

HIGH-TEMPERATURE TRIAXIAL TORSIONAL CREEP TESTS OF CONCRETE AT VARIOUS HYGRAL CONDITIONS

Zdeněk P. BAŽANT * and Santosh PRASANNAN **

Center for Concrete and Geomaterials, The Technological Institute, Northwestern University, Evanston, IL 60201, USA

Received 8 October 1985

Results of an initial series of six-day creep tests under a program aimed at establishing fundamental deformation properties of concrete at high temperatures under triaxial loading with shear and various hygral conditions, both constant and transient, are reported. The tests are conducted in a novel large triaxial torsional testing machine with hygrothermal control. Tested are cylinders of six inch diameter, sealed or unsealed, loaded by compressive axial force, chamber pressure and torque. Some specimens are sealed wet, some are sealed after drying in an oven, and some are let to dry during the test. Significant differences in creep at various hygro-thermal conditions are observed. Particularly interesting is the fact that hygro-thermal changes affect not only normal creep strains but also shear creep strains. The results are of interest for the formulation of constitutive relations needed for the analysis of nuclear reactor accidents, radioactive waste disposal, and fire resistance.

1. Introduction

Assessment of safety of concrete structures for nuclear reactors, as well as certain problems of radioactive waste disposal, fire resistance, and chemical technology vessels, pose the need for a better knowledge of the constitutive relation for concrete than available at present. Much experimental research has been carried out to meet these needs, and considerable information has been gathered over the last two decades [1,8-13,15-24]. Nevertheless, certain rather serious gaps remain, especially for temperatures above 100°C. Most tests up to now have been limited to uniaxial compression and dried concrete which has lost its pore water due to heating. Attempts to seal the specimens have been made, however, the seals bulged under internal steam pressure, and water still exited the specimens and collected under the seal. The only way to keep pore water in the specimen is to apply lateral pressure that is at least equal to the saturation steam pressure for the given temperature. Hence, triaxial loading is required for the basic tests at constant water content. Uniaxial stress response of the material at saturation water content is a meaningless, nonexistent property at temperatures over 100°C. To carry out a uniaxial test at

constant water content, it would in fact be necessary to apply the lateral pressure only on the vapor in the surface pores and not on the solids, which is technically impossible. Yet, in massive concrete walls, or in non-massive concrete walls subjected to rapid heating or sealed by a steel liner, pore water does not have sufficient time to escape prior to the heating of concrete. Finite element analysis reveals that these conditions are typical of many accident situations.

Some experimental information was obtained [4] for the behavior of hardened Portland cement paste under triaxial loading (without shear) at various hygral conditions, including specimens that are sealed wet, sealed dry, and unsealed, drying during the test. However, it is unclear to which extent the results of these tests, carried out on small cylinders of 15 mm diameter, can be applied to concrete. Some rather limited information has also been reported [9,14] for the response of concrete at biaxial stress and for shear failure, however, these tests were limited to temperatures under 100°C, for which the drying rates are two orders of magnitude slower [2,3,5] and the specimen retains most of its moisture for a considerable length of time even if unsealed.

Most of the previous high temperature testing of concrete was restricted to uniaxial loading and specimens freely losing their moisture (e.g., Naus, 1981). Some limited data are available on triaxial loading

* Professor of Civil Engineering and Director.

** Graduate Research Assistant.

without torsion, but only for dried specimens (Thelandersson, 1983; Schneider, 1982) and on the shear failure load of nonhomogeneously stressed notched specimens (Naus, 1981). Limited data is also available for torsional loading alone (Illston, 1973) of mortar specimens. No data exist for deformation under shear stress, either alone or in combination with axial stresses and pressure, and for triaxial behavior of concrete in massive (or lined) walls.

In response to these needs, a testing program concerned with the multiaxial deformation of concrete at temperatures over 100°C and various hygral conditions has been initiated at Northwestern University, and the results of the initial test series are now reported.

2. Testing machine

The tests are conducted in a unique, large testing machine which was recently rendered operational at

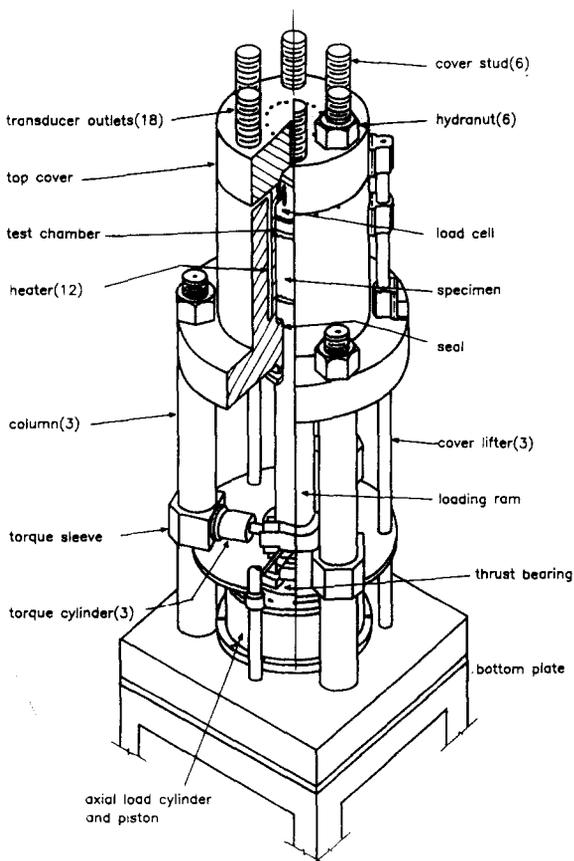


Fig. 1. Cut-out view of the high-temperature triaxial-torsional testing machine at Northwestern University.

Northwestern University. The machine has a test chamber with a cylindrical cavity 216 mm (8.5 in.) in diameter and 686 mm (27 in.) in length. The maximum axial load is 5 MN (1.13 million lbs), the maximum torque is 5.6 kNm (50 000 in. lb), and the maximum chamber pressure is 138 MPa (20 000 psi). The axial and torque loadings have closed-loop servocontrol. Tests can be conducted at temperatures from room to 600°C (1110°F). The chamber pressurizing fluid is either water or gas (e.g., air or nitrogen). For a detailed description of this novel testing machine, shown in figs. 1 and 2, see ref. [7].

3. Test specimens

The test specimens were cylinders of diameter 152 mm (6 in.) and length 305 mm (12 in.). The specimens were solid rather than hollow, even though torsional loading was used. A thin-wall cylinder might have been easier for evaluation, however, a wall thickness of 50



Fig. 2. View of testing machine from underneath.

mm (2 in.) or less would seriously limit the aggregate size that could be used and would produce the so-called "wall effect" on the inside surface (i.e., the disturbance due to the fact that the large aggregate content in the layer near the surface is less than it is in the rest of the concrete specimen). However, the use of a solid cylinder is not a serious obstacle because the strains are uniform along each circle and linearly distributed over the radius, and thus are known at each point of the specimen (in contrast to direct shear tests, in which both the strain and stress distributions are unknown, depending on the material properties to be measured).

The specimens were cast in the laboratory using a concrete mix with the ratio 1:2:2:0.59 of cement, sand, aggregate and water (by weight). The aggregate was crushed dolomitic limestone (Racine quarry, Wisconsin, USA) of maximum size 13 mm (0.5 in.), and the sand was a river sand (uninucological type, from Antioch, Illinois, USA) passing through sieve No. 4, i.e., the maximum size of sand was 5 mm. Ordinary Portland

cement of ASTM Type I (ASTM-C150) was used in the mix. The concrete was mixed in a Hobart vertical mixer according to the specifications of ASTM C-192-76. Steel molds, also conforming to this specification were used for casting. The end plates of the molds had a ribbed molding surface, with eight radial ribs which form corresponding radial grooves at the specimen ends and thus enable transmission of torque.

The specimens were cured for 24 h in the mold, at room temperature 21°C (70°F). Then the specimens were demolded and placed in a water bath saturated with lime. The bath was kept at an elevated temperature of 65°C (150°F), in which the specimens were cured for 84 h. The elevated curing temperature was used for the purpose of accelerating the hydration. This type of curing used produces approximately the same compressive strength as does the standard 28 day curing at room temperature. At the end of the 84 h period, the specimens were removed from the bath and stored in a curing room kept at 27°C (80°F) and 98% R.H. (rela-

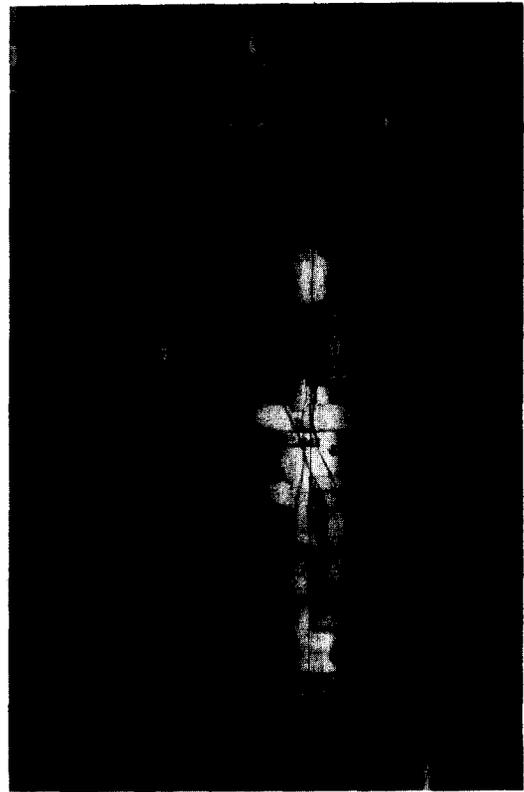
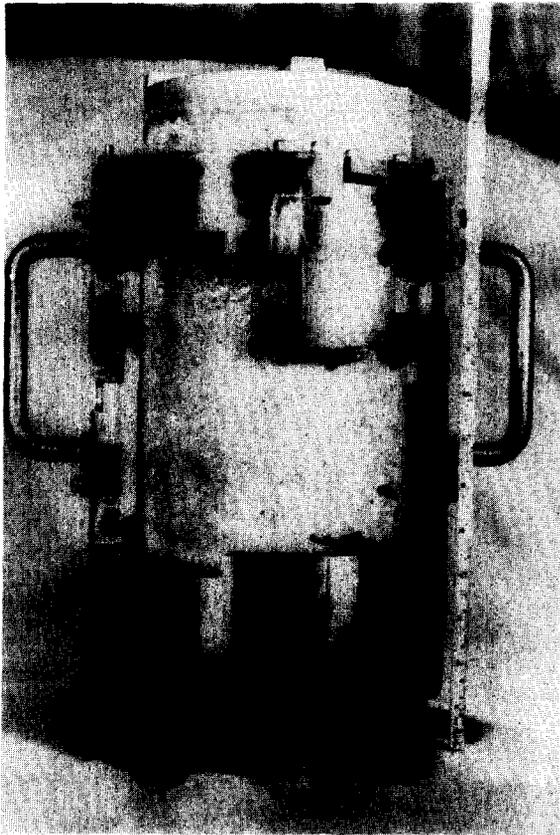


Fig. 3. Left: specimen with the extensometer frame attached. Right: specimen with extensometer frame and strain measuring elements on top of the shaft, uncoupled from the load cell.

tive humidity) until the time of test. The time period in the curing room was approximately 6 days (± 2 days), varying somewhat according to the needs of the work schedule.

Control cylinders of diameter 76 mm (3 in.) and length 152 mm (6 in.) were cast from each concrete batch along with the test specimens. Some control cylinders were placed in the elevated temperature bath along with the test cylinders and cured for 84 h. Others were cured in the standard manner, in the curing room at 27°C (80°F) and 98% relative humidity for 28 days. The cylinders subjected to both types of curing were then tested under uniaxial compression in a servo-controlled MTS testing machine. These tests were displacement controlled so as to maintain a constant rate of axial shortening (0.02 mm per min). The stress-strain diagrams obtained are shown in fig. 6. As it is seen, the difference in the maximum stress (strength) is not very

large and, most importantly, the entire shape of the stress-strain diagram is about the same. This justifies the use of accelerated curing.

Some of the specimens were tested without any seal, while others were sealed to prevent the escape or ingress of pore water. The sealed specimens were of two types: (1) those sealed in the wet state, right after they were taken out of the curing room, and (2) those sealed after drying; these specimens, after being taken out of the curing room, were heated in an oven at 120°C for 60 h, which must have driven out all evaporable water from the specimen, and then they were sealed.

The seals were made by applying several coats of Dow Corning 3145RTV silicone sealant (fig. 4). This sealant, which cures at room temperature by absorbing moisture from the air, can withstand temperatures up to 300°C. After its curing, the sealant forms a flexible rubbery coating around the specimen. The tensile

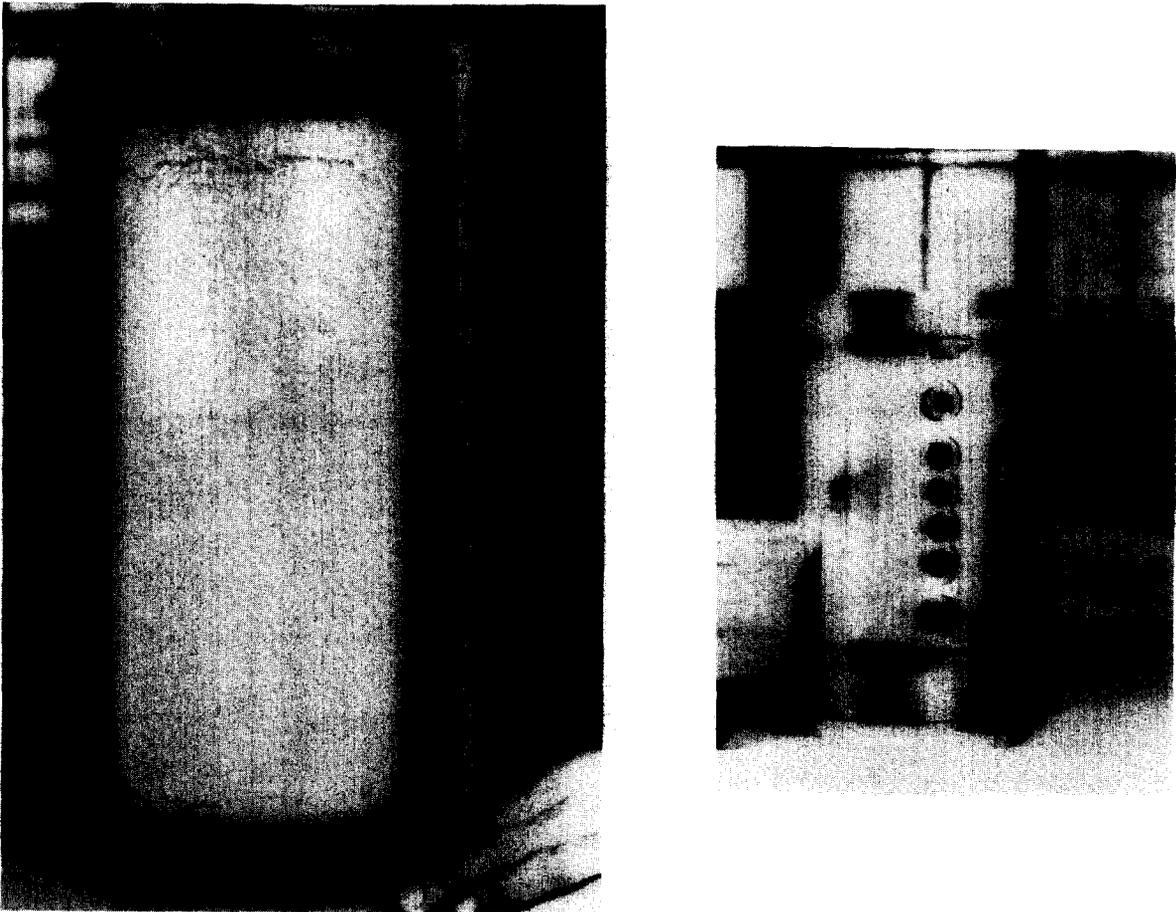


Fig. 4. Left: specimen coated with silicone sealant. Right: specimen with drilling jig.

strength of the coating is estimated to be 2.1 MPa (300 psi) (at room temperature).

The axial deformation, relative rotation and change of diameter were measured by an extensometer attached to the specimen surface. For this purpose, steel buttons which support the fixing pins of the extensometer were attached on the specimen. These buttons were glued by high temperature epoxy (Duralco-Cotronics Corp.) into shallow cylindrical depressions precisely drilled into the specimen surface with the help of a drilling jig (fig. 4). The same jig was used to drill in the steel buttons conical seats in which the pins of the extensometer are

to be seated. The silicone coating covered all concrete surface up to the steel buttons, but not the buttons themselves. The extensometer frame was fixed onto the specimen by means of pins that matched the conical seats in the steel buttons. Due to its considerable weight, the extensometer frame was counterbalanced inside the chamber by leaf springs attached to the bottom end cap of the specimen (fig. 3).

For the purpose of installing the specimen and the extensometer in the machine, the design is such that the axial loading shaft has a large stroke and can be pushed all the way up through the testing chamber so that the

Table 1
Characteristics of eight types of tests conducted

	T (°C)	H (%)	p (MPa)	σ_z (MPa)	$\max \tau_{xy}$ (MPa)	T (°C)	H (%)	p (MPa)	σ_z (MPa)	$\max \tau_{xy}$ (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. 4 (Unsealed)				
1	120	100	2.1	0	0	65	100	0	0	0
2	120	100	9.7	0	0	65	100	0	0	0
3	120	100	9.7	9.7	0	65	100	0	9.7	0
4	120	100	9.7	9.7	3.8	65	100	0	9.7	2.8
5	200	100	9.7	9.7	3.8	120	0	0	9.7	2.8
6	200	100	2.1	0	0	120	0	0	0	0
	Test No. 5 (Unsealed)					Test No. 6 (Sealed wet)				
1	120	100	2.1	0	0	65	0	2.1	0	0
2	120	100	9.7	0	0	65	0	9.7	0	0
3	120	100	9.7	9.7	0	65	0	9.7	9.7	0
4	120	100	9.7	9.7	2.8	65	0	9.7	9.7	3.8
5	120	0	0	9.7	2.8	120	0	9.7	9.7	3.8
6	120	0	0	0	0	120	0	2.1	0	0
	Test No. 7 (Unsealed)					Test No. 8 (Sealed wet-Control test)				
1	65	100	2.1	0	0	25	0	2.1	0	0
2	65	100	9.7	0	0	25	0	9.7	0	0
3	65	100	9.7	9.7	0	25	0	9.7	9.7	0
4	65	100	9.7	9.7	3.8	25	0	9.7	9.7	3.8
5	120	100	9.7	9.7	3.8	25	0	9.7	9.7	3.8
6	120	100	2.1	0	0	25	0	2.1	0	0

Compressive strength of accelerated cured control specimens $f'_c = 31.7$ MPa.

In figs. 9, 10 and 11: t = time after start of test,

t_1 = time at axial load change,

t_2 = time at torque change,

t_3 = time at temperature or humidity change,

t_4 = time at unloading.



Fig. 5. Load cell with torsional grips, specimen during installation and extensometer parts before attachment.

specimen can be set up on the shaft above the chamber, while the top cover is lifted (fig. 3). After that the specimen is lowered into the chamber by retracting the shaft.

To provide torque transfer, the steel end caps of the specimens are provided with eight radial ribs, each of them 18 mm (0.7 in.) wide and 6.4 mm (0.25 in.) deep. These ribs are precisely machined to match the grooves at the specimen ends which were formed during casting. The opposite side of each end cap again has cruciform ribs which fit into corresponding grooves on the ends of the loading shaft and the load cell coupler (fig. 3). This provided the torque transfer from the loading shaft onto the specimen and the load cell.

4. Test program and procedure

Since the tests are rather expensive and tedious, the testing program has been designed so as to obtain maximum information on various types of loading with a minimum number of tests. Whereas at room temperature the interest is in creep up to many years of duration, for temperatures over 100°C the analysis of nuclear reactor accidents and fire resistance requires only short-time creep tests of durations from several hours to several days. Therefore, all the tests have been of six-day duration.

Eight types of tests were carried out so far, as

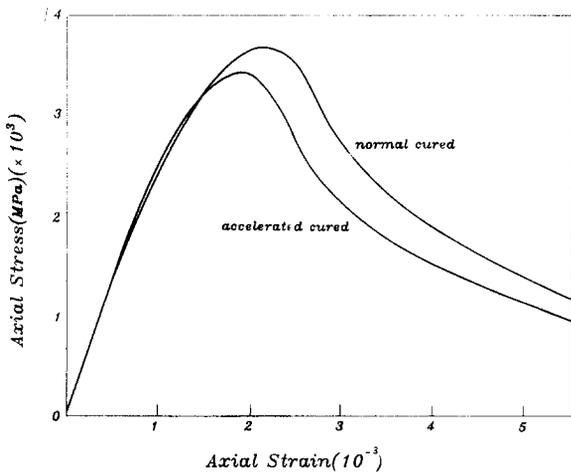


Fig. 6. Stress-strain diagrams of control cylinders in uniaxial compression.

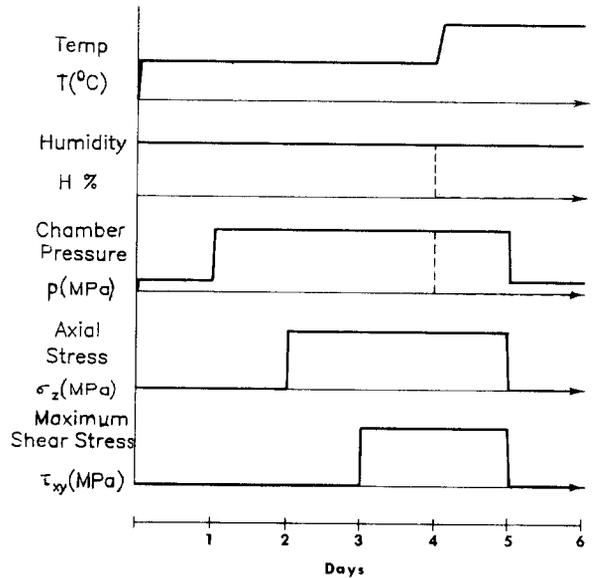


Fig. 7. Histories of loads and environment used in the tests.

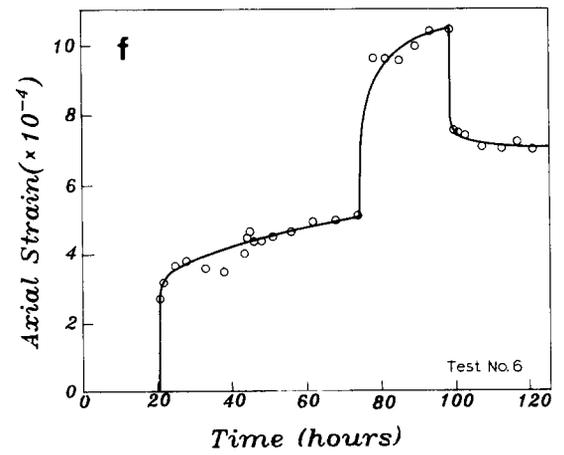
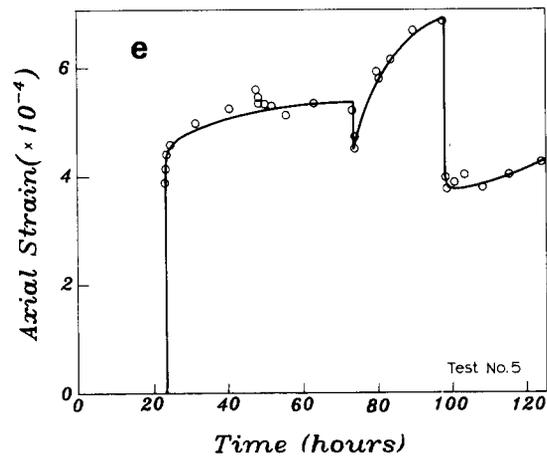
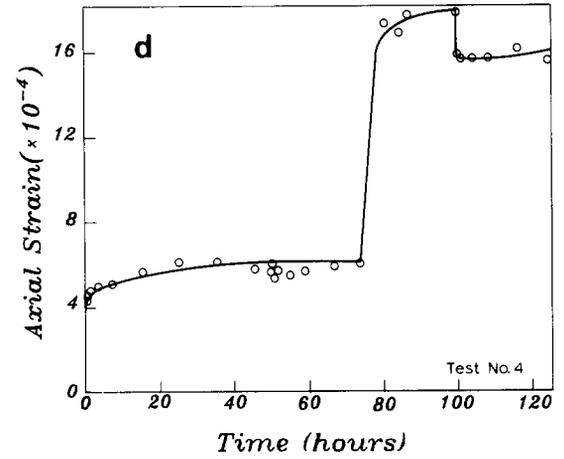
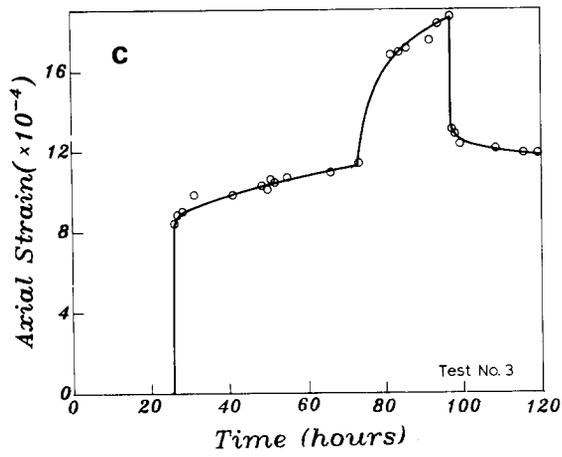
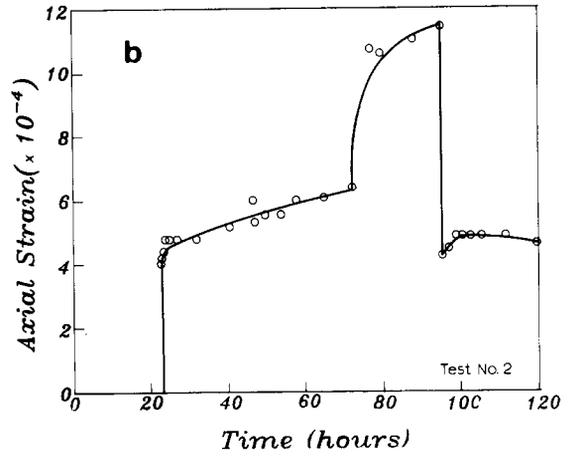
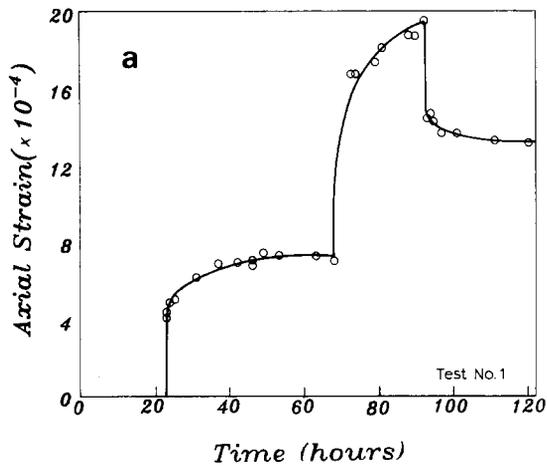


Fig. 8. Measured responses for various types of tests.

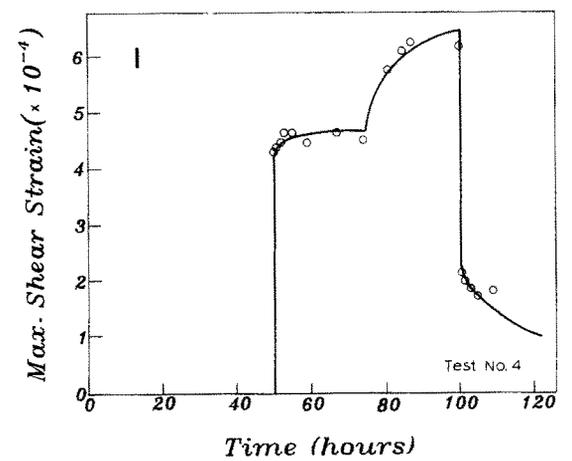
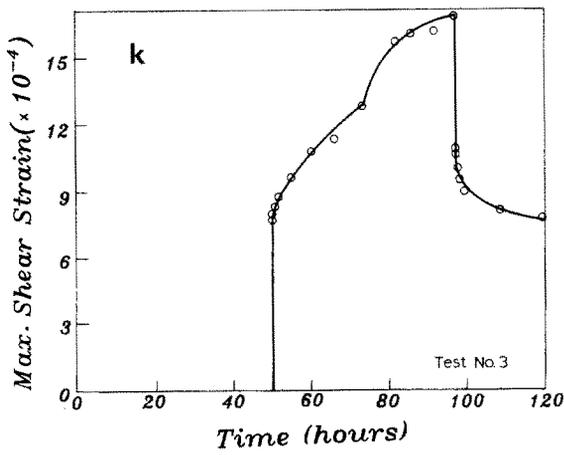
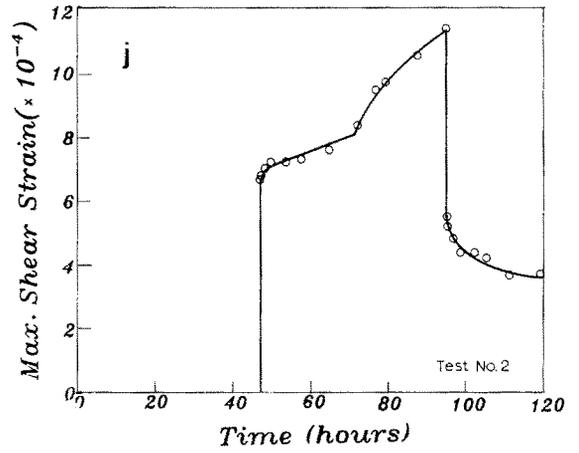
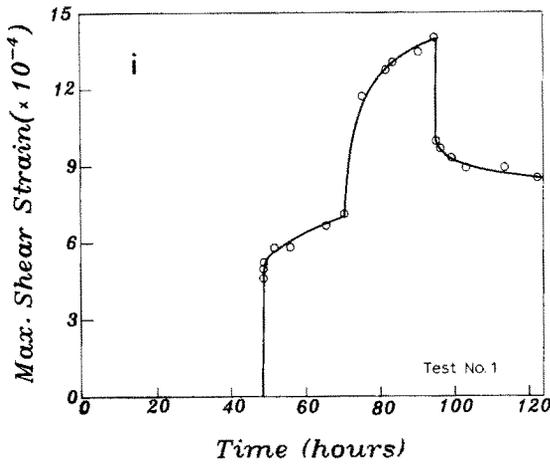
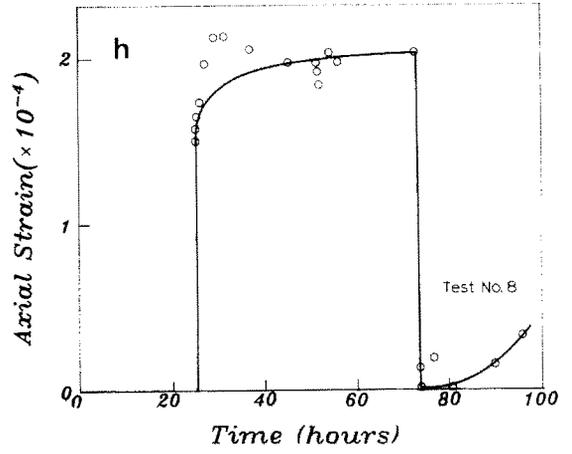
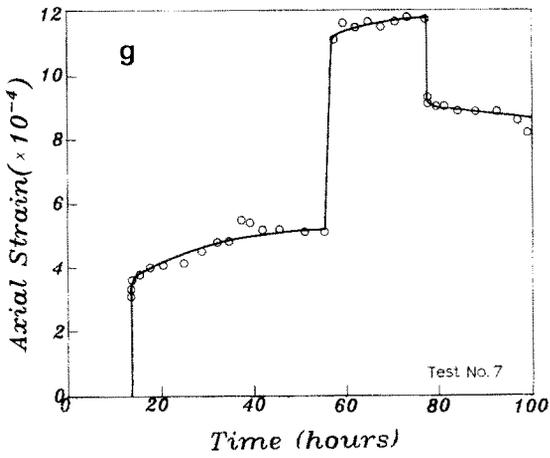


Fig. 8. Continued.

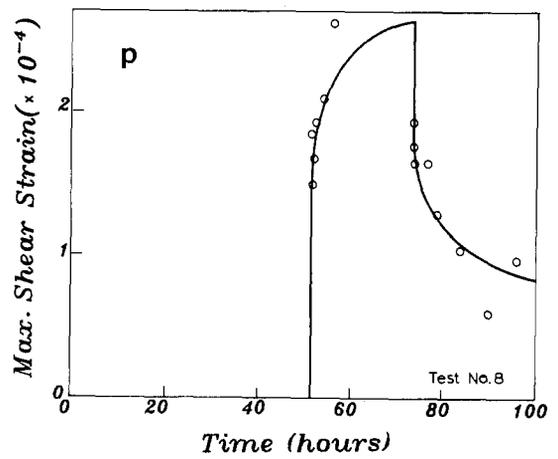
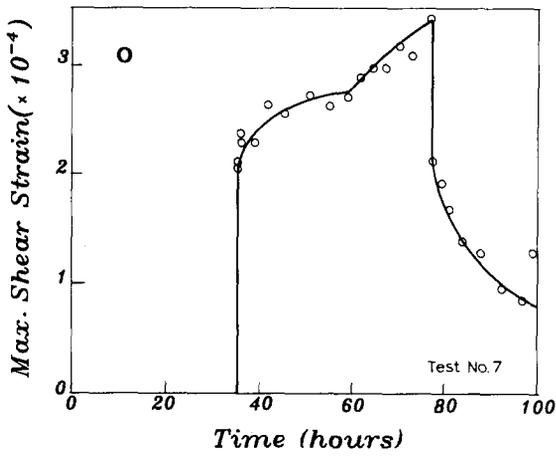
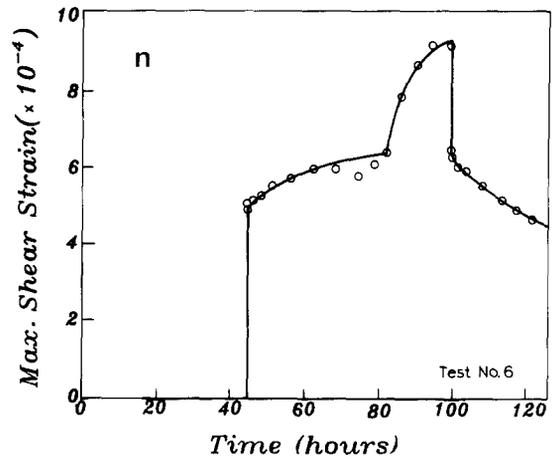
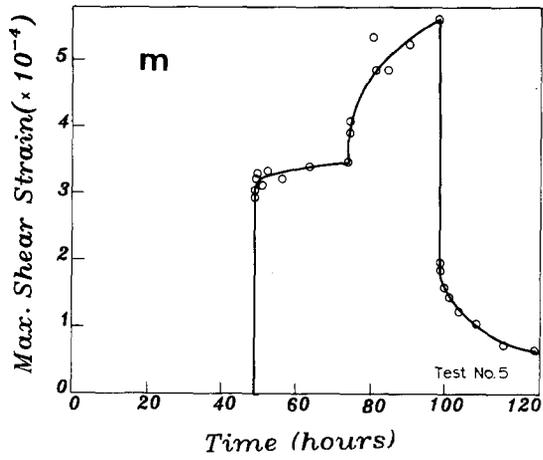


Fig. 8. Continued.

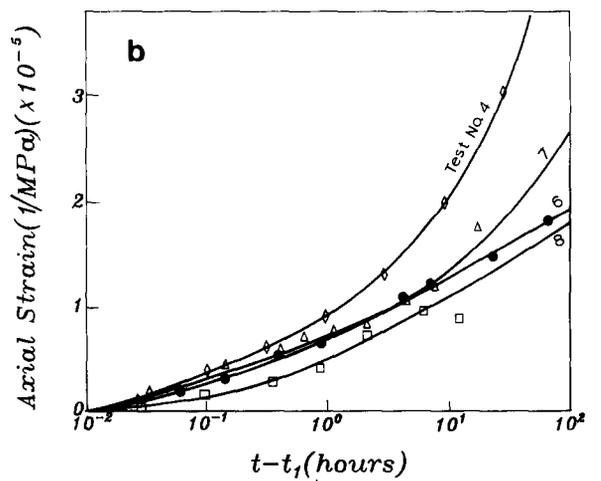
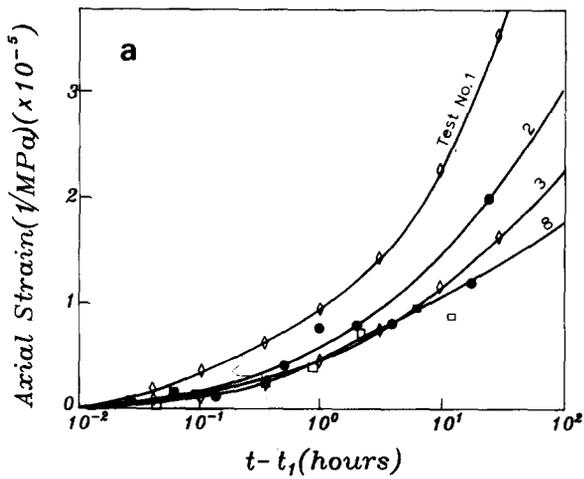


Fig. 9. Comparisons of strains due to load.

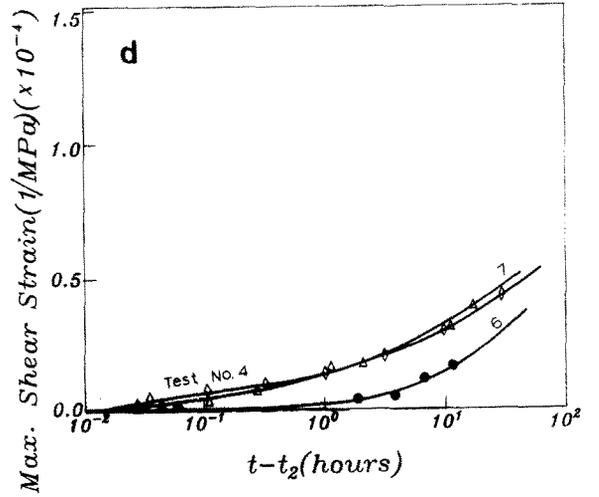
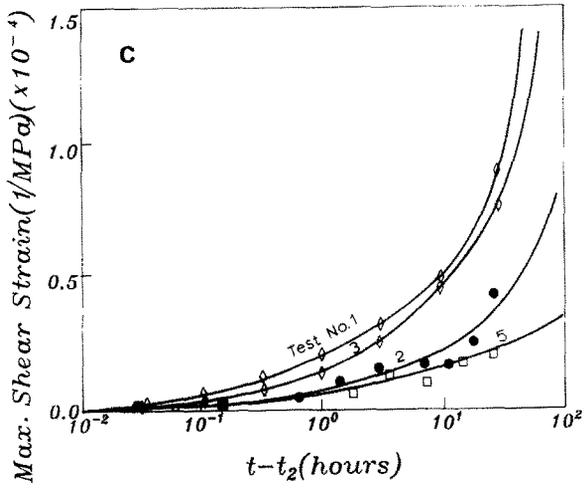


Fig. 9. Continued.

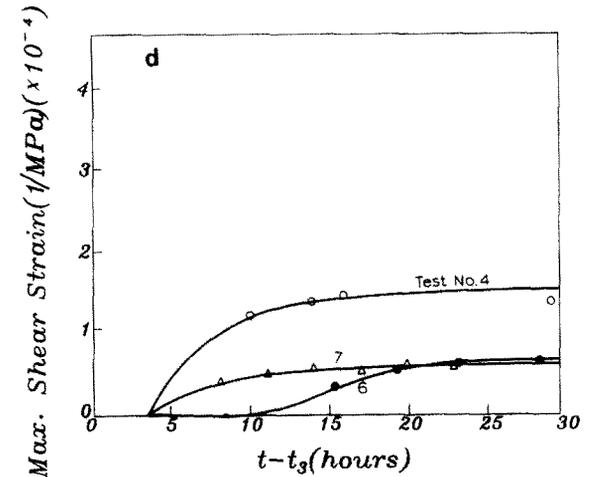
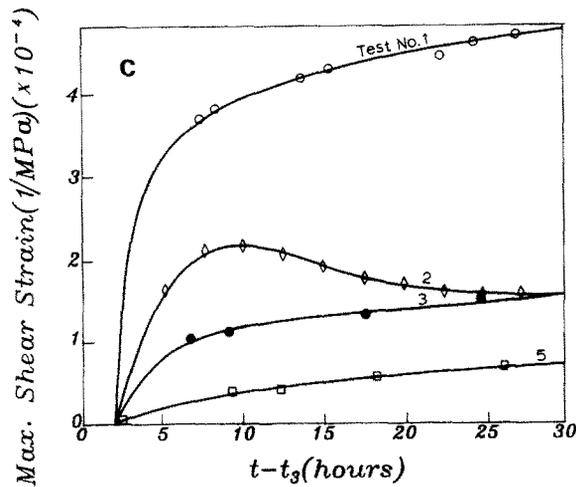
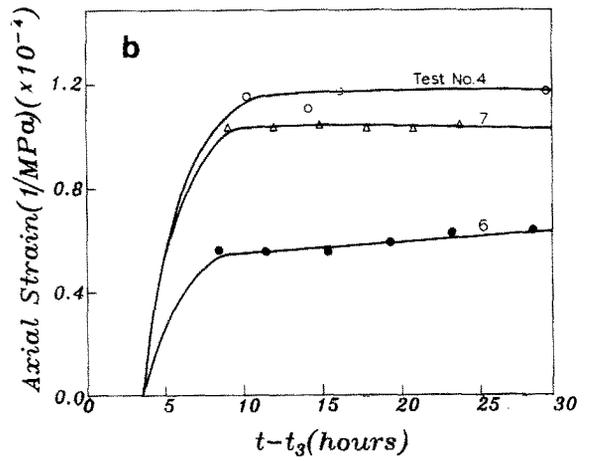
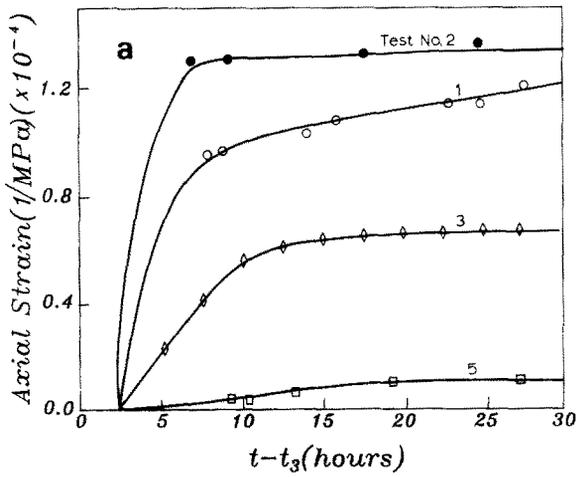


Fig. 10. Comparison of additional creep due to environmental changes.

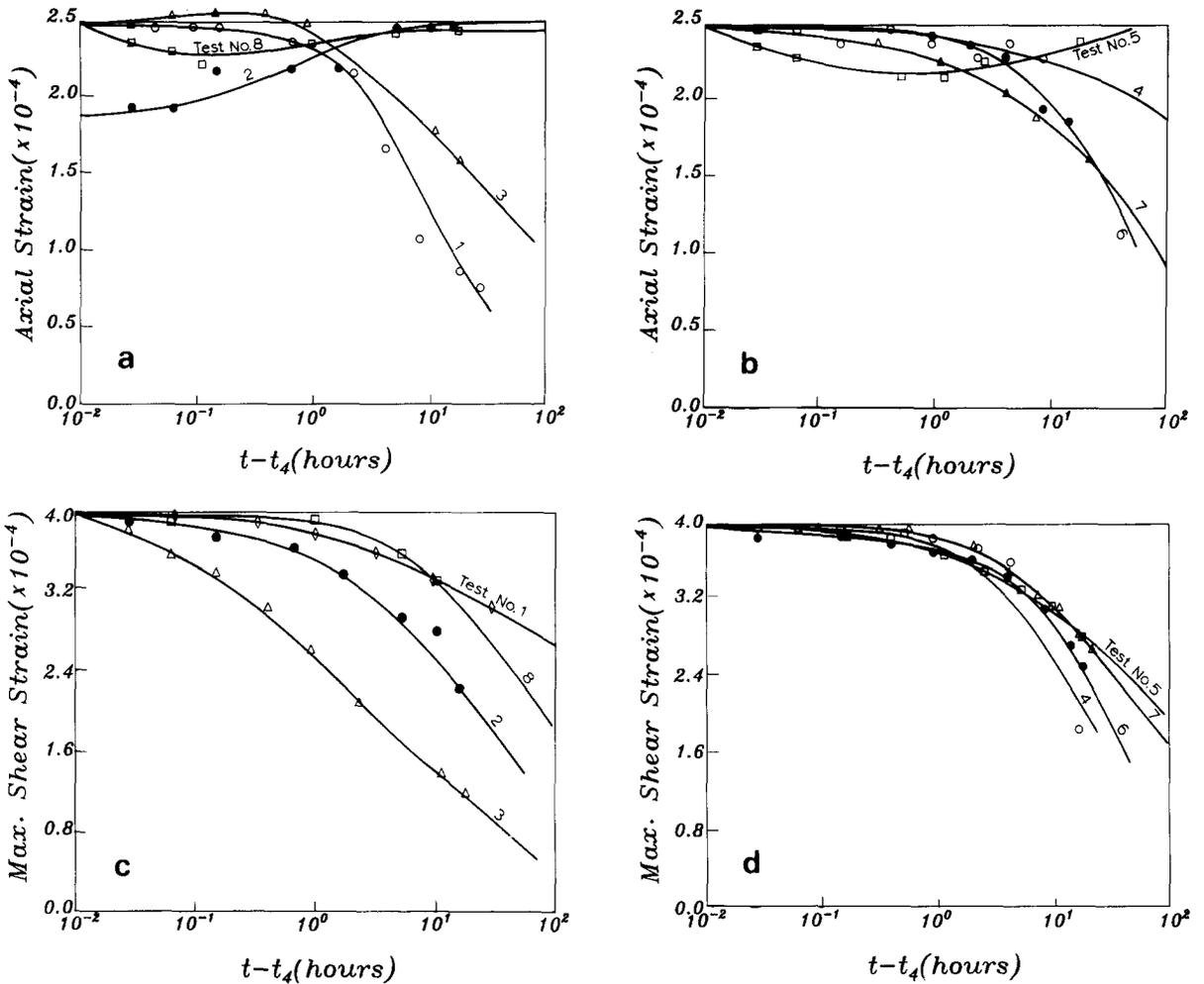


Fig. 11. Comparison of strain recovery curves.

characterized by the conditions listed in table 1 and by the time histories of loads and environment defined in fig. 7. Each change of load or environmental condition is carried out rapidly and is then held constant for one

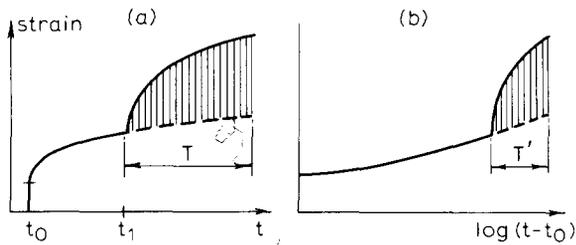


Fig. 12. Extrapolation in log-time scale used to determine additional creep due to environmental or load changes.

day (fig. 7). After one day, one of the conditions is changed. For the sealed specimens, it is necessary to apply before heating a certain small confining pressure at least equal to the saturation vapor pressure for the given temperature (found, e.g., in ASTM Steam Tables). The effect of an increase of the confining pressure, resulting in a purely volumetric deformation, is observed upon increasing the confining pressure on the second day. The axial compressive stress is superimposed on the third day and the torque is superimposed on the fourth day. Sudden environmental changes are made on the fifth day, and finally, on the sixth day the specimen is unloaded and creep recovery is monitored.

In the present program, all stress levels were intended to remain less than about half of the failure

values. For torsional loadings, the axial load and the confining pressure were always such that the maximum principal stress would always be compressive and not too close to zero, in order to avoid possible failure of the specimen during the tests due to tensile fracture. The initial temperatures for half of the tests are over 120°C, and for comparison the remaining tests are conducted at an elevated temperature of 65°C, equal to the temperature presently allowed by codes for nuclear reactor vessels. For comparison, a room temperature test is also carried out.

Note that the specimens which are at a temperature of 65°C can be assumed to maintain during the short test period a pore humidity of almost 100%; they would in fact need several years to reach hygral equilibrium with the environment. However, the specimens heated over 100°C can be assumed to lose most of their evaporable pore water content within about one or two hours, i.e., reach pore relative humidity of essentially 0%. This is because the pore water diffusivity of portland cement concrete increases approximately 200-times when the temperature passes above 100°C, as discovered in 1977 [2].

5. Test results

Fig. 8 (a–p) shows the response curves of axial strain and maximum shear strain as a function of time, in the actual time scale. Fig. 9 (a–d) shows comparison of the strains due to applied loads, and fig. 10 (a–d) shows comparisons of the strains caused by temperature increase. For the axial normal strains, the strains are plotted per unit stress; for torsion, they are plotted as the measured maximum shear strain divided by the maximum shear stress as calculated from the torque assuming a linear stress distribution along the radius. Thus, the plotted response curves represent the compliance. Fig. 11 (a–d) shows a comparison of the creep recovery strains at the end of each test.

The strains due to loading changes and to environmental changes were determined graphically, exploiting the fact that within a one-day interval other than the first one the response curves are nearly straight in the logarithmic time scale (fig. 12). Thus, a graphical extrapolation in the semilog plot is quite reliable, and the effect of the change of environment or load can be determined as the difference of the measured response from a smooth extrapolation of the previous response plotted in the log-time scale (fig. 12). In this manner, one can avoid for the present types of tests the need for testing companion load-free specimens subjected to the

same environmental history, in order to determine the difference between the two tests. The avoidance of comparison specimens improves the test results because this difference exhibits a large statistical scatter as the properties of a companion specimen are never the same, due to the random nature of the material.

For some of the loading cases, two tests were run. These were the cases indicated by the diamond-shaped data points in figs. 9, 10 and 11. These points, as well as their smoothing curves, represent the averages from two tests. The coefficient of variation for the measured values for each pair of the curves for the same load never exceeded 15%. All other data points and curves represent the results of single tests for each loading case.

6. Observations from tests and their interpretations

As we can see from fig. 9a, at 120°C the axial creep strain under triaxial loading with $\sigma_z - p = 0.3 f'_c$ (where f'_c = standard cylinder strength, p = chamber pressure, σ_z = axial normal stress) is larger for a specimen sealed wet than it is for a specimen sealed dry or for an unsealed specimen immersed in water. Also, the creep rate does not seem to decrease noticeably even after 24 h of loading, while the creep rate of a sealed specimen at 25°C diminishes with time (fig. 9a) (and is generally much smaller).

In previous tests of very small specimens of hardened Portland cement paste [4] it was established that the creep rate of a fully dried specimen is about 10% of that for a fully saturated specimen, at room temperature. This behavior is observed only on specimens that have been dried to thermodynamic equilibrium prior to loading. Due to the extremely small value of moisture diffusivity of concrete at temperatures below 100°C, the state of thermodynamic equilibrium can be achieved within a reasonable time period only if the specimen is extremely thin (≈ 1 mm). An often used alternative is to dry the specimen by heating to 105°C but this slightly alters the microstructure. The decrease of the creep rate at a lower moisture content was discovered only relatively recently (in the 1960's) and came as a surprise. Up to that time it was believed that the creep rate increases rather than decreases due to drying. However, this increase, often termed the Pickett effect, is now known to be due to the effect of the rate of humidity change, combined with the effect of distributed cracking (strain-softening, see ref. [6]). The same effects were previously found to be exhibited by very small cement paste specimens at temperatures over 100°C [4].

The transient effect of the rate of water content is rather short-lived, due to the fact that moisture diffusivity increases about 200-times upon heating over 100°C [2]. Thus, whenever heating starts over 100°C before loading, the tests essentially occur at a dried state, and the drying is the reason that a much lower creep rate is observed than for a sealed specimen.

The comparisons between the sealed and unsealed specimen make sense, of course, only for triaxial loading. Without the confining chamber pressure it would be impossible to prevent rupture of the seal due to internal vapor pressure and keep the specimen saturated. Uniaxial basic creep (i.e., at constant water content) does not exist above 100°C.

As seen from fig. 9a, the effects of the pore water content are similar for concrete specimens at high temperatures, however, the magnitude of the effect is much smaller; the ratio of the creep rates of a fully dried specimen and a fully saturated specimen is about 0.6 rather than 0.1. This reduced effect is probably caused by the restraining action of the aggregate in concrete, but still it is interesting that this restraining action reduces not only the total creep rate magnitudes but also their relative values. Explanation of this phenomenon in terms of the composite nature of concrete deserves further study.

The specimens (in tests 1–3) were exposed to a temperature of 120°C for 24 h before loading. Since the specimens were simultaneously under pressure, the condition was similar to autoclaving, a curing process used to accelerate hydration.

The analogy with autoclaving is, however, fully applicable only if additional water is forced into the specimen due to external pressure, as it happens in an autoclave. Ingress of water is of course prevented when the specimen is sealed, but for unsealed specimens tested in water one must assume that water penetrates into the specimen. In such specimens, the autoclaving effect is probably much stronger, which might explain why specimens immersed in pressurized water at 120°C show a distinctly smaller creep rate than do the specimens sealed in the initial wet state; see fig. 9a. By contrast, at lower temperature (65°C) the creep rates of the specimens sealed wet and the unsealed specimens immersed in water are about the same (fig. 9b). The behavior at high temperatures is again qualitatively similar to that observed previously on very small cement paste specimens [4].

Rather interesting is the fact (fig. 9a) that, at least within the first 24 h period, the creep rate at high temperature does not decrease significantly with the one-day duration while at room temperature it does.

Apparently, at high temperature the idea of gradual exhaustion of the sites of weakened bonds in the solid microstructure [6] does not quite apply. It must be that new sites of potential load ruptures are gradually generated by the creep deformation. Thus, at high temperatures, creep might be better described as a viscous deformation. Progressive microcracking might also play a role.

The axial creep of a specimen sealed wet and tested at 65°C is seen to be lower (fig. 9b) than it is at 120°C, but the creep of an unsealed specimen in water under triaxial loading shows the opposite behavior, i.e., it is greater at 65°C than it is at 120°C (figs. 9a,b). Furthermore, the creep of an unsealed specimen in water at 65°C under uniaxial loading is greater than that of a specimen under triaxial loading, $\sigma_z - p$ being the same. The difference seems to be too large to be attributed to the creep due to confining pressure, which means that linear superposition might not be applicable.

Note also that the creeps of a sealed wet specimen and an unsealed specimen in water are about the same at 65°C (fig. 9b). The present tests confirm for uniaxial as well as triaxial loading the fact, known before only for uniaxial loading [13], that the creep rate (after a fixed loading duration) of unsealed specimens does not increase monotonically with temperature. As established by Maréchal [13], the uniaxial tests show first an increase of creep according to the activation energy theory up to about 70° to 90°C, then an abrupt decline as 100°C is passed, and with a further increase of temperature again a smooth increase of the creep rate according to the activation energy theory.

In the light of the present test, as well as the previous tests of very small cement paste specimens [4], the decline of the creep rate of unsealed specimen as the threshold of 100°C is passed is due to the loss of pore water. In fact, comparison of the responses of these specimens above and below 100°C is physically unjustified, since one specimen is wet and the other is dry. Of course, to keep the specimen sealed wet above 100°C, it is inevitable to use triaxial loading with sufficient confining pressure, and then a monotonic smooth increase of the creep rate according to a single activation energy appears to take place. It may also be noted that when the monotonic temperature dependence of the creep rate of unsealed (dried) specimens above 100°C is extrapolated to room temperature in a smooth manner (according to the same activation energy curve), the creep rate appears to be about the same as for a predried specimen (although at room temperature this can be tested only on extremely thin specimens, about 1 mm thick).

The torsional creep of a specimen sealed wet at 120°C is observed to be, as in the case of axial creep, higher than that of a specimen sealed dry as well as that of an unsealed specimen (fig. 9c). However, the creep of an unsealed specimen is higher than that of a specimen sealed dry, and so is the creep rate. Moreover, the torsional creep in unsealed specimens at 120°C due to a torque superimposed on constant triaxial loading does not appear to be proportional to the maximum shear stress value ($\max \tau_{xy}$), i.e., the creep strain appears to depend nonlinearly on stress (fig. 9c).

In accordance with these observations, it appears that the ratio of deviatoric to volumetric creep increases with temperature. This means that the creep Poisson ratio of concrete also increases with temperature. Previously, in tests of cement paste [4], the creep Poisson ratio was observed to increase from 0.25 at room temperature to 0.46 at 200°C. The behavior of concrete now appears to be qualitatively similar. The explanation of this phenomenon might be that the contribution to creep from the changes of thickness of the interlayer space and gel pores becomes less at higher temperatures than is the contribution due to interparticle sliding resulting from bond ruptures.

The changes of the creep rate caused by sudden environmental variations are rather interesting. Such changes have apparently not yet been observed for high temperatures and triaxial loading. When the temperature is rapidly raised from 120°C to 200°C, the axial creep rate increases considerably. The increase is larger for the specimen sealed wet than for the unsealed specimen in water (fig. 10a). If the temperature is held constant at 120°C, the pressure is dropped to zero, water is allowed to evaporate from the chamber, and the unsealed specimen initially submerged in water is allowed to dry, then the creep rate seems to initially decrease and then increase. In all cases, the creep rate increase in excess of the steady-state creep rate, induced by a sudden environmental change during the creep test, is not constant but rapidly decays to zero.

An unsealed specimen in water, heated during the creep test from 65°C to 120°C, shows a larger creep rate increase than a specimen sealed wet. If the unsealed specimen is allowed to dry, the creep rate increase is even larger (fig. 10b). The creep rate increase for an unsealed specimen in water is higher for heating from 65°C to 120°C than for heating from 120°C to 200°C. This behavior is, however, reversed, for the sealed specimens. Again, the creep rate increase is not constant but decays with time.

The initial torsional creep rate increase due to heating from 120°C to 200°C during the creep test is the

highest for the sealed specimen (fig 10c). Generally, the initial creep rate increases for torsion and axial loading at rapid heating are similar (figs. 10a,c). Drying of the specimen at constant temperature of 120°C increases the torsional creep rate.

Similar to axial creep, the torsional creep rate of an unsealed specimen in water heated from 65°C to 120°C during the creep test is higher than that of a specimen sealed wet. Also, the creep rate increase is higher for an unsealed specimen in water heated from 65°C to 120°C and allowed to dry (fig. 10d). Again, the initial creep rate increase is not constant but decays. The creep rate increases of unsealed specimens in water are about the same for heating from 65°C to 120°C and heating from 120°C to 200°C. By contrast, for sealed specimens the initial creep rate increase for heating from 65°C to 120°C is much lower.

The axial creep recoveries at 200°C of the unsealed specimens in water and the specimens sealed wet are about the same. However, the creep recovery of the specimens sealed dry is much less (fig. 11a). The axial creep recoveries of the unsealed specimens in water and of the sealed specimens are less at 120°C than at 200°C. Moreover, the unsealed dried specimen recovers less than the specimen sealed wet or the unsealed specimen in water.

The recovery of torsional creep at 200°C is larger for unsealed specimens in water than it is for sealed specimens.

The creep recovery of all specimens at 200°C is much higher than that of the control specimen at 25°C during the same time period.

The recoveries of torsional creep at 120°C are about the same for all specimens: unsealed in water, unsealed and drying, and sealed dry or wet.

Finally, it is important to note that the axial creep rate does not change when torque is superimposed during the creep test on the triaxial loading.

7. Conclusions

The basic conclusions which may be drawn from these test results are as follows:

- (1) Heating to high temperatures increases the shear creep more than the volumetric creep. Thus, the creep Poisson ratio increases with temperature.
- (2) A higher water content normally results in a higher creep.
- (3) When, however, excess water is forced into the specimen at high temperature, the creep rate is reduced. This seems to be a stiffening effect like that caused by autoclaving.

- (4) During a decrease in pore water content the creep rate is increased, both for axial and torsional creeps.
- (5) When the temperature is raised during the creep test, the creep rate is significantly increased, both for axial and torsional creeps. However, the creep rate increase does not remain constant in time, but decays with time.
- (6) Creep recovery after unloading exists at high temperatures, both for axial and torsional loadings, and its value is affected by pore water content and its changes.

Acknowledgment

Partial financial support under NSF Grant No. FED 7400, monitored by Dr. G. Albright, and under subcontract No. 9-L54-M8196-1 of Los Alamos National Laboratory with Northwestern University, monitored by Dr. C. Anderson, is gratefully acknowledged.

References

- [1] Y. Anderberg and S. Thelandersson, Stress and deformation characteristics of concrete at high temperatures, Bulletin 54, Div. of Str. Mech. and Concrete Constr., Lund Institute of Technology, Lund, Sweden (1976).
- [2] Z.P. Bažant and W. Thonguthai, Pore pressure and drying of concrete at high temperature, *J. of Engrg. Mech. Div. ASCE* 104 (1978) 1059–1079.
- [3] Z.P. Bažant and W. Thonguthai, Pore pressure in heated concrete walls: Theoretical prediction, *Mag. Concr. Res.* 31 (1979) 67–76.
- [4] Z.P. Bažant, S.S. Kim and S. Meiri, Triaxial moisture-controlled creep tests of hardened cement paste at high temperature, *Materials and Structures (RILEM, Paris)* 12 (1979) 447–456.
- [5] Z.P. Bažant, J.C. Chern and W. Thonguthai, Finite element program for moisture and heat transfer in heated concrete, *Nucl. Engrg. Des.* 68 (1981) 61–70.
- [6] Z.P. Bažant and J.C. Chern, Concrete creep at variable humidity: Constitutive law and mechanism, *Materials and Structures (RILEM, Paris)* 18 (1985) 1–20.
- [7] Z.P. Bažant, S. Prasannan, M. Hagen, S. Meiri, R. Vaitys R. Klima and J.D. Hess, Large triaxial-torsional testing machine with hygrothermal control, Report 85-7/285L, Center for Concrete and Geomaterials, Northwestern University, Evanston, Illinois (July 1985); also, *Materials and Structures (RILEM)* (approved for publication).
- [8] H.M. Fahmi, M. Polivka and B. Bresler, Effect of sustained and cyclic elevated temperature on creep of concrete, *Cement and Concrete Research* 2 (1979) 591–606.
- [9] M.P. Gillen, Short-term creep of concrete at elevated temperatures, Final Report to Nat. Bur. of Stds., Dept. of Commerce, from Construction Technology Laboratories (PCA), Skokie, Ill. (March 1979).
- [10] J.M. Illston and I.J. Jordaan, Creep prediction for concrete under multiaxial stress, *ACI Journal* (March 1972) pp. 158–164.
- [11] J.M. Illston and P.D. Sanders, The effect of temperature change upon the creep of mortar under torsional loading, *Mag. of Concrete Res.* 25 (1973) 136–144.
- [12] T.W. Kennedy, An evaluation and summary of a study of the long-term multiaxial behavior of concrete, Report No. ORNL/TM-5300, Oak Ridge National Laboratory (December 1975).
- [13] J.C. Maréchal, Creep of concrete as a function of temperature, *Concrete for Nuclear Reactors*, Vol. 1, ACI SP-34 (1972) 547–564.
- [14] J.E. McDonald, An experimental study of multiaxial creep in concrete, ACI-SP-34, *Concrete for Nuclear Reactors*, Vol. 2 (1972) pp. 735–797.
- [15] D.J. Naus, C.B. Oland and G.C. Robinson, Testing program for concrete at temperatures to 894°K, 6th Int. Conf. on SMiRT, Vol. G-H, Paper H 1/5, Paris 1981.
- [16] D.J. Naus, Task 2: Concrete properties in nuclear environment – A review of concrete material systems for application to prestressed concrete pressure vessels, ORNL/TM-7632, Oak Ridge National Laboratory (May 1981).
- [17] C.G. Oland, D.J. Naus and G.C. Robinson, Final report of comprehensive testing program for concrete at elevated temperatures, Report ORNL/BRP-80/5, Oak Ridge National Laboratory, Oak Ridge, Tennessee (October 1980).
- [18] U. Schneider and K. Kordina, On the behavior of normal concrete under steady state and transient conditions (in German), 3rd Int. Conf. on Struct. Mech. in Reactor Technology, Vol. 3, Paper H 1/6, London, September 1975.
- [19] U. Schneider, Ein Beitrag zur Frage des Kriechens und der Relaxation von Beton unter hohen Temperaturen, Technical University of Braunschweig, Germany (1979, in German).
- [20] U. Schneider, Behavior of concrete at high temperatures, *Deutscher Ausschuss für Stahlbeton*, Heft 337 (1982).
- [21] U. Schneider, and U. Diederichs, Hydrothermal effects on the microstructure and corrosion properties of concrete, 7th International Conference on Structural Mechanics in Reactor Technology, 1983, Vol. H., H 3/2.
- [22] S. Thelandersson, Mechanical behavior of concrete under torsional loading at transient, high-temperature conditions, Bulletin 46, Div. of Str. Mech. and Concrete Constr., Lund Institute of Technology, Lund, Sweden (1973).
- [23] S. Thelandersson, On the multiaxial behavior of concrete exposed to high temperature, *Nucl. Engrg. Des.* 75 (1983) 271–282.
- [24] G.P. York, T.W. Kennedy and E.S. Perry, Experimental investigation of creep in concrete subjected to multiaxial compressive stresses and elevated temperatures, Research Report 2864-2, University of Texas, Austin, Texas (June 1970); *Concrete for nuclear reactors*, American concrete Institute Spec. Publ. No. 34 (1972) pp. 647–700.