CREEP OF CONCRETE UNDER VARIOUS TEMPERATURE,

MOISTURE, AND LOADING CONDITIONS *

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Synopsis: An investigation was conducted to develop information on the time-dependent deformation behavior of concrete in the presence of temperature, moisture, and loading conditions similar to those encountered in a prestressed concrete reactor vessel (PCRV). Variables were one concrete strength (6000 psi (41 MPa) at 28 days), three aggregate types (chert, limestone, and graywacke), one cement (Type II), two types of specimens (as-cast and air-dried), two levels of temperature during test 73° and 150°F (23° and 66°C), and four types of loading (uniaxial, hydrostatic, biaxial, and triaxial). There were 66 test conditions for creep tests and 12 test conditions for unloaded or control specimens.

Experimental results are presented and discussed. Comparisons are made concerning the effect of the various test conditions on the behavior of concrete and general conclusions are formulated.

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INTRODUCTION

One of the most important aspects in the design and safety evaluation of a prestressed concrete reactor vessel (PCRV) is the time-dependent deformation behavior of concrete in the presence of varying temperatures, moisture, and loading conditions. Creep and shrinkage in the concrete can have serious consequences because they produce (a) a loss of initial prestress, (b) large deformations of the vessel, which could result in misalignment of the control rod passages, and (c) residual stresses that may be introduced as the loading conditions change. Consequently, a basic research program formulated and directed by the Oak Ridge National Laboratory to develop and improve the technology of PCRV's in the United States included a sizeable investigation of the time-dependent conditions existing in a PCRV. This program was intended to provide basic information that could be used, first, as a basis for developing analytical techniques for examining the time-dependent behavior of a PCRV, and second, as the data necessary when using these techniques for design and safety evaluations. One of the projects included in this effort was a multiaxial creep program performed at the Concrete Laboratory, U. S. Army Engineer Waterways Experiment Station (WES)[1] and summarized generally herein.

TEST CONDITIONS

Although numerous factors affect the time-dependent deformation behavior of concrete, this study concerned only four of the more important variables, i.e., modulus of elasticity of the aggregate, curing history prior to loading, temperature during loading, and state of stress during loading. Sixty-six test conditions involving loaded specimens were investigated. In addition, 12 test conditions involving unloaded or control specimens were investigated. The 78 test conditions are summarized in Table 1.

Concrete made with crushed limestone aggregate (3/4-in. (19 mm) maximum size) was chosen as the main mixture since it was representative of mixtures that might be used in a PCRV in most sections of the United States. Two other mixtures containing crushed graywacke and chert gravel, aggregates with elastic moduli lower and higher, respectively, than that of limestone, were used to provide information for comparison.

The two curing histories selected for this study were designated "as-cast" (AC) and "air-dried" (AD). The AC specimens were sealed shortly after casting and remained so throughout the test to prevent evaporation losses. The resultant saturated concrete was representative of the interior of a mass of concrete such as a PCRV. After 7 days curing, the AD specimens were allowed to dry in air at 73°F (23°C) and 50 percent relative humidity for the remainder of the 90-day period preceding testing. These specimens exhibited considerable moisture loss and were representative of concrete near the exterior of a PCRV.

The temperature levels during loading were selected as representative of the limits of the range of concrete temperatures experienced in a nuclear reactor containment vessel during normal operation, 73° and 150°F (23° and 66°C) corresponding to temperatures expected at the outer and inner surfaces, respectively.

Until recently, the majority of creep work has concerned uniaxial loading only; however, the reinforcement of a PCRV is such that other states of stress exist. As a result, test specimens were loaded in uniaxial, biaxial, hydrostatic, and triaxial states of stress with both axial stress and radial confining stress ranging from 0 to 2400 psi (0 to 17 MPa).

MIXTURE PROPORTIONS

Three concrete mixtures were proportioned with Type II portland cement and 3/4-in. (19 mm) maximum size aggregates, the moduli of elasticity of which ranged from 3.8 to 13.65 x 10^6 psi (2.6 to 9.4 x 10^4 MPa), to have compressive strengths of 6000 psi (41 MPa) at 28 days. Proportions of the resultant concrete mixtures, designated high, main, and low modulus according to aggregate moduli were previously reported.[1,2]

SPECIMENS

Creep and control specimens were 6 in. (152 mm) in diameter by 16 in. (406 mm) in length and were attached to 1-in. (25 mm) thick steel end plates. Two vibrating wire strain gages were embedded in each specimen to measure axial and radial strain. Ninety-eight such specimens were cast from eight batches of concrete. In addition, 249 6-by-12-in. (152- by 305-mm) strength cylinders were cast. Specimen preparation procedures were previously described in detail.[1,2]

LOADING SYSTEM

In general, creep specimens were placed in the test units located in the proper testing temperature for 7 days prior to loading at 90-days age. All loads were applied incrementally with a hydraulic hand pump at a rate of approximately 35 psi/min (0.24 MPa/min). When the desired maximum load was attained, the test unit was switched to a pressure distribution system which maintained a constant load using an oil reservoir under regulated high-pressure gas.

STRAIN MEASUREMENTS

Strain and temperature measurements were obtained on the creep and control specimens throughout the 90-day curing period, immediately prior to loading, upon attaining full load, and throughout the test period. In addition, strain readings were obtained on the creep specimens at each load increment. After applying the full test loads, gages were generally read every 15 to 30 min for the first 2 to 3 hr or until the readings began to stabilize and then daily for one week after loading; as the readings tended to further stabilize with increased time under load, the time between readings was increased.

EXPERIMENTAL RESULTS

Detailed results of tests conducted to determine the elastic and time-dependent deformation behavior of concrete subjected to a variety of test conditions are reported in Reference 1. These results are summarized in the following and a number of general comparisons are made concerning the effects of the various test conditions on the behavior of concrete.

Strength and Elastic Deformation

Even though the concrete mixtures contained aggregates with a wide range of moduli, they did have similar compressive strengths. The compressive strength of AC specimens from each of the three concrete mixtures was lower than that of AD specimens at both 28 and 90 days.

However, after 90 days curing, both curing procedures resulted in concretes which exhibited lower strengths than concrete cured in limewater (standard specimens) until tested. Beyond 90 days both AC and AD specimens were sealed in copper and, after approximately 1 year of additional curing at 73°F (23°C), the compressive strengths of AC and AD concrete were essentially equal.

Elastic strains were determined by taking the difference in strain measurements on the creep specimens immediately before and after loading. These elastic strains were used to compute Poisson's ratio and the modulus of elasticity as follows:

$$\mu = \frac{\sigma_a \varepsilon_r - \sigma_r \varepsilon_a}{2\sigma_r \varepsilon_r - \varepsilon_a (\sigma_r + \sigma_a)}$$

$$E = \frac{\sigma_a - 2\mu\sigma_r}{\varepsilon_a}$$

Where

μ = Poisson's ratio

σ_a = axial stress, psi

ε_r = elastic radial strain

σ_r = radial stress, psi

ε_a = elastic axial strain

E = modulus of elasticity, psi

Average values for the various test conditions indicate the modulus of elasticity of concrete is proportional to the modulus of elasticity of the aggregate (Fig. 1). A similar relation would appear to exist for Poisson's ratio with the exception of the high-modulus mixture where Poisson's ratio for the concrete was higher than that for the chert aggregate (Fig. 2).

Time-Dependent Deformation

Strains were monitored intermittently during the curing period to determine concrete deformations due to autogenous volume changes. The reference reading for calculating these strains was the 7-day reading because this was the earliest time at which the various environmental test conditions could be considered comparable and stable. Axial and radial strains for the AC control specimens were similar in magnitude and remained essentially constant during the curing period. Each of the three concrete mixtures exhibited very small shrinkage strains at the end of the curing period with an overall average of 13 millionths. The AD specimens were allowed to air-dry at 50 percent relative humidity and 73°F (23°C) from 7 to 90 days age. The resultant moisture loss caused significant shrinkage strains in all AD control specimens (Fig. 3). The shape of the relation between the shrinkage of AD concrete and the modulus of elasticity of aggregate is similar to that previously reported by Rüsch, et al.[3]

The strain data obtained from the loaded creep specimens during the course of the testing period represented total strains, i.e., those which included the elastic deformation upon application of load, and the time-dependent deformations due to load and chemical or physical volume changes within the specimen. Specific creep strains for a given time were determined by subtracting the elastic strain from the total strain, correcting this value for the appropriate volume-change (control) strain, and dividing it by the applied load. To form a numerical basis of comparison for the various test conditions, logarithmic creep expressions of best fit based on a least squares analysis were computed for the creep strain-time relationships. These equations were then used to compute specific axial and radial creep strains at 1 year after loading.

Temperature

There were 5 and 12 cases where the effect of testing temperature could be compared directly for tensile and compressive creep, respectively. At 150°F (66°C), the tensile creep was larger in four of five cases as compared with 11 of 12 cases for the compressive creep. In these cases, the increase in creep at the higher temperature was slightly higher for the compressive mode, averaging 79 and 51 percent for the compressive and tensile creep, respectively. AD concrete at 150°F (66°C) exhibited a greater increase in compressive creep than did the AC concrete whereas the opposite was true for tensile creep.

Specimens tested by Nasser and Neville[4] were stored continuously in a water bath at the desired testing temperature from 24 hr after casting until they were loaded at 14 days. Results of specimens loaded (underwater) to a stress-strength ratio of 0.35 indicated the uniaxial compressive creep after 15 months under load at 160°F (71°) was 1.75 times that of specimens at 70°F (21°C). In comparison, AC specimens loaded uniaxially to an average stress-strength ratio of 0.31 at 90 days indicated the compressive creep after 12 months under load at 150°F (66°C) was 2.0 times that at 73°F (23°C). Overall for the 17 cases where effect of temperature could be compared directly for tensile and compressive creep, the absolute average creep at 150°F (66°C) was 1.76 times that at 73°F (23°C).

Moisture

It is generally concluded that creep depends on the loss of water under load and the amount of water present at the time of application of load, with the latter possibly having the larger effect. Thus, the environment for specimens during the curing period prior to application of load and the environment during the sustained loading period are important. AD specimens would be expected to have a lower moisture content upon loading than AC specimens, and therefore might be expected to exhibit less creep. However, in 12 of 16 cases where a direct comparison between AC and AD specimens was possible, the higher compressive creep was associated with the AD concrete. AD specimens of the high- and main-modulus concretes averaged 27 percent greater compressive creep strain than comparable AC specimens. Three of the four cases where creep was greater for AC concrete occur in the low-modulus concrete. The AC specimens of low-modulus concrete averaged 45 percent greater compressive creep strain than comparable AC specimens. It should be noted that shrinkage strains in AD control specimens averaged 127, 178, and 552 millionths at the time of loading for high-, main-, and low-modulus concrete mixtures, respectively. If the significantly larger compressive strains in the low-modulus concrete are indicative of a greater moisture loss compared with the remaining mixtures, then this might explain why the compressive creep behavior of the low-modulus specimens was opposite the other two mixtures. During the loading period, AD control specimens generally exhibited tensile (expansion) strains, the magnitudes of which were essentially proportional to the concrete modulus of elasticity ranging up to approximately 130 millionths. This would indicate moisture movement within the AD specimens, and since the direction of the moisture movement is immaterial as far as its effect on creep is concerned,[5] drying creep in the loaded AD specimens would tend to increase the ultimate creep.

In general, tensile creep strains behaved in a manner opposite that of compressive creep. AC specimens of the high- and main-modulus concretes averaged 11 percent greater tensile creep strain than comparable AD specimens, whereas AD specimens of the low-modulus concrete averaged 17 percent greater tensile strain than comparable AC specimens. However, it should be noted that in three of the four low-modulus cases, AC strains averaged 16 percent greater than AD, and it was the remaining case in which the AD strain was 201 percent greater than AC that caused the overall average to be reversed. In comparison, York, et al.,[6] in similar tests on the main-modulus mixture, found that compressive and tensile creep strains were generally larger for AD concrete than for AC concrete except in the case of low tensile creep, where the reverse was true.

Modulus of Elasticity

Except for some unusual aggregates, the magnitude of creep in the aggregate at stresses to which aggregate particles are subjected in concrete is very small, particularly in comparison with the creep of concrete. The most probable explanation of the influence of aggregate type on creep involves the modulus of elasticity of aggregate; the higher the modulus, the greater the restraint offered by the aggregate to the potential creep of the cement paste.[7] This restraining effect of aggregate on the deformation of concrete is largely independent of the cause of the deformation (i.e., shrinkage or creep).

There were five cases in which loading, moisture, and temperature conditions allowed a direct comparison of compressive creep strains concerning the effect of concrete modulus. The average strains for these cases were 0.092, 0.118, and 0.270 millionths/psi (13.3-, 17.1-, and 39.2-millionths/MPa) for high-, main-, and low-modulus concrete, respectively. These strain values correlate generally with the inverse of the modulus of elasticity of the concrete and hence the inverse of the modulus of elasticity of the aggregate (Fig. 4). The shapes of the curves relating compressive creep and the elastic modulus of concrete and aggregate are similar to those previously reported[3,8] for longitudinal and lateral creep. Also, the shape of the curves relating creep and modulus of elasticity are similar to those relating shrinkage and modulus of elasticity (Fig. 3). There was only one case in which a direct comparison could be made concerning the effect of concrete modulus on tensile creep. In this case, strains were 0.0202, 0.0321, and 0.0561 millionths/psi (2/9-, 4.7-, and 8.1-millionths/MPa) for high-, main-, and low-modulus concrete, respectively (Fig. 5). In comparison, an overall average gave values for tensile creep of 0.0183, 0.0302, and 0.0705 millionths/psi (2.7-, 4.4-, and 10.2-millionths/MPa) for the three concretes. Obviously, with only one direct comparison, the data are limited and the averages are slightly biased; however, the data do offer a general indication that tensile creep also increases as the elastic modulus of the aggregate and concrete decreases.

State of Stress

There were only two cases in which moisture and temperature conditions allowed a direct comparison concerning the effect of the four loading modes on compressive creep; both of these cases involved main-modulus concrete. Average values of compressive creep for these two cases differed by a factor of 1.00:0.45:0.69:0.84 for uniaxial, hydrostatic, biaxial, and triaxial loading, respectively (Fig. 6). In comparison, the overall averages for all values of compressive creep in the main-modulus concrete differed by a factor of 1.00:0.50:0.84:0.90 for the same states of stress, which is in fairly good agreement with the direct comparison, particularly considering the slight bias in the overall average resulting from differences in moisture and temperature conditions for the various states of stress. On the same basis, overall average values for the high- and low-modulus concrete differed by factors of 1.00:0.48:1.10:0.80 and 1.00:----:0.92:0.89 for the various states of stress. No measurements were available for hydrostatically loaded low-modulus concrete.

With the exception of biaxially loaded high-modulus specimens, creep under multiaxial stress was less than that associated with uniaxial stress. It should be noted that this result was particularly biased by temperature difference, i.e., all available biaxial results were for the 150°F (66°C) environment, whereas at least half of the measurements for each of the remaining states of stress were for 73°F (23°C) where strains were generally lower. Thus the overall results are in general agreement with results previously reported by Hannant[9] and Gopalakrishnan.[10]

There were 13 cases in which a direct comparison could be made concerning the effect of increased stress level on compressive creep for a given state of stress. In 9 of the 13 cases, the higher compressive creep strain was associated with the higher stress level. For the uniaxial, hydrostatic, and biaxial loadings, the specific creep strain at the 2400-psi (17 MPa) stress level averaged 1.17 times that at the 600-psi (4 MPa) stress level. This increase in strain was essentially the same for all three states of stress, ranging from 1.15 for biaxial loading to 1.23 for the hydrostatic case. The higher stress level resulted in an average stress-strength ratio upon loading of 0.31, which is, as the data would indicate, approaching the generally accepted limit for creep-stress proportionality. The application of a 600-psi (4 MPa) radial stress reduced an average of 14 percent the compressive creep strains in the direction of the axial load relative to compressive creep strains in comparable uniaxially loaded specimens.

The effect of uniaxial and biaxial loadings on tensile creep could be compared directly in seven cases; in six of these cases, the higher tensile creep strain was associated with the biaxial stress condition. For these seven cases, the tensile creep strains for biaxially loaded specimens averaged 1.26 times that obtained for comparable specimens uniaxially loaded. There were eight cases in which a direct comparison could be made concerning the effect of increased stress level on tensile creep for the uniaxial and biaxial stress states. In these eight cases, the higher tensile creep strain was equally divided between the two stress levels. Averaging the two states of stress, there was less than 1 percent difference in tensile creep strain for the two stress levels. However, the tensile creep strain at 600 psi (4 MPa) was 1:35 times that at 2400 psi (17 MPa) for the uniaxial stress state, whereas the tensile creep at 2400 psi (17 MPa) was 1.20 times that at 600 psi (4 MPa) for the biaxial state of stress.

CREEP POISSON'S RATIO

Different methods have been used to compute the magnitude of Creep Poisson's Ratio (CPR) under multiaxial stresses, depending on the investigator's definition of CPR. In this paper values of CPR were calculated by the same equation used to calculate elastic Poisson's ratio (EPR) by substituting the appropriate creep strains for elastic strains, a method previously used by York, et al.[6] On this basis CPR values were calculated for the various environmental conditions at selected intervals during the test period. Although average CPR values over the entire test period were somewhat biased due to differences in loading conditions, they should offer general indications as to the effects of the various test conditions.

Overall, CPR's averaged approximately 0.10, 0.15, and 0.11 for high-, main-, and low-modulus concrete, respectively. CPR was generally smaller than EPR, averaging 68, 66, and 92 percent for the high-, main-, and low-modulus concrete, respectively. York, et al.[6] reported an average CPR of 0.16 which was approximately 65 percent of the average EPR for main-modulus concrete. This finding is almost identical to the results of this investigation on the same concrete mixture.

It was shown previously that tensile creep strains for AD specimens were smaller than those of comparable AC specimens of the high- and main-modulus concretes. Therefore, it would be expected that CPR would be less for AD concrete; for the limited data available, the CPR for AC specimens averaged 23 percent more than for comparable AD specimens.

Similarly, it was previously shown that average tensile creep strains for AD specimens were slightly higher than for comparable AC specimens of low-modulus concrete, and as might be expected, the CPR for AD specimens averaged approximately 5 percent higher than for comparable AC specimens.

The limited data available indicated the CPR at 73°F (23°C) averaged 34 percent higher than at 150°F (66°C). This apparent trend agrees with results reported by others.[6, 9, 11]

The state of stress also appeared to influence the magnitude of CPR. For each concrete mixture, the higher overall average CPR was associated with the biaxial loading and the lower CPR with the triaxial loading. Values for uniaxial loading ranged between these two bounds. The overall average CPR's for all three concrete mixtures were in the proportion 1.00:0.80:0.54 for biaxial, uniaxial, and triaxial loading, respectively.

The effect of time on CPR is shown in Fig. 7. While the CPR of low-modulus concrete appears to remain essentially constant throughout the test period, CPR for the two remaining mixtures would appear to be increasing slightly with time. In all three cases, CPR after 1 year under sustained load is still slightly lower than EPR. The data, particularly for the high- and low-modulus concrets in the later part of the sustained load period, are limited; however, it would appear, particularly for the main-modulus concrete, that CPR increases somewhat with time under load. In similar tests, York, et al.,[6] did not draw definite conclusions due to lack of sufficient [illegible] however, they believe that time does not significantly affect CPR.

ELASTIC RECOVERY STRAINS

Strain measurements were made immediately prior to and after unloading at the end of the sustained load test period to determine elastic recovery. Modulus of elasticity and Poisson's ratio values for elastic recovery were calculated in a manner similar to that used for calculating elastic values.

Overall for the three mixtures, elastic recovery strains in the axial direction ranged from 77 to 121 percent of elastic strains upon loading with an average of 99 percent. While the range of recovery strains in the radial direction was much greater (61 to 257 percent), the overall average (101 percent) was again essentially the same as for the elastic strains.

Elastic recovery strains for the main-modulus concrete averaged 8 percent larger than elastic strains at loading. This finding agrees with the results of similar tests on the same concrete mixture at the University of Texas.[6] In comparison, average elastic recovery strains for the high- and low-moduli concretes were 2 and 13 percent less than elastic strains, respectively. Gopalakrishnan[10] found that, for concrete cubes subjected to multiaxial stresses, the elastic recovery strains were less than the elastic strains upon loading in all cases.

Elastic recovery strains for three of the four temperature and curing conditions investigated were essentially the same, averaging approximately 3 percent higher than elastic strains upon loading. The exception was AD specimens loaded at 150°F (66°C) in which elastic recovery strains averaged 12 percent less than elastic strains upon loading. The modulus of elasticity and Poisson's ratio for elastic recovery were essentially the same as those at the time of loading, except for those for low-modulus concrete which were somewhat higher than at the time of loading.

CREEP RECOVERY

After unloading, strains in the creep and control specimens were monitored intermittently for a period of approximately 4 months to determine creep recovery. Results indicate that from 4 to 60 percent of the creep strain at time of unloading, an average of 31 percent, was recovered 117 days after the loads were released. This recovery, still continuing at the time comparisons were made, was in the direction opposite that of creep strains with the exception of three cases in which there were small strain recoveries in the same direction as the creep strain.

Overall, creep recovery for AC and AD specimens was essentially the same, averaging 29 and 32 percent of the creep strains at time of unloading, respectively. Results reported by Gopalakrishnan, et al,[12] indicated that, for uniaxially loaded specimens, the percentage of axial creep strain recovered was slightly higher for wet-stored than dry-stored cylindrical specimens. Under comparable test conditions in this investigation, results indicate that the percentage of axial creep recovered for the AC specimens was 4 percent greater than that for AD specimens.

Although only limited test results were available for the 150°F (66°C) test condition, the data indicate no significant difference in the percentage of creep recovered at the two test temperatures. Average creep recovery at 73°F (23°C) and 150°F (66°C) was 31 and 30 percent, respectively.

Creep recovery of main- and low-modulus concrete specimens was essentially the same, averaging 27 and 28 percent, respectively, of the creep strain at the time of unloading. In comparison, creep recovery of high-modulus concrete specimens averaged 35 percent of the creep at the time of unloading.

The percentage of creep recovered was essentially the same for both stress levels, averaging 33 and 35 percent of the creep at the time of unloading for the 2400- (17-) and 600-psi (4-MPa) stress levels, respectively. The type of stress applied also appeared to have only a small effect on the percentage of creep recovered, with multiaxial states of stress averaging 5 percent more creep recovery than uniaxial states. In comparison, York, et al.[6] in similar tests on the main-modulus concrete mixture, reported no significant effect of type stress applied, whereas Gopalakrishnan[10] found that the percentage of creep strain recovered was approximately 20 percent higher for multiaxial than uniaxial states of stress. It should be noted that in the latter tests the age at loading was 8 days and the duration of load ranged from 22 to 98 days, with the majority of the tests being 28 days duration.

CONCLUSIONS

For the concretes used and the actual test conditions investigated, it appears that the following general conclusions can be drawn.

a. Strength and elastic deformation

(1) It is possible to proportion concrete mixtures containing widely varying aggregate moduli with subsequent variations in concrete moduli to obtain similar compressive strengths.

(2) The secant modulus of elasticity of concrete was proportional to the modulus of elasticity of the aggregate.

b. <u>Time-dependent deformation</u>

(1) Average axial and radial shrinkage strains for AD specimens at the end of the curing period were inversely proportional to the concrete and aggregate moduli, ranging from 127 to 552 millionths for the high- and low-modulus concretes, respectively.

(2) During the testing period, axial and radial expansion strains in sealed AD specimens at 73°F (23°C) were generally inversely proportional to concrete and aggregate moduli, ranging up to approximately 130 millionths for the low-modulus specimens at the end of the test period.

(3) During the curing and test periods, axial and radial strains for AC control specimens at 73°F (23°C) were similar in magnitude with a maximum recorded strain of 26 millionths shrinkage.

(4) Specific creep strains were larger for the 150°F (66°C) condition during loading, averaging 1.79 and 1.51 times that at 73°F (23°C) for the compressive and tensile creep, respectively. AD concrete exhibited a greater increase in compressive creep than AC concrete at 150°F (66°C), whereas the reverse was true for tensile creep. Overall, the absolute average creep at 150°F (66°C) was 1.76 times that at 73°F (23°C).

(5) AD specimens of the high- and main-modulus concrete exhibited greater compressive creep strain than comparable AC specimens, whereas AC specimens of the low-modulus concrete exhibited greater compressive creep strain than comparable AD specimens. The reverse was true for tensile creep.

(6) Compressive and tensile creep strains were generally proportional to the inverse of the elastic modulus of both concrete and aggregate.

(7) Compressive creep under multiaxial stress was less than that under uniaxial stress. Values of compressive creep for main-modulus concrete differed by a factor of 1.00(uniaxial): 0.45(hydrostatic):0.69(biaxial):0.84(triaxial).

(8) The increase in compressive specific-creep strain at the 2400-psi (17 MPa) level was essentially the same for the uniaxial, hydrostatic, and biaxial states of stress, averaging 1.17 times that at the 600-psi (4 MPa) level.

(9) Creep Poisson's ratio was generally smaller than elastic Poisson's ratio, averaging 68, 66, and 92 percent of the elastic values for high-, main-, and low-modulus concretes, respectively.

c. Elastic and creep recovery strains

(1) Overall, average elastic recovery strains for the three concrete mixtures were slightly less than elastic strains except for the main-modulus concrete, where the reverse was true.

(2) The modulus of elasticity and Poisson's ratio for elastic recovery were essentially the same as those at the time of loading, except for those for low-modulus concrete which were somewhat higher than at the time of loading.

(3) From 4 to 60 percent of the creep strain at time of unloading, an average of 31 percent, was recovered 117 days after the loads were released. This recovery, still continuing at the time comparisons were made, was in the direction opposite of the direction of creep strains, except for three cases in which there were small strain recoveries in the same direction as the creep strain.

(4) The percentage of creep recovered was essentially the same for variations in curing, temperature, concrete modulus, and stress level investigated, ranging from 27 to 35 percent of the creep at the time of unloading.

(5) The state of stress applied appeared to have a small effect on the percentage of creep recovered, with multiaxial states of stress averaging 5 percent more creep recovery than unixial states.

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Table 1

Summary of Experimental Test Conditions

Modulus of Elasticity		High				Main				Low			
Testing Temperature, °F		73		150		73		150		73		150	
Curing History		AC	AD	AC	AD	AC	AD	AC	AD	AC	AD	AC	AD
Stress, psi													
Axial	Radial												
2400	2400	*	*	*	*	*	*	*	*	*	*	*	*
	600	*	*	*	*	*	*	*	*	*	*	*	*
	0	*	*	*	*	*	*	*	*	*	*	*	*
600	600	*	*	—	—	*	*	—	—	—	—	—	—
	0	*	*	*	*	*	*	*	*	—	—	*	*
0	2400	—	—	*	*	*	*	*	*	—	—	*	*
	600	—	—	*	*	*	*	*	*	—	—	*	*
	0	*	*	*	*	*	*	*	*	*	*	*	*

* Test conditions investigated.

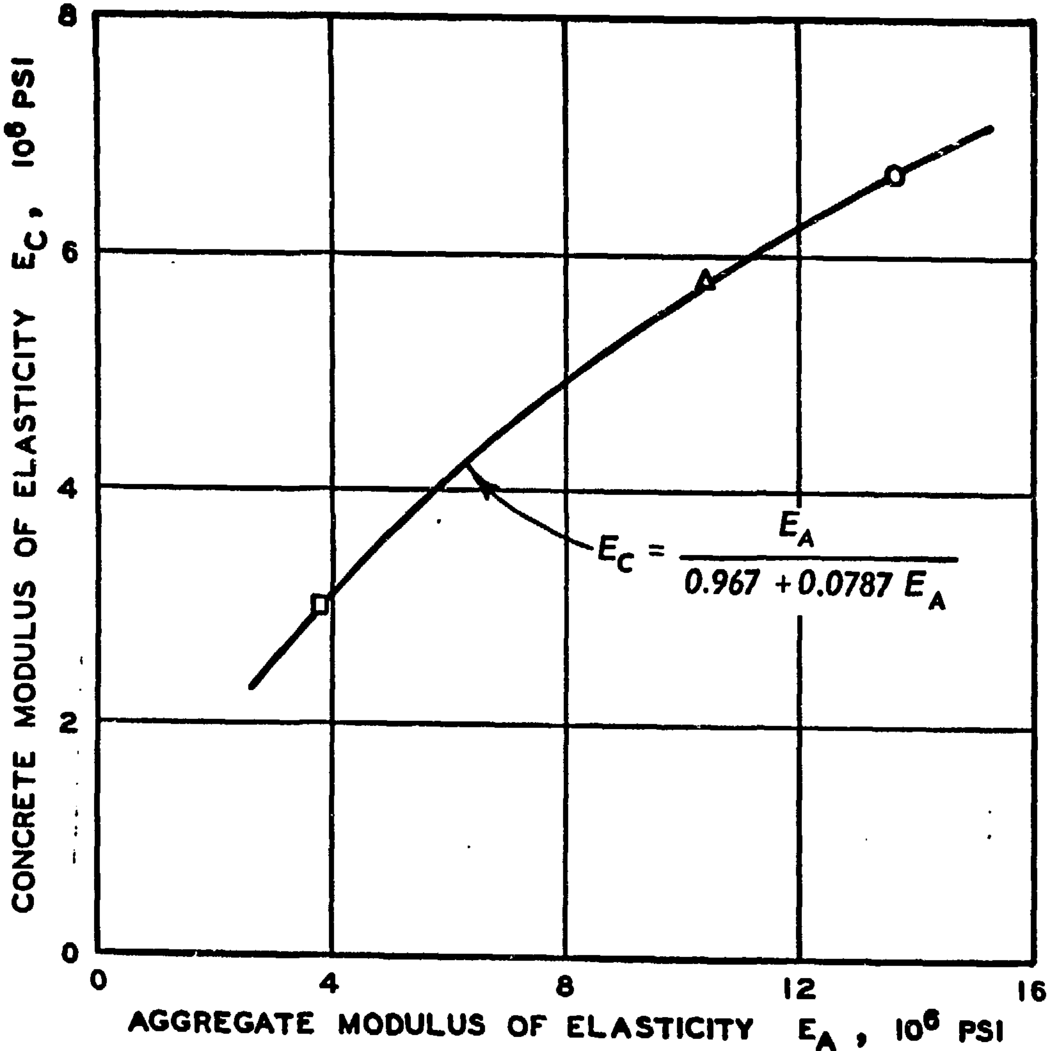

Figure 1. Relationship of moduli of elasticity of aggregate and concrete

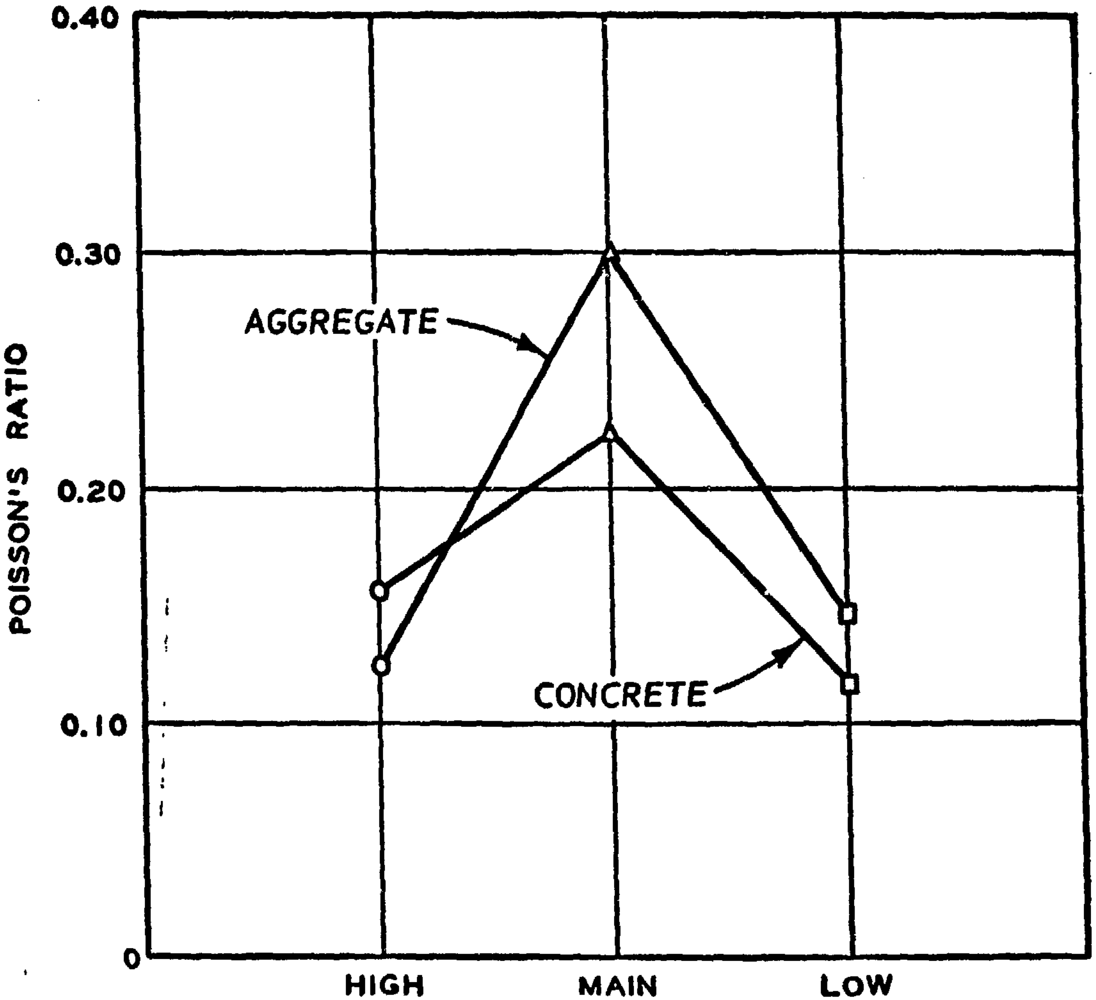

Figure 2. Relationship of Poisson's ratio of aggregate and concrete

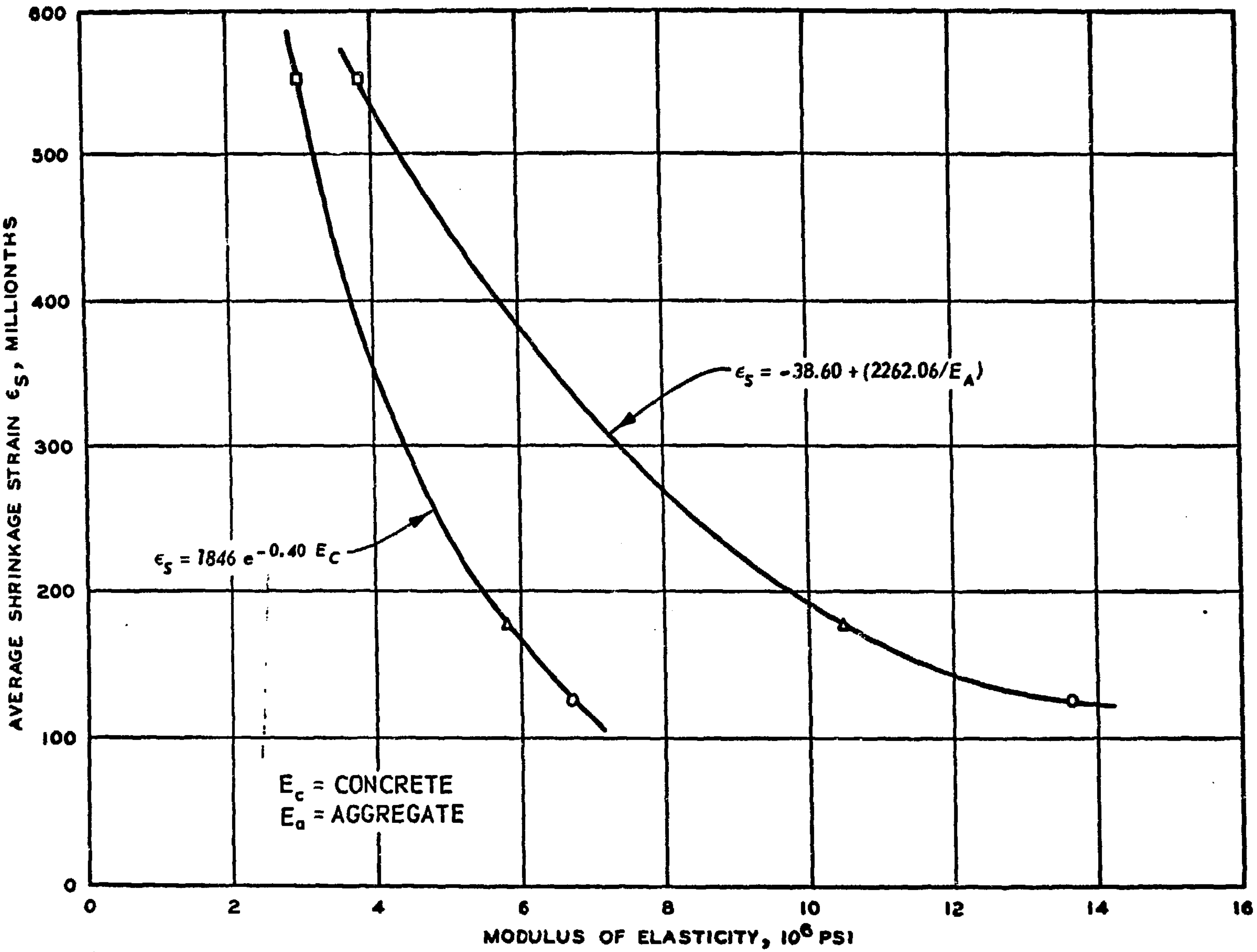

Figure 3. Relationship of shrinkage strain of air-dried concrete and modulus of elasticity of air-dried concrete

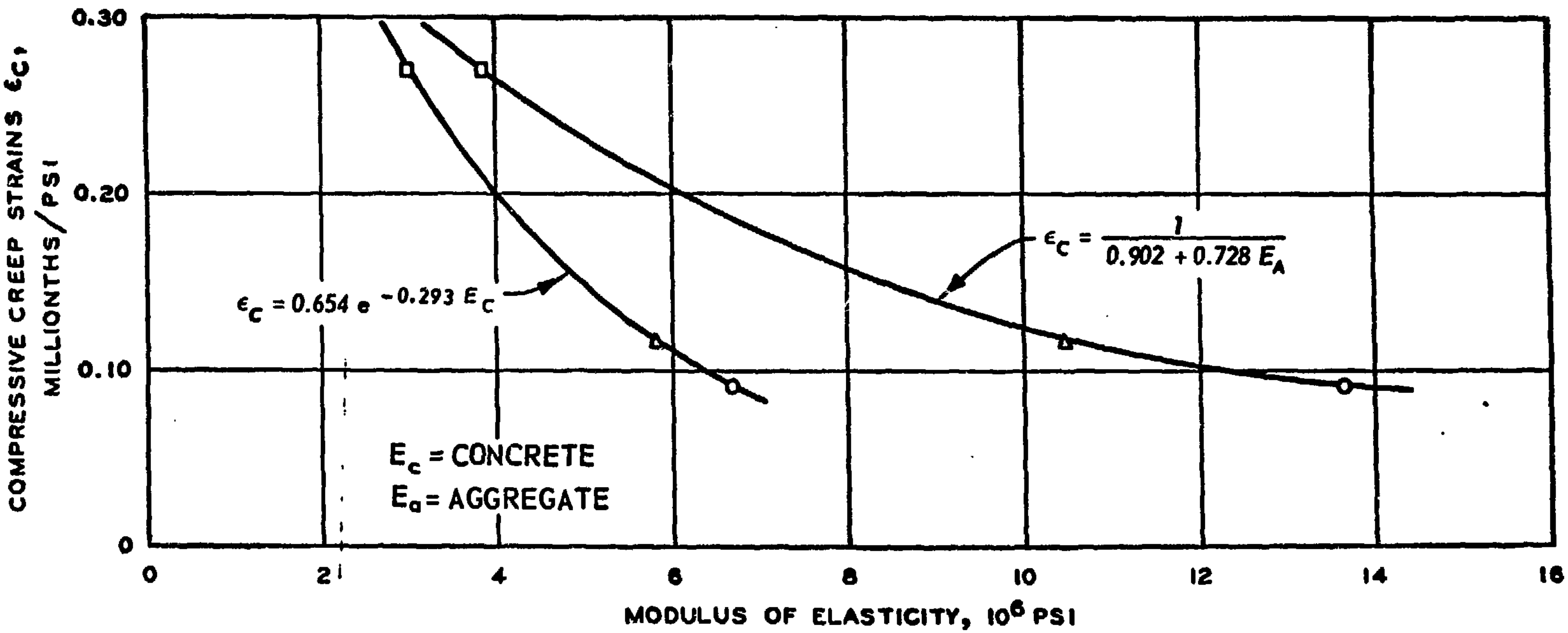

Figure 4. Relation of compressive creep and elastic modulus of concrete and aggregate

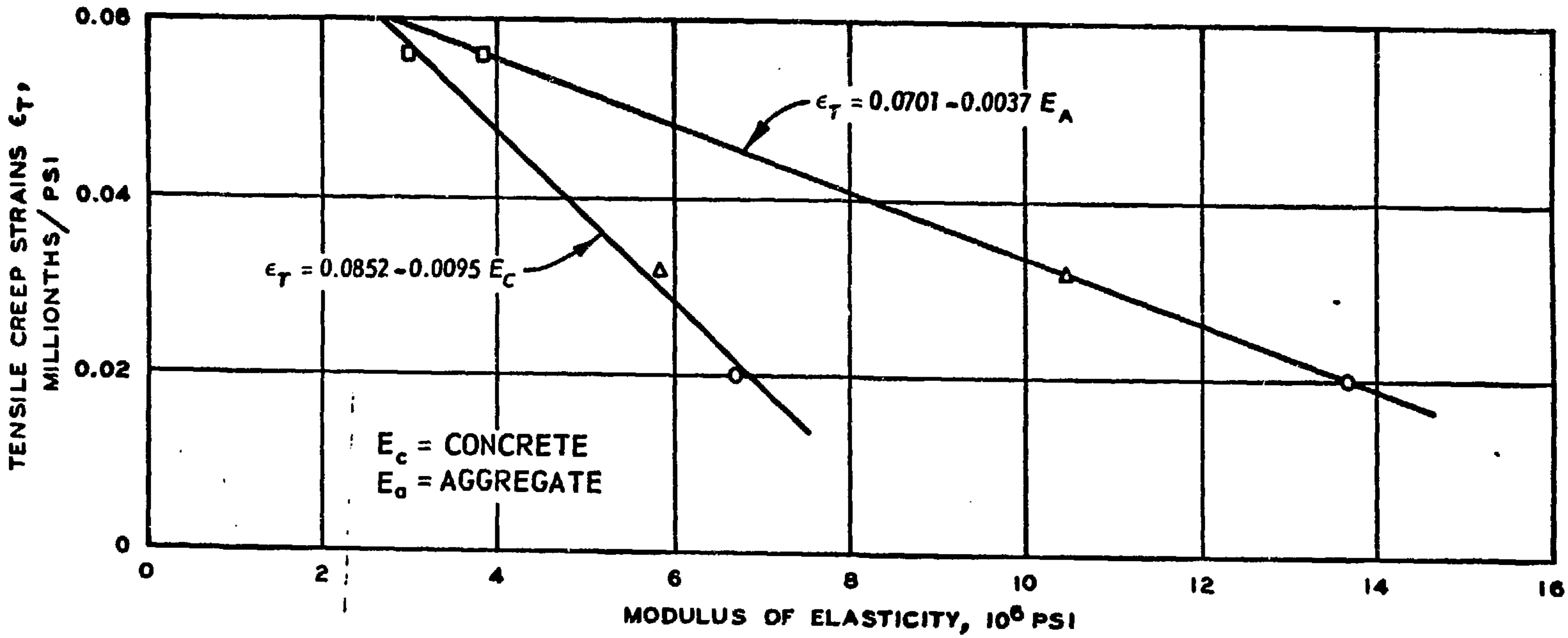

Figure 5. Relation of tensile creep and elastic modulus of concrete and aggregate

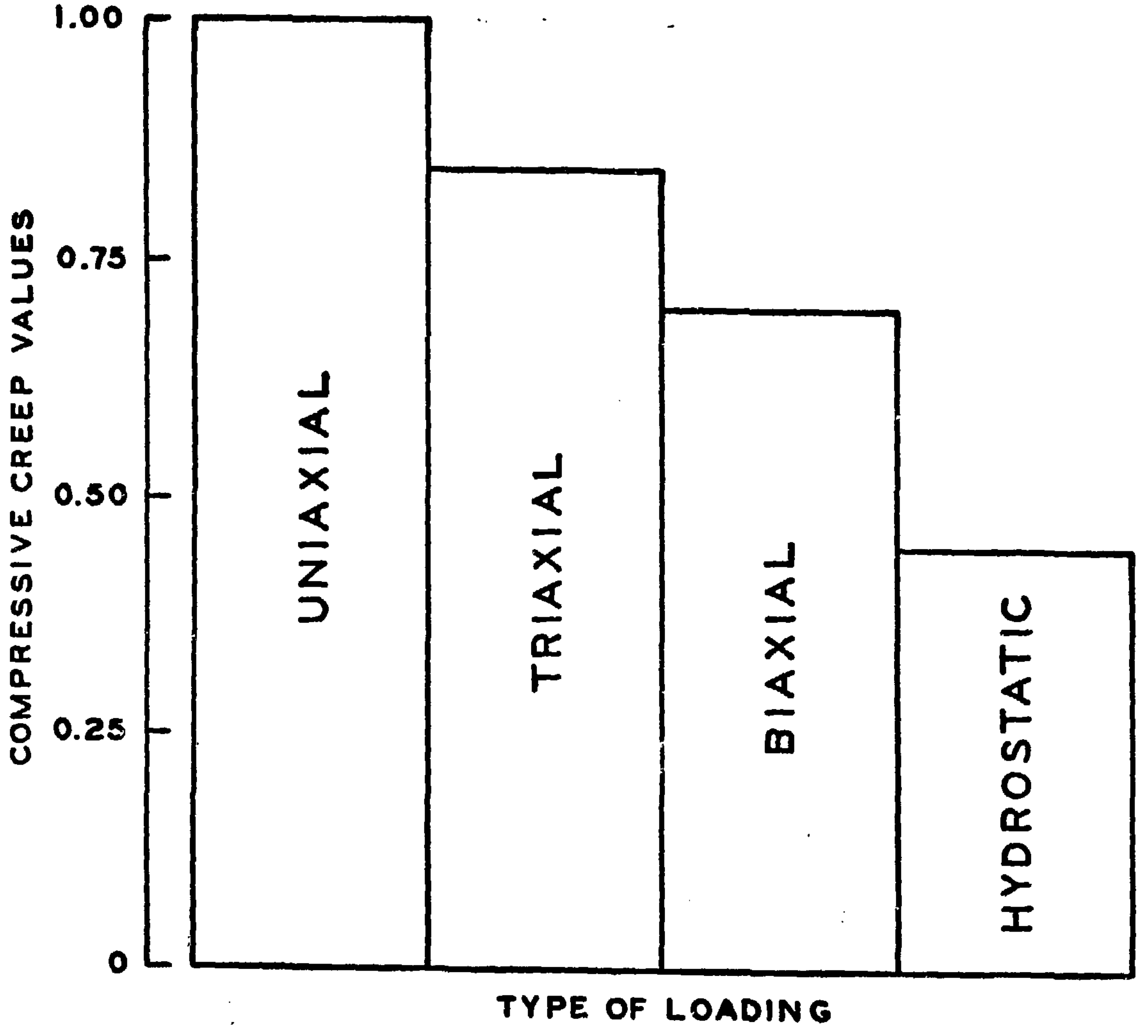

Figure 6. Effect of type of loading on compressive creep

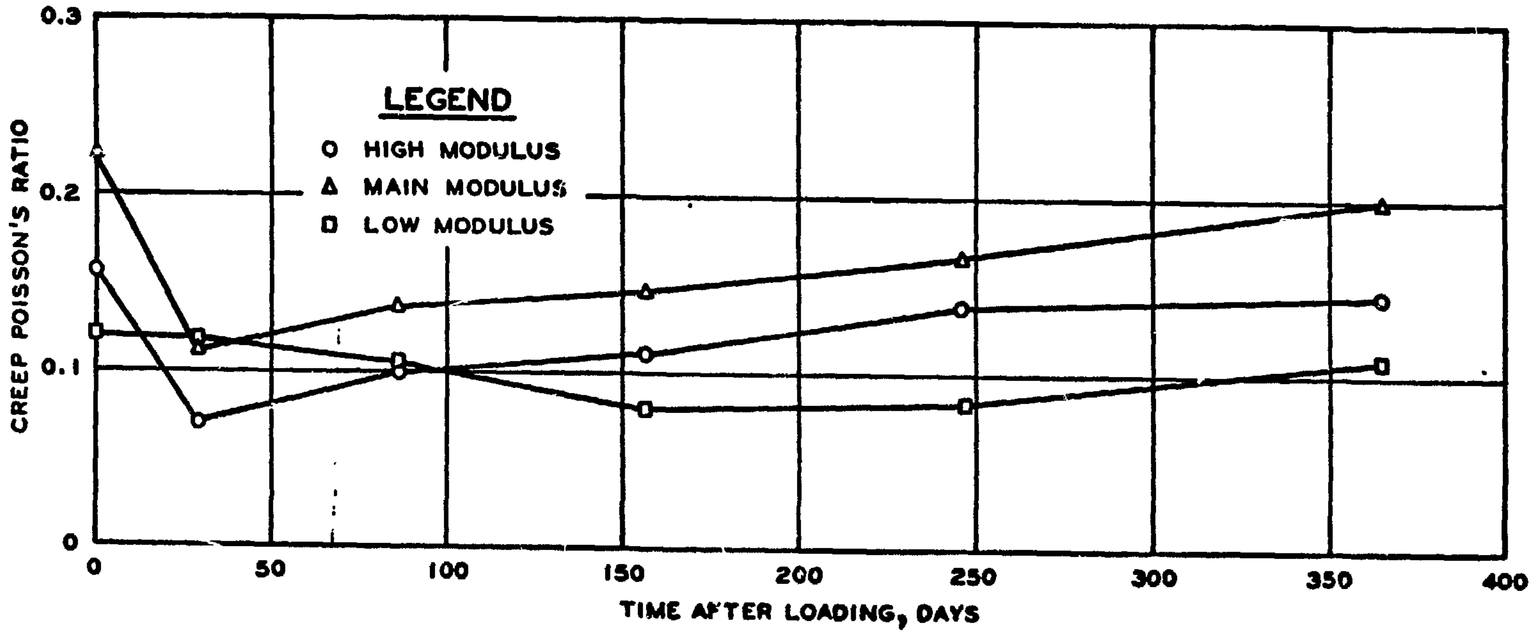

Figure 7. Effect of time after loading on CPR