computer control of the machine is also possible with the microcomputer (Fig. 3).

Test Specimens

Typically the test specimens are cylinders 305mm (12 in.) long, either solid or hollow (Fig. 6). The external diameter is typically 152mm, 102mm, and 76mm (6 in., 4 in., and 3 in.). The specimen's external surface may be either unsealed or sealed. For temperatures up to about 250°C (480°F), sealing is achieved by two coats of silicon rubber. For higher temperatures, a thin copper foil with a brazed longitudinal seal and copper end rings is used for sealing. At specimen ends, the copper rings are leak-tightly connected to the end platens by means of knife edges. Special seals are required around the targets that serve as the supporting points of the extensometer. Specially designed end caps, provided with eight radial ribs, are used to transmit torque (*fig.* 6).

SPECIAL CAPABILITIES OF THE MACHINE

Large-Size Specimens

Although the test specimens are of standard size, they are nevertheless quite large for the loading conditions used. The previous triaxial testing for portland cement concretes under triaxial loading and temperatures over 100°C (212°F) has been carried out on much smaller specimens, the diameter of which was 15 mm (0.6 in.) [3]. The increase in specimen size has greatly raised the cost of the machine, however, it was inevitable in order to test specimens with realistic aggregate sizes up to 30 mm (1.2 in) and possibly also with reinforcement or cracks. Still larger specimens would, of course, be desirable to better simulate conditions in a massive concrete wall of several meters in thickness, as used, e.g., in nuclear reactor vessels. Nevertheless, although the effects of statistical heterogeneity in the specimens are larger than they will be for more massive specimens, the present size range does make it possible to observe the true nonlinear behavior and fracture response of concrete, which is rather different from that of mortar (concrete with small aggregate) or cement paste.

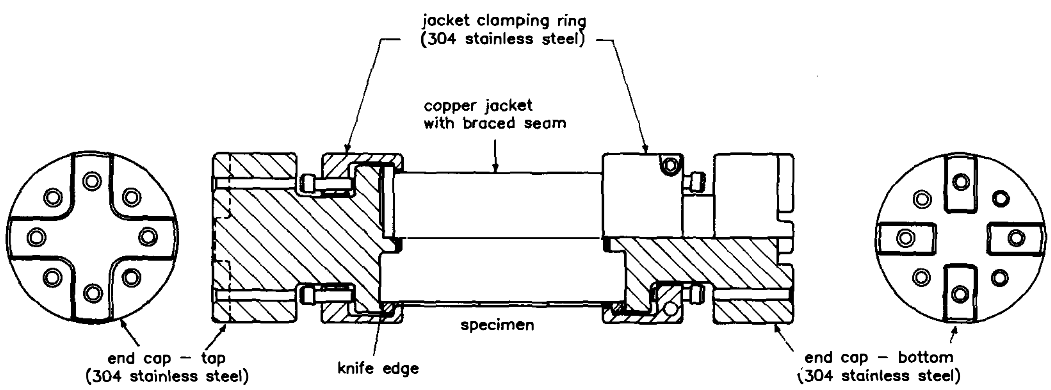
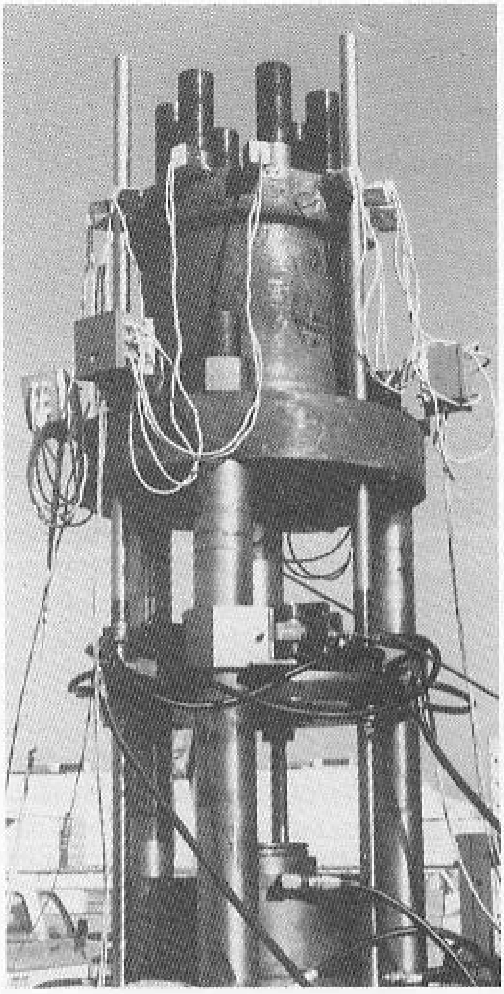


Fig. 6. – Test specimen with end caps and sealing jacket.



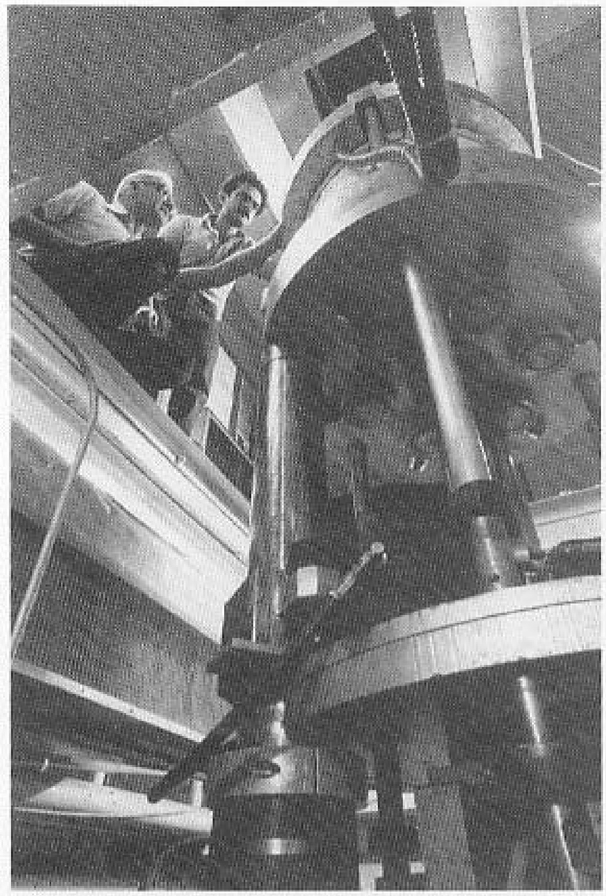


Fig. 7. — Machine before installation in laboratory (left) and after installation (right)

Another reason for a large specimen size appears when deformation under simultaneous drying or moisture movement is to be observed. For the very small specimens used before, the diffusion process leads to drying or wetting times that are unrealistically short compared to the creep test duration of interest, and so the long range effect of transient moisture state on creep cannot be captured. The drying or wetting times are approximately proportional to the square of specimen diameter. Thus, for the present specimen of 6 in. diameter, these times are about 100-times longer than they were for the previously used specimens of 15 mm (0.6 in.) diameter.

High Temperature

In certain hypothetical nuclear reactor accidents, a massive wall of concrete can be rapidly heated well over 100°C (212°F). Questions of high-temperature exposure also arise in the study of fire resistance of a concrete structure, or in safety assessment of a concrete plug for a radioactive waste disposal site, as well as in designing certain chemical technology vessels (e.g., concrete vessels for coal gassification).

The triaxial properties of concrete under such temperature conditions, and especi
deformations due to heating, are at the present only insufficiently known.

Torsional Loading

One important purpose of the triaxial loading
bility with torsion is to produce loading paths in which the principal stress di
during the loadi
are impossible with the conventional triaxial devices as well as with the recent true triaxial
Tests with combinations of axial load and torque have been conducted before, however only for the purpose of determining the failure envelope. In these older tests, the deformation history has not been monitored and the loading path has not been controlled [6-11].

The rotation of the principal stress axes during the deformation process brings into play the stress-induced anisotropy of the material caused by previous loading. It allows study of the incremental stiffness of the material for stress increments which are not only normal but also tangential or generally inclined with respect to the current loading surface (in the sense of plasticity theory). These aspects are essentia
of a general constitutive relation [4].

Another need for triaxial loading of concrete arises when a material
(or joints, in the case of rock) is considered. The new machine makes it possible to test a concrete or rock cylinder with a transverse crack or joint which is subjec-

ted to controlled normal stress across the crack, controlled confining stress on the material, or controlled shear and normal relative displacements across a crack in concrete (or rock joint). Thus, the frictional and dilatant aspects of the deformation due to the cracks or joints can be determined. Compared to the direct shear test specimens, the use of torsional loading has some important advantages, namely that the relative shear displacement across the crack is uniform along the circumference, is linearly distributed along the radius (regardless of the material properties to be measured), and thus is known at each point of the crack plane if the relative rotation of the opposite surfaces of a crack is measured. In the direct shear test, by contrast, both the strain and stress distributions along the crack are unknown, depending on the properties to be measured.

Torsional loading is also useful for the study of creep because no shrinkage shear strains and thermal shear strains exist. Thus, in torsion it is possible to obtain deformations produced by stress which are not obfuscated by overlaid shrinkage and thermal strains.

EXAMPLE OF MEASUREMENTS

To demonstrate some of the results which have already been obtained with this machine, we show an application to triaxial and torsional creep of concrete above 100°C. Table 1 shows the applied load and environmental histories of 4 solid concrete specimens 152 mm (6 in.) in diameter and 305 mm (12 in.) long, tested in the machine. The specimens were sealed dry or wet, or unsealed and immersed in water. The objective was to compare the axial and shear creep due to

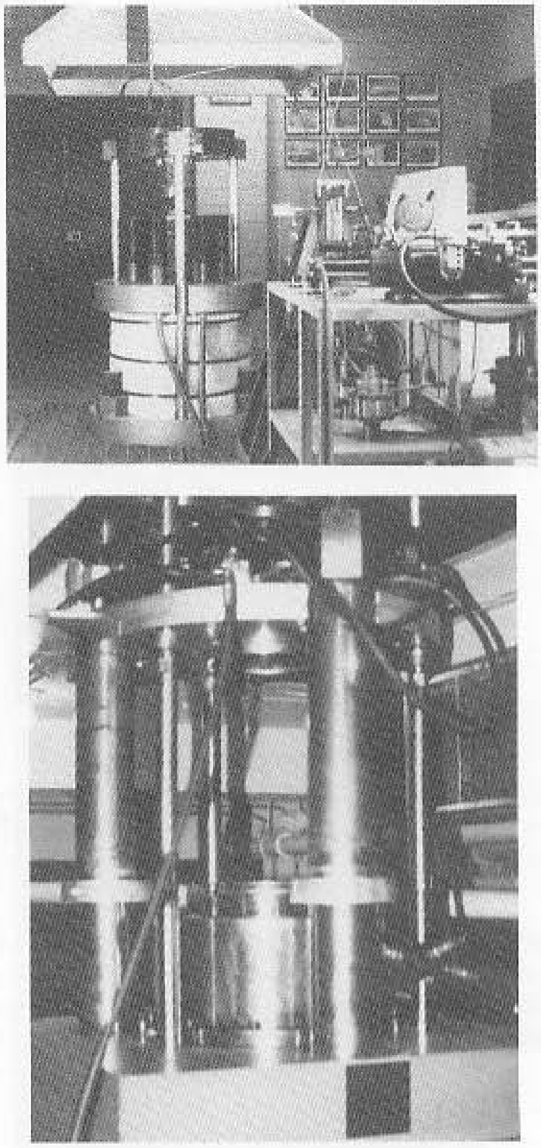


Fig. 8. — Top upper half of the machine with views of the chamber pressurizing system and the exhaust duct, upper floor. Bottom: Lower half of the machine, lower floor.

TABLE 1

	T °C	H %	p MPa	σ_z MPa	Max τ_{xy} MPa	T °C	H %	p MPa	σ_z MPa	Max τ_{xy} MPa
Day	Test No. 1 (Sealed wet)					Test No. 2 (Sealed dry)				
1	120	0	2.1	0	0	120	0	2.1	0	0
2	120	0	9.7	0	0	120	0	9.7	0	0
3	120	0	9.7	9.7	0	120	0	9.7	9.7	0
4	120	0	9.7	9.7	3.8	120	0	9.7	9.7	3.8
5	200	0	9.7	9.7	3.8	200	0	9.7	9.7	3.8
6	200	0	2.1	0	0	200	0	2.1	0	0
	Test No. 3 (Unsealed) Test No.					Test No. 5 (Unsealed)				
1	120	100	2.1	0	0	120	100	2.1	0	0
2	120	100	9.7	0	0	120	100	9.7	0	0
3	120	100	9.7	9.7	0	120	100	9.7	9.7	0
4	120	100	9.7	9.7	3.8	120	100	9.7	9.7	2.8
5	200	100	9.7	.7	3.8	120	0	0	9.7	2.8
6	200	100	2.1	0	0	120	0	0	0	0
	Test No. 8 (Sealed wet-Control test)									
1	25	0	2.1	0	0					
2	25	0	9.7	0	0					
3	25	0	9.7	9.7	0					
4	25	0	.7	9.7	3.8					
5	25	0	.7	9.7	3.8					
6	25	0	2.1	0	0					

T, temperature; H, environmental humidity; p, chamber pressure; σ_z, axial Stress; τ_{xy}, shear stress.

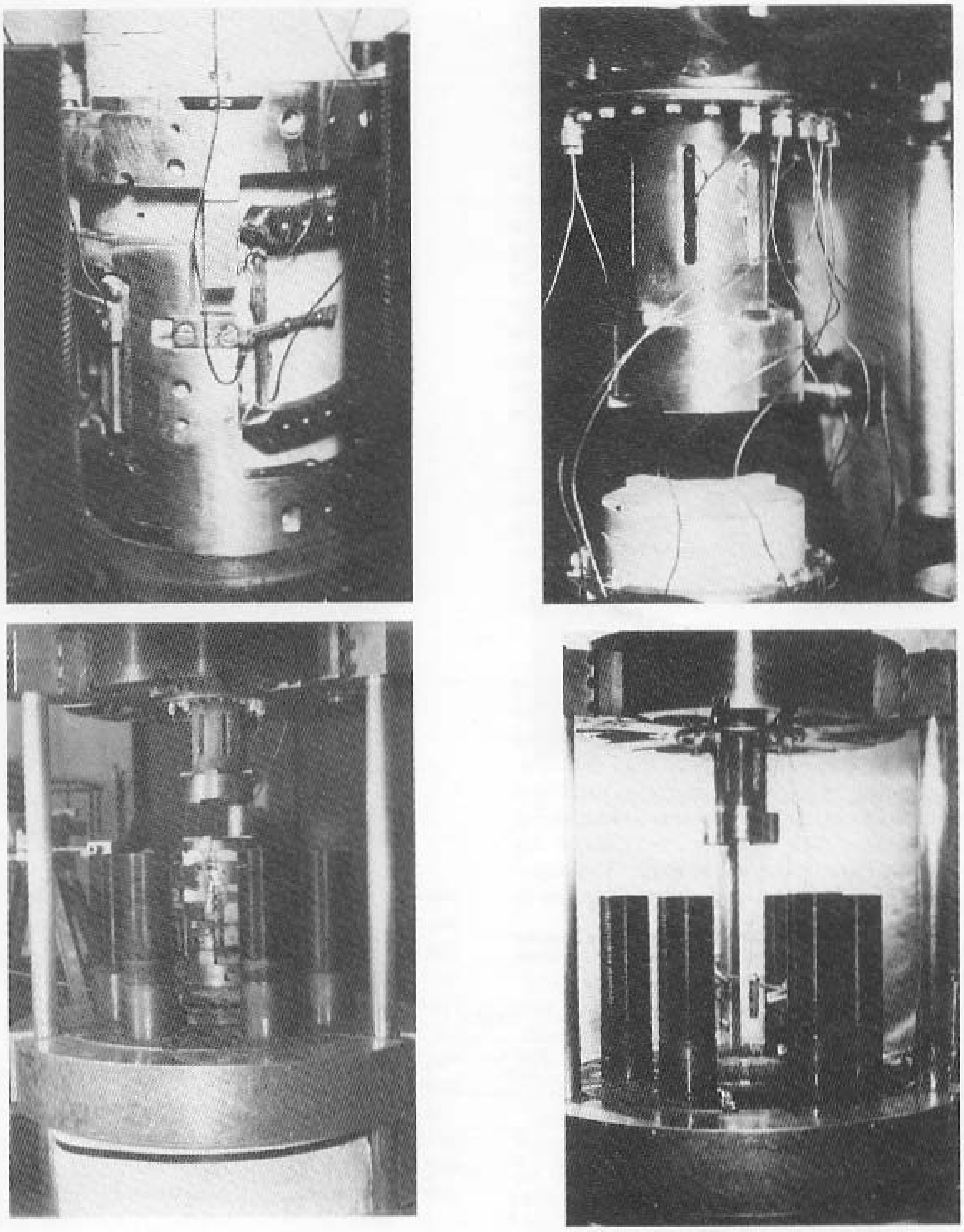


Fig. 9. — Left top: extensometer assembled, on a 6-inch cylinder. Left bottom: extensometer with specimen and load cell before the test. Right top: load cell, disengaged from torque transmitting platten. Right bottom: load cell with dissassembled measuring parts of the extensometer.

these various types of loading. The measured strains, converted to axial and shear compliance values (strain per unit stress) are plotted as the data points in figure 7 a, b, and the solid lines represent estimated smoothing of the results traced by hand. These compliance values represent the additional strains caused during a 24-hour period after a change of loading defined in Table I.

An interesting conclusion from these measurements is that the specimen sealed wet creeps more than the specimen sealed dry as well as the unsealed specimen immersed in water. This is true for the axial creep, and also for the shear creep (although for the unsealed specimen in water to a lesser extent). This behavior is different from that observed in uniaxial creep at room temperature, for which the specimens sealed wet and the specimens immersed in water creep about the same, and an unsealed specimen drying during the test creeps much more than the other two.

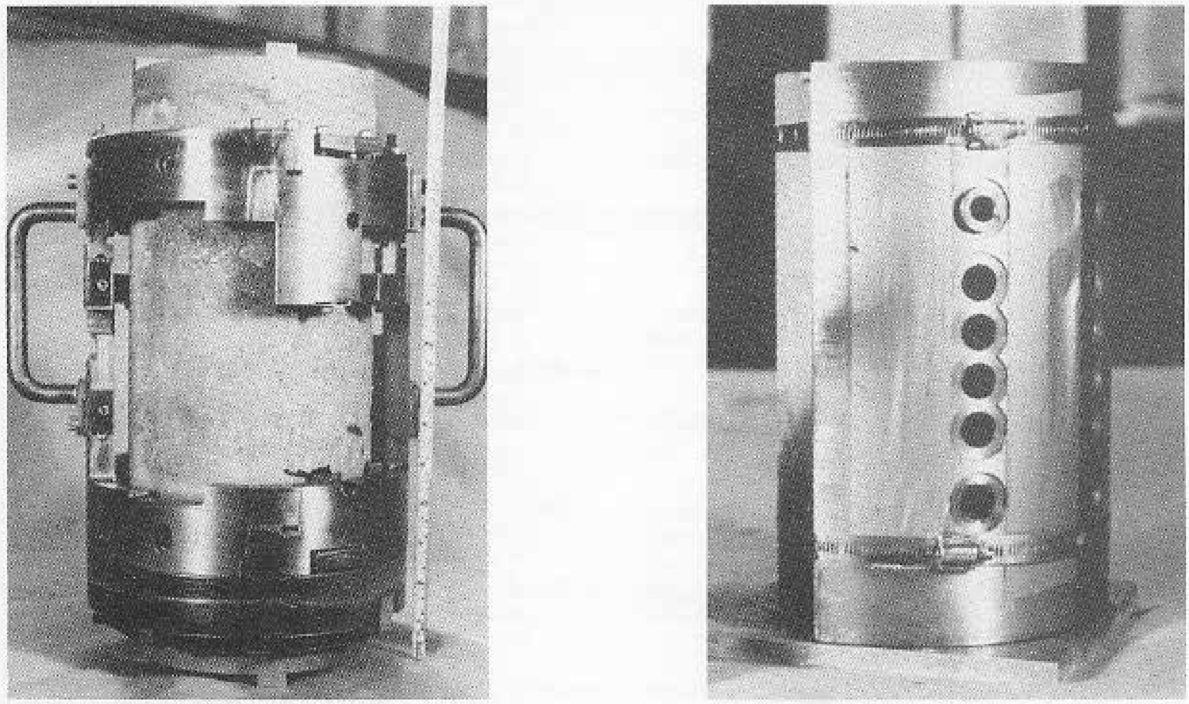


Fig. 10. — Left: test specimen with extensometer frame but without strain measuring parts. Right: drilling jig for setting extensometer support buttons.

Also, it may be noted that the ratio of the shear creep to the axial creep is generally higher than it is for room temperature, which points to an increase in the creep Poisson ratio with temperatures. It is interesting too, that the observed behavior is qualitatively similar to that found in previous tests [3] of very small tubular thin-wall cement paste specimens.

For a detailed analysis and many further test results, see a separate paper which follows [5].

CONCLUSION

The new machine put in operation at Northwestern University opens a new dimension of material testing. The tests that can be performed with this machine should considerably broaden the current knowledge of the constitutive relations and fracture laws for concrete and geomaterials. The first test series aimed at high-temperature triaxial creep at various hygrothermal conditions is in progress.

ACKNOWLEDGMENT

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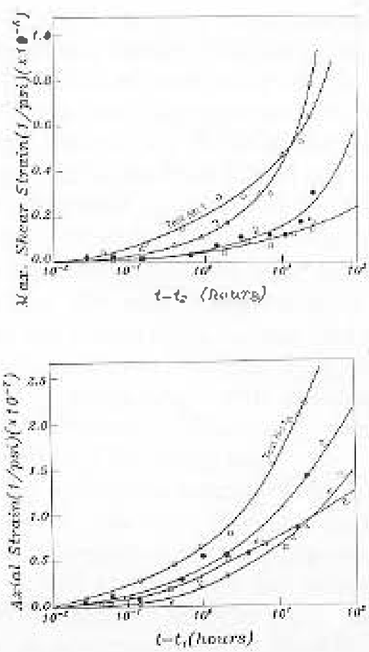

Fig. 11. — Example of measured deformation histories at high temperatures.

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RÉSUMÉ

Grande machine d'essai triaxial et en torsion avec contrôle hygrothermique. — *Une nouvelle machine d'essai triaxial en torsion avec contrôle de température a été conçue, construite et rendue opérationnelle au Centre du Béton et des Géomatériaux de la Northwestern University. On décrit ses caractéristiques techniques et ses possibilités. Grâce au diamètre de son caisson d'essai* (216 *mm*), *la machine peut recevoir de grandes éprouvettes. La charge axiale maximale s'élève à* 5 *MN et le couple maximal à* 5.6 *kNm. La température varie de celle de la pièce à* 600°*C. On peut remplir l'enceinte de gas ou d'eau à une pression maximale de* 138 *MPa, et confiner les éprouvettes ou non. Cette machine ouvre de nouvelles perspectives pour l'essai des propriétés constitutives et des propriétés de rupture du béton et des roches.*