ORNL-SUB 3899-1

LONG TERM CREEP BEHAVIOR OF CONCRETE

By Thomas W. Kennedy

RESEARCH REPORT 3899-1

to

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

JANUARY 1975

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PREFACE

This is the sixth in a series of reports dealing with the findings of a research project conducted at The University of Texas at Austin and concerned with the evaluation of the creep behavior of concrete subjected to triaxial compressive stresses and elevated temperature. This report evaluates the long term creep behavior of concrete subjected to uniaxial stresses for 4.5 and 5 years at 75°F.

The experimental investigation was conducted and financed under Union Carbide Subcontract 2864, and three reports were prepared. Two additional reports were prepared and financed under Union Carbide Subcontract 3661. This report was prepared under Union Carbide Subcontract 3899. All three contracts were with the Oak Ridge National Laboratory, which is operated by the Union Carbide Corporation for the United States Energy Research and Development Administration.

The planning and conducting of the experimental investigation required the assistance and cooperation of many individuals and organizations; the author would like to acknowledge the cooperation and assistance obtained from the Concrete Division of the Waterways Experiment Station of Vicksburg, Mississippi, and the Department of Civil Engineering of the University of California at Berkeley. In addition, special thanks are extended to Dr. J. P. Callahan, Manager of the Prestress Concrete Pressure Vessel Program Office, and Mr. G. D. Whitman, Manager of the Solid Mechanics Department, of the Oak Ridge National Laboratory, whose active participation and support allowed this investigation to be successfully conducted, and to Dr. J. M. Corum and Mr. J. G. Stradley of the Oak Ridge National Laboratory. Appreciation is also extended to Professor Clyde E. Kesler, Department of Civil Engineering, University of Illinois, who served as a consultant to the original project.

A future report will be concerned with a detailed evaluation of the experimental techniques, the equipment, the specimens, and the findings of the investigation.

Thomas W. Kennedy

January 1975

ABSTRACT

This report presents the findings of an experimental investigation to evaluate the long term creep behavior of concrete subjected to sustained uniaxial loads for an extended period of time at 75°F. The factors investigated were (1) curing time (90, 183, and 365 days); (2) curing history (as-cast and air-dried); and (3) uniaxial stress (600 and 2400 psi).

The portion of the experimental investigation covered by this report consisted of applying uniaxial compressive loads to cylindrical concrete specimens and measuring strains with vibrating wire strain gages that were cast in the concrete specimen along the axial and radial axes. Specimens cured for 90 days prior to loading were subjected to a sustained load for a period of one year, at which time the loads were removed; the specimens which were cured for 183 or 365 days, however, were not unloaded and have been under load for 5 and 4.5 years, respectively.

The effect of each of the above factors on the instantaneous and creep behavior is discussed and the long term creep behavior of the specimens cured for 183 or 365 days is evaluated. The findings of these evaluations are summarized in the report. A previous report evaluated the behavior during the first 2.5 and 2 years for the specimens cured for 183 and 365 days.

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CHAPTER 1. INTRODUCTION

An important consideration in the design and safety evaluation of prestressed concrete nuclear reactor vessels is the time-dependent behavior of the concrete subjected to different temperatures, curing times, curing histories or moisture conditions, and loading conditions. The three basic forms of time-dependent deformation that can occur are shrinkage, creep, and creep recovery. Any one of these three types of deformation can have serious effects on the behavior of a reactor vessel unless carefully considered during the design of the reactor. Because of the long term nature and complexity of the required tests, information on creep and the factors affecting creep is limited.

At the request of the United States Atomic Energy Commission, the Oak Ridge National Laboratory formulated and coordinated a basic research and development program to develop the technology of prestressed concrete reactor vessels. As a part of this program, an experimental investigation was initiated at The University of Texas at Austin to study the creep behavior of concrete subjected to multiaxial compressive stresses and elevated temperatures. The investigation consisted of measuring strains in cylindrical specimens subjected to 58 test conditions involving a variety of multiaxial loading conditions (compressive stresses ranging from zero to 3600 psi), three curing times (90, 183, and 365 days), two curing histories (air-dried and as-cast), and two temperatures (75°F and 150°F). After curing, the specimens cured for 90 days were subjected to a prescribed load and temperature for 12 months, followed by a five-month recovery period. Specimens cured for 183 or 365 days were subjected to uniaxial stresses of 600 or 2400 psi and were to remain under load for an indefinite period of time. During the curing, loaded, and unloaded periods, strain measurements were made in order to evaluate the creep and creep recovery behavior of the concrete.

This report summarizes and discusses the findings from an evaluation of the data obtained from that portion of the overall experiment which was intended to evaluate the long term creep behavior and extends the data previously reported (Ref 9). The investigation involved 12 creep specimens and three shrinkage specimens. The factors investigated were (1) curing time (90, 183, and 365 days), (2) curing history (as-cast and air-dried), and (3) uniaxial stress (600 and 2400 psi). All specimens were cured and tested at 75°F. Specimens cured for 90 days were subjected to a sustained load for a period of one year, at which time the loads were removed; the specimens which were cured for 183 or 365 days were not unloaded and have been under load for 5 and 4.5 years, respecitvely.

The report consists of five chapters. Chapter 2 describes the total experimental program, including the preparation of specimens, equipment and instrumentation, experimental procedures, and experimental designs. A summary of the test findings primarily associated with the portion of the investigation involving specimens cured for 90 days prior to loading is presented in Chapter 3, and the data obtained from the portion devoted to evaluation of the long term creep behavior and the effects of curing are summarized in Chapter 4, along with a discussion of the analysis and findings. Conclusions and recommendations are contained in Chapter 5.

CHAPTER 2. EXPERIMENTAL PROGRAM

This chapter contains a brief description of the overall experiment and a discussion of the factors investigated, the design of the experiment, the techniques used to prepare the specimens, the equipment used, and the test procedure. A more detailed discussion and description are contained in Refs 3 and 7.

The tests consisted of applying compressive loads along the three principal axes of cylindrical concrete specimens and measuring the strains in the axial and radial directions throughout the testing period. The axial and radial loads were applied by means of a hydraulic loading system and were varied independently, permitting triaxial, biaxial, and uniaxial states of stress to be developed. Strains were measured by two vibrating wire strain gages embedded in the concrete along the axial and radial axes of the cylindrical specimen.

TEST CONDITIONS

Although numerous factors affect the creep and creep recovery behavior of concrete, the basic study included only temperature during loaded and unloaded recovery periods, curing time, curing history, and state of stress.

Temperature During Test Period

During the loaded and unloaded periods, the concrete was subjected to one of the two temperatures which are the limits of the range of temperatures that would be expected to occur in the concrete of a nuclear reactor vessel. The low level was 75° F, which approximates the temperature at the outer surface of a reactor, and the high level was 150° F, which approximates the temperature at the inner surface of a vessel. The temperature was controlled within ±2° F of the desired levels and was recorded continuously.

Curing Time

The major portion of the study involved specimens cured for a period of 90 days prior to being loaded. In addition, a limited number of specimens were cured for periods of 183 or 365 days prior to loading in order to ascertain the effect of curing time.

Curing History

Two curing histories which simulate the range of curing conditions to which concrete in a prestressed concrete reactor would be subjected during curing were selected for study and were designated as "as-cast" and "air-dried." The as-cast condition represented the curing history of concrete at the inner face of a reactor or of concrete in any massive structure except that near a free-air surface. This condition involved sealing the specimens shortly after casting to maintain their initial water content by preventing evaporation losses. The air-dried condition represented the curing history of the concrete at the outer surface of a reactor or other mass-concrete structure, or of concrete in relatively thin members. In this case, the concrete was moist cured for approximately seven days and then allowed to air-dry for the remainder of the curing period.

Thus, curing history was closely related to moisture condition in the concrete during the curing and loading periods. However, since it was difficult to determine the actual moisture conditions which resulted from the two types of curing, and because it was impossible to assign the cause of an observed effect to anything but the curing procedure, this variable was designated as curing history. The procedures associated with the various curing histories are described in detail in this chapter.

All specimens were removed from the molds 24 hours after casting and were placed in a moist curing room for 24 hours. Subsequent to this initial 48-hour curing period, the as-cast specimens were sealed in copper and allowed to cure for an additional 81, 174, or 356 days, depending on the designated curing period for each specimen, and then they were placed in the test temperature environment until their time of loading. After the initial 48-hour curing period, the air-dried specimens were placed in lime-saturated water for five days (a total of seven days of moist curing), after which they were removed and allowed to air-dry in the laboratory at 75° F and 60 percent relative humidity long enough to give a total curing period of 83, 176, or 358 days after casting, when they were sealed and placed in the test temperature environment.

State of Stress

Specimens were loaded triaxially at five stress levels, ranging from 0 to 3600 psi for both axial stress σ_a and radial confining stress σ_r. Since the combination of stresses involved some zero stress levels, the loading conditions were classified as uniaxial, $\sigma_r = 0$; biaxial, $\sigma_a = 0$; and triaxial. The five stress levels involved were 0, 600, 1200, 2400, and 3600 psi nominal pressures. A schematic of the basic test unit and photographs of the units used to achieve these loading conditions are shown in Figs 1 and 2.

Prior to the actual testing, it was determined that the actual stress in the axial direction was somewhat less than the indicated stress, due to friction in the hydro-mechanical system which was used to load the specimens axially. Therefore, each loading unit was calibrated using a standard load cell.

TEST SPECIMENS

Description of Specimens

A total of 430 specimens were cast in nine batches, which were designated A through I.

Three basic types of specimens were utilized in this investigation: creep, shrinkage, and strength. All creep and shrinkage specimens were 6 inches in diameter by 16 inches in length and were attached to 3-inch-thick steel end slugs, through which the axial load was applied (Fig 3). The specimens were cast horizontally in specially designed molds. The tensile and compressive strength specimens were 6 inches in diameter by 12 inches in length and were cast vertically in standard 6 × 12-inch molds.

The experiment design contained 66 creep specimens and 36 shrinkage specimens, which were used to measure the total strains experienced by the concrete under the various combinations of the four test conditions. For each batch of concrete and for each environmental test condition, an unloaded shrinkage specimen was placed in the same test environment as its companion loaded specimens. These shrinkage specimens were used to evaluate shrinkage strains in order to estimate the time-dependent strains due to the load and in order to check batch-to-batch variations.

In addition, a total of 328 strength specimens were cast. These were distributed among the nine batches and consisted of as-cast, air-dried, and standard cured specimens. The as-cast and air-dried specimens were subjected

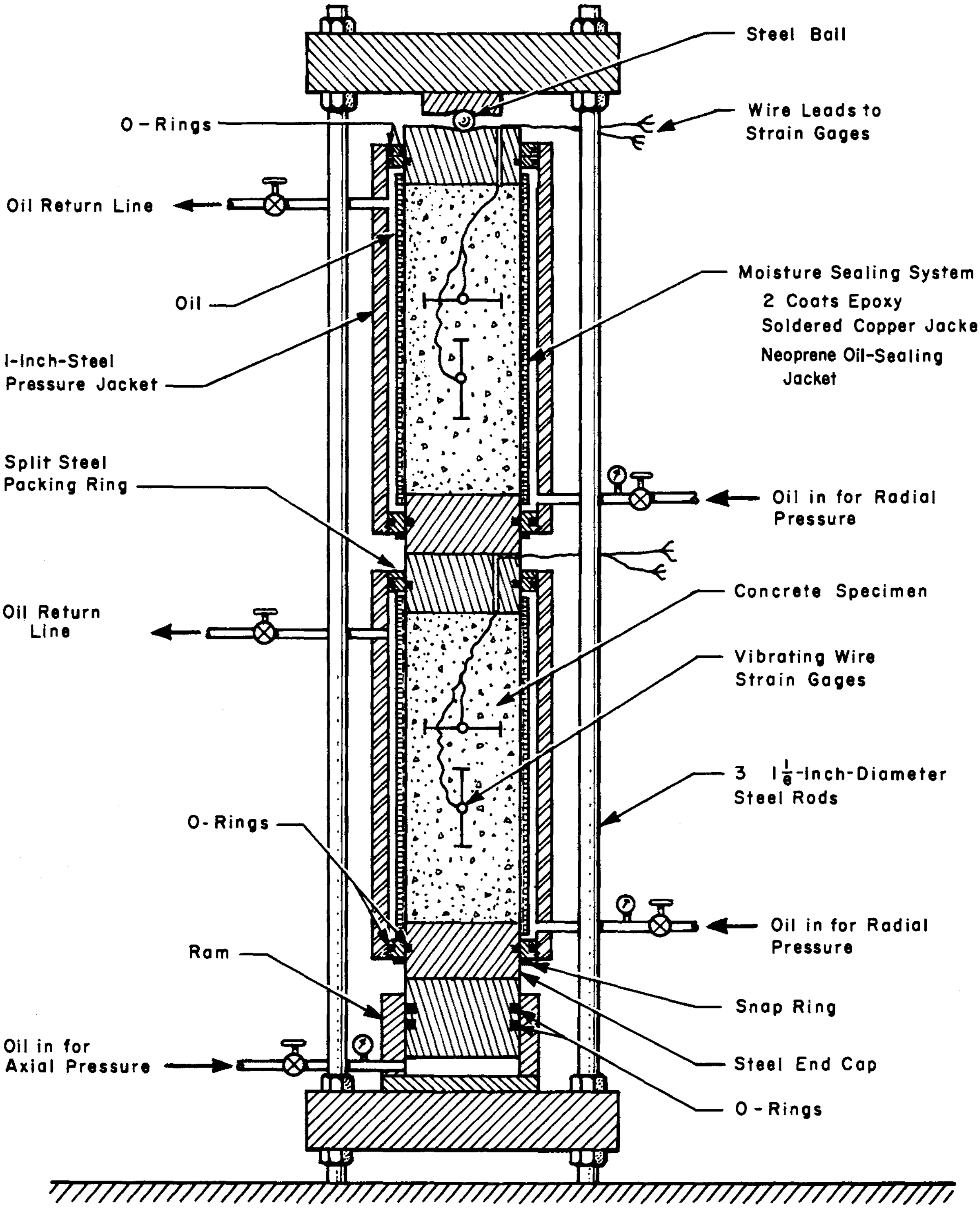
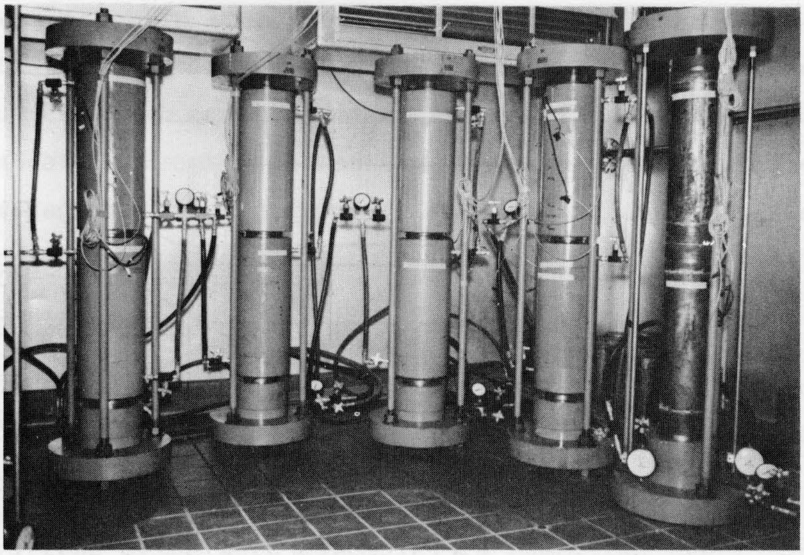
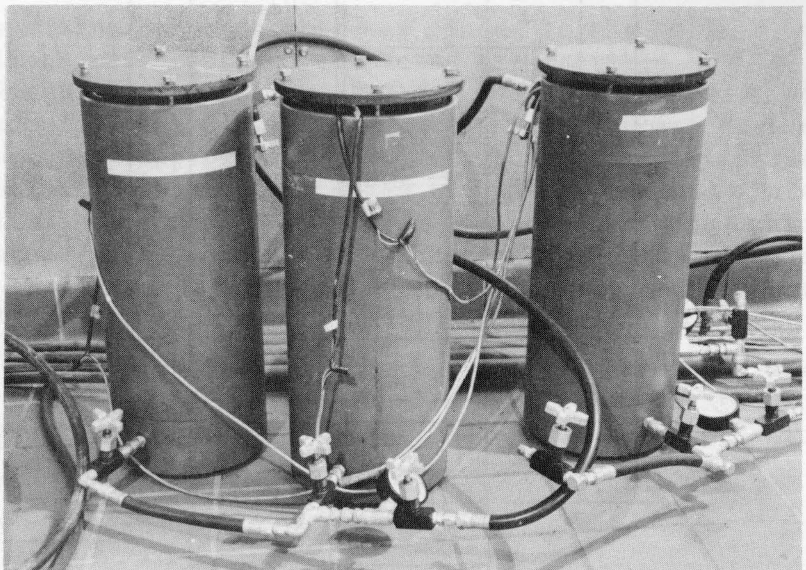


Fig 1. Schematic of triaxial test unit.



(a) Uniaxial and triaxial loading conditions.



(b) Biaxial loading condition.

Fig 2. Test units.

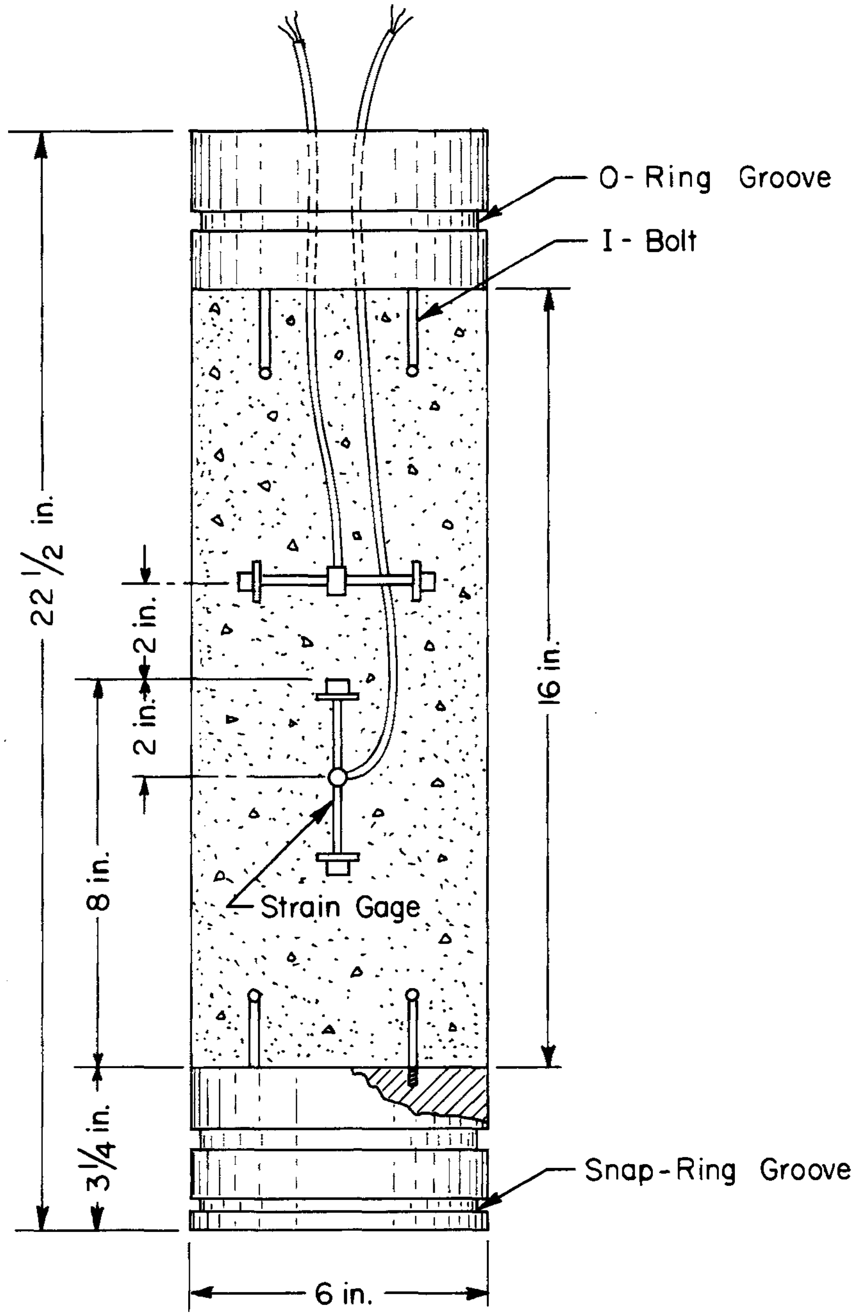


Fig 3. Test specimen and gage locations.

to the same curing and temperature conditions as the creep and shrinkage specimens. These strength specimens were used to evaluate the compressive and tensile strengths of the concrete for the various test conditions at various times throughout the test and to compare any existing batch-to-batch variations. The standard strength specimens were cured by being submerged in lime-saturated water and were used to compare the as-cast and air-dried concrete with concrete cured in accordance with ASTM Specification C-192.

Casting and Compaction

A detailed description of the preparation of the test specimens for various test conditions is presented in Ref 3. A brief summary of the casting and compaction operations follows:

(1) The various molds were assembled in numerical order for casting, and the strain gages were positioned in the 6 x 16-inch molds by use of a wooden template and held in place with steel wire and nylon strings. The 6 x 12-inch specimens were cast in standard molds except that those for the as-cast specimens contained 0.008-inch-thick copper inserts which were used for sealing the specimens.

(2) After mixing, the concrete was placed in the molds. The 6 x 12-inch specimens were cast and compacted as described by ASTM Specification C-192 and then vibrated for 3 seconds at a frequency of 3600 cycles per minute. The 6 x 16-inch specimens were cast horizontally and compacted by approximately 200 strokes of a 1/4-inch-diameter rod. A specially constructed curved trowel was used to finish the exposed longitudinal surface of the 6 x 16-inch specimens, which were then vibrated for 5 seconds on a vibrating table at a frequency of 3600 cycles per minute. The entire casting and compaction operation to this point took approximately 45 minutes.

(3) Four hours after casting, the 6 x 12-inch specimens were capped with neat cement and a glass plate was used to smooth the end surfaces. The exposed sides of the 6 x 16-inch specimens were also finished, with neat cement applied with the curved trowel.

Curing and Sealing

All specimens were completely covered with wet burlap immediately after casting and cured in the laboratory for 24 hours. Forms were removed after 24 hours and the specimens were stored in the curing room at 100 percent relative humidity for an additional 24 hours. Immediately after the forms were removed, the surfaces of the 6 x 16-inch specimens were scrubbed with a wire brush and a pumice stone to remove surface irregularities. All surface voids were filled with a neat cement paste. Subsequent curing and sealing procedures depended on the specimen type.

The sealing procedure included the application of two coats of epoxy to the surface of the specimens, 24 hours apart. For as-cast specimens the first coat of epoxy was applied 48 hours after casting; the first coat of epoxy for air-dried specimens was applied 81, 174, or 356 days after casting, depending on the age of loading. While the second coat of epoxy was still wet, an 0.008-inch-thick copper jacket was wrapped around the specimen and soldered to the steel end slugs and to itself along the longitudinal seam. Just prior to assembly of the specimens in the test units, a 6-inch-diameter, 0.12-inch-thick neoprene sleeve was slipped over the copper jacket of the specimens to be loaded biaxially or triaxially, for added protection against the possibility of oil penetrating the specimen. The ends of the neoprene jacket were sealed with liquid neoprene and clamped to the specimen with a 1/4-inch-wide stainless steel clamp.

MIXTURE DESIGN

The mixture design and all materials utilized in this investigation except water were furnished by the Concrete Division, Waterways Experiment Station, Jackson, Mississippi. Prior to shipping, the materials were proportioned into thirteen 12-cubic-foot batch quantities and placed in sealed containers.

The materials consisted of Type II cement and crushed fine and coarse limestone aggregates with a maximum size of 3/4 inches. The concrete was designed for a 28-day compressive strength of 6000 ± 600 psi for specimens cured while submerged in lime-saturated water (ASTM C-192). Mix proportions and a summary of the results of engineering tests on the materials are presented in Refs 3 and 7. A brief summary of the concrete design proportions is shown in Table 1.

EQUIPMENT AND INSTRUMENTATION

A detailed description and a discussion of the test equipment used in this experimental program are contained in Refs 3 and 7; therefore, the loading unit, hydraulic system, environmental control system, instrumentation, and recording system are discussed only briefly in this section.

TABLE 1. MIX DESIGN SUMMARY

Water-cement ratio, by weight	0.425
Cement content, sacks/cu yd	7.25
Maximum size of coarse aggregate, inches	3/4
Slump, inches	2

		Mix Proportion, Percent	
Material	Size Range	By Volume	By Weight
Cement	----	15.5	17.8
Fine aggregate	Sand	37.1	35.9
Coarse aggregate (A)	No. 4	14.2	13.9
Coarse aggregate (B)	3/8 inch	16.6	16.2
Coarse aggregate (C)	1/2 inch	16.6	16.2

Loading Unit

The schematic of the loading unit (Fig 1) shows all components of the loading systems. The radial load was applied directly to the sealed specimen by hydraulic oil pressure contained within a 1-inch-thick steel pressure jacket; the axial load was applied by a hydraulic ram. Thus, the triaxial loading unit consisted of both an axial and a radial loading system, each of which could be varied independently. The axial loading frame without the pressure jackets was used for the uniaxial case. The radial pressure jacket without the axial loading frame was used for the biaxial case (Fig 2b).

Each loading unit contained two specimens from the same batch, one as-cast and one air-dried, which were simultaneously subjected to the same temperature and stress conditions. The relative positions of the as-cast and air-dried specimens within the frame were assigned randomly in order to minimize bias in the results due to specimen location. The biaxial specimens were also simultaneously loaded in pairs under identical conditions.

The loading system developed for this investigation was generally satisfactory; however, preliminary tests (Refs 4, 5, and 6) revealed that the axial stresses were less than those indicated by the pressure gage, due to frictional losses in the hydraulic-mechanical pressure system. Therefore, each of the loading units was calibrated with a standard load cell. The axial stress for the various units ranged from 90 to 97 percent of the desired stress and the average axial stresses for the units were 0, 545, 1080, 2185, and 3460 psi. The variation of the axial stresses with time was monitored with mechanical dial gages and found to be negligible.

Hydraulic System

Hydraulic pressure was supplied to the loading units by using the 100-psi air pressure available in the laboratory to drive oil pressure intensifiers. The hydraulic system consisted of a pressure control console, eight pressure manifolds to the loading units and the necessary return lines. The pressure control console housed the pressure control valves, pressure intensifiers, air reservoir, auxiliary air compressor, and pressure gages for the four different pressures.

The pressure system was designed for 5000-psi pressure and consisted of hydraulic pressure pipes with flexible pressure hoses to the test units. A dual system was employed for each of the four pressures (600, 1200, 2400, and

3600 psi). One manifold system supplied pressure to the 75° F laboratory and the other to the 150° F temperature control room. Each manifold system contained a return line with connections to each test unit to allow oil to be circulated in order to remove air from the system and prevent the control valves from sticking.

The control system automatically regulated the pressure to within ± 5 percent of the assigned gage pressure. Each of the eight pressure lines could be independently controlled, and each test unit had separate controls.

Environmental Control

An attempt was made to maintain a constant temperature and relative humidity throughout the test period. The tests performed under the nominal 75° F test condition were conducted in an air-conditioned laboratory, while the tests performed under the nominal 150° F test condition were conducted in a temperature chamber which was designed to maintain a constant temperature anywhere in the range of -20° F to 150° F. The relative humidity was maintained by the air-conditioning system at an average value of about 60 percent, although it fluctuated from about 50 to 65 percent. This fluctuation was important only during the curing periods, since the air-dried specimens were not sealed until just prior to loading.

Vibrating Wire Strain Gage

A Perivale vibrating wire strain gage, PC 641, was used to measure strains. This gage was approximately 4 inches long, had a gage length of approximately 3.5 inches, was stable over a relatively long period of time, and was relatively inexpensive.

A cross section of the Perivale gage is shown in Fig 4. The gage basically consisted of a hollow brass tube with a steel cap at each end; a steel wire was tensioned between the caps. The gage measured strain, or change in strain, by detecting changes in the frequency of vibration of the wire. The frequency of the wire was measured by an electronic comparator which, when activated, plucked the wire by means of an electromagnet in the gate. A magnetic coil was used to measure the vibration of the wire and the frequency was compared with a standard frequency generated in the comparator. From this comparison, the frequency of the gage wire could be estimated and used to calculate the change in strain by means of the following equation:

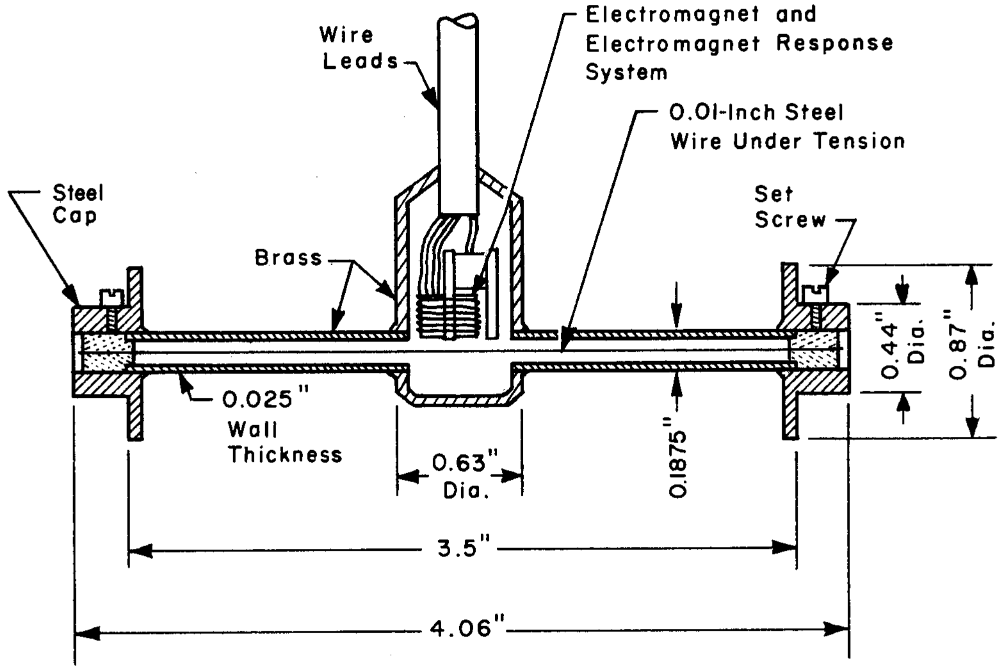


Fig 4. Cross section of Perivale vibrating wire strain gage.

$$\Delta\varepsilon = \varepsilon_i - \varepsilon_f = K\left(F_i^2 - F_f^2\right)$$

where

K = the gage factor,

F_i = the initial (or reference) frequency,

F_f = the frequency at the strain point desired,

ε_i = the initial (or reference) strain,

ε_f = the strain point desired.

The Perivale gage, when cast in concrete, had a gage factor of 1.24×10^{-3}, which was determined experimentally by the manufacturer. The range of the gage was approximately 1000 microunits of strain and it could be read to an accuracy of one microunit of strain. The gage was supplied with an initial frequency or wire tension which allowed strain measurements ranging from 285 microunits in tension to 1050 microunits in compression.

Temperatures in the creep and shrinkage specimens were measured throughout the test period by a wheatstone bridge circuit in the comparator which measured the change in resistance of the electromagnetic coil in each gage. Thus, two internal temperature readings were recorded for each specimen. An equation relating coil resistance to temperature change was provided by the manufacturer.

For recording strain and temperature data, the comparator was connected to a switchboard. Each gage was connected to the switchboard by an individual cable, and the strain or temperature in each one of the 204 gages (102 specimens) was measured at a central location.

OUTLINE OF EXPERIMENTAL PROCEDURE

The actual test program began with the casting of Batch A on October 29, 1968. Another batch was cast each week, and each was designated in order, through Batch G. Batches H and I were cast in June 1969. Batches A through G provided concrete for specimens of the 90-day loading condition, while H and I provided concrete for specimens of the 183 and 365-day loading conditions and for replacements of specimens which failed in Batches A through G. The casting and testing procedures were identical for all batches. All specimens cured for 90 days were loaded for a period of 12 months, after which the load was removed and observations of creep recovery continued for five months. Specimens cured for 183 or 365 days were loaded for an indefinite period of time.

The loading and unloading operations for each batch followed the same procedure. Each as-cast specimen was loaded or unloaded simultaneously with its companion air-dried specimen. Both axial and radial loads were applied or removed at the same time, with maximum stress applied or removed at a rate of 35 psi per second. The ratio of the axial to radial loads during loading or unloading was maintained constant and equal to the ratio of the final axial and radial loads. The gages in each test unit were read in the following order: as-cast axial gage, as-cast radial gage, air-dried axial gage, air-dried radial gage.

In addition, the unconfined compressive and tensile strengths were determined for various environmental conditions during the test period. The compressive strength was determined at 28, 90, 183, 365, and 538 days after casting (ASTM C-39). Tensile strengths at 28, 90, and 538 days were determined for Batches B through F using the indirect tensile test (ASTM C-496).

EXPERIMENTAL DESIGN

Specimens cured for 90 days were randomly assigned to the first seven batches, with the restriction that each batch contain specimens for both test temperatures and an equal number of specimens for each curing history. Batches H and I provided specimens for the 183 and 365-day loading conditions and replacements for specimens cured for 90 days that failed before or during the test. The specimens in each batch were prepared and tested in a random numerical sequence in order to eliminate bias resulting from the casting and testing operations. The various combinations of test variables for the creep and shrinkage specimens are shown in Table 2.

SPECIMENS CONSIDERED IN THIS REPORT

The results from only a portion of the overall experiment are considered in detail in this report although the results from the overall investigation are briefly summarized. The purpose of this report is to summarize the

TABLE 2. EXPERIMENTAL DESIGN FOR CREEP AND SHRINKAGE SPECIMENS

Age of Loading, Days*	Temperature, °F	Axial Load, psi	Radial Load, psi	Creep Specimens**		Companion Shrinkage Specimens**		
				As-cast	Air-dried	As-cast	Air-dried	
90	75	0	600	F-13	F-42	F-23	F-17	
		0	3600	H-22r	H-14r	H-24	H-1	
		600	0	E-39	E-40	E-28	E-23	***
		600	600	E-5	E-13	E-28	E-23	
		600	3600	G-35	G-30	G-18	G-10	
		1200	1200	C-16x	C-17	C-39	C-6	
		1200	2400	B-41	B-42	B-29	B-23	
		2400	0	B-7	B-19	B-29	B-23	***
		2400	600	C-23	C-11	C-39	C-6	
		2400	2400	F-9	F-30	F-23	F-17	
		3600	1200	D-26	D-44	D-20	D-33	
		3600	3600	D-31	D-40	D-20	D-33	
	150	0	600	A-35	I-13rf	A-22	I-1	
		0	1200	I-27r	D-3	I-21	D-23	
		0	2400	E-43	E-1	E-10	E-42	
		0	3600	I-16r	I-30rf	I-21	I-1	
		600	0	B-4	B-1	B-13	B-26	
		1200	0	D-15	D-22	D-12	D-23	
		1200	1200	C-12	C-46x	C-41	C-36	
		1200	2400	D-2x	D-41	D-12	D-23	
		2400	0	F-33	F-34	F-15	F-21	
		2400	600	E-18	E-4	E-10	E-42	
		2400	2400	G-9	G-19	G-1	G-21	
		3600	0	B-16	B-5	B-13	B-26	
		3600	3600	F-20	F-6	F-15	F-21	
183	75	600	0	H-45	I-39	H-28	I-17	***
		2400	0	H-34	I-20	H-28	I-17	
365	75	600	0	H-5	H-31	H-28	H-35	***
		2400	0	H-24	H-17	H-28	H-35	

* Age of loading for creep specimens

** Specimen designation: the letter indicates the batch and the numeral indicates the specimen within the batch

*** Specimens used in the evaluation of the effect of curing time and the long term creep behavior

r Replacement specimens

x Radial pressure zero ($\sigma_r = 0$) due to oil leak in specimen

f Specimen failed shortly after loading

findings of a study to evaluate the long term creep behavior of concrete subjected to sustained loads for 4.5 and 5 years. A previous report (Ref 9) considered the behavior after 2 and 2.5 years under load.

The twelve creep specimens and the corresponding shrinkage specimens involved in this portion of the analysis are designated in Table 2. These creep specimens were subjected to a sustained uniaxial stress of 600 or 2400 psi after curing for either 90, 183, or 365 days. Curing procedures were either as-cast or air-dried. All specimens were cured and tested at 75°F.

CHAPTER 3. SUMMARY OF EXPERIMENTAL RESULTS AND FINDINGS

This chapter contains a summary of the data obtained from the portion of the investigation primarily associated with the specimens cured for 90 days prior to loading, most of which has been presented and discussed in previous project reports (Refs 1, 2, 7, and 9). Nevertheless, these results are briefly summarized in order to completely describe the overall experiment and to incorporate information for the evaluation of the observed creep behavior. Test results and findings concerned with creep recovery are summarized and discussed in Ref 2.

The experimental results obtained from the twelve specimens which were tested to obtain information on the effects of curing time and long term creep behavior of the concrete are contained in Chapter 4 along with the discussion of the analysis and findings.

STRENGTH

The compressive strengths of all 252 specimens were determined in accordance with ASTM C39-66 testing procedures, and the tensile strengths of 76 specimens were obtained in accordance with ASTM C496-69.

The average compressive and tensile strengths for the nine batches of concrete are shown in Table 3. The individual compressive and tensile strengths of the specimens tested at ages of 183 days or less are presented in Appendices B and C of Ref 7, while the individual strengths at 365 and 538 days are contained in Appendix A of Ref 2.

The average compressive strength of the standard cured specimens at 28 days was 6420 psi, which was within the design strength range of 6000 ± 600 psi, and the average compressive strength at 90 days was 8220 psi. The air-dried specimens had a higher average compressive strength than the as-cast specimens up to 90 days after casting. Subsequent to this time, the as-cast specimens were stronger. The average tensile strength of specimens in all batches increased slightly with age.

TABLE 3. AVERAGE COMPRESSIVE AND TENSILE STRENGTHS

	Age at Testing	Curing Conditions	Temperature °F	Average Strengths of Batches, psi									Avg Strengths of all Batches psi
				A	B	C	D	E	F	G	H	I	
Compressive	28	Standard	75	6760	6650	6140	6200	6520	6510	6440	6340	6260	6420
		As-Cast		6580	4710	5700	5980	5410	5650	5940	5650	5790	5710
		Air-Dried		7060	6200	6520	6640	6540	6680	6570	6320	6440	6550
	90	Standard	75	8550	8690	8290*	8540	8200	8090	7730	8110	7870	8220
		As-Cast		6880	6110	6430*	6500	7290	7410	7460	6330	6160	6640
		Air-Dried		6960	7790	7370*	7790	7420	7870	7460	7280	7060	7450
	183	As-Cast	75	8260	-	-	-	-	-	7620	7660	6960	7630
			150	8120	-	-	-	-	-	8280	-	7730	8040
		Air-Dried	75	7030	-	-	-	-	-	7310	7470	7200	7250
			150	7760	-	-	-	-	-	7100	-	6960	7270
	365	As-Cast	75	8840	-	-	-	-	-	8190	6930	7340	7830
			150	7600	-	-	-	-	-	8310	-	7660	7860
		Air-Dried	75	7480	-	-	-	-	-	7810	6860	7590	7440
			150	7010	-	-	-	-	-	7860	-	7170	7350
	538	As-Cast	75	8430	-	-	-	-	-	9010	7530	7170	8040
			150	9130	-	-	-	-	-	8270	-	7470	8290
		Air-Dried	75	8570	-	-	-	-	-	8070	7550	7470	7920
			150	7940	-	-	-	-	-	7550	-	7860	7780
Tensile	28	Standard	75	-	630**	580	620	570	550	-	-	-	590
		As-Cast		-	-	-	520	-	-	-	-	-	-
		Air-Dried		-	560**	-	530	-	-	-	-	-	-
	90	Standard	75	-	540	680	510	710	690	-	-	-	630
		As-Cast		-	550	610	530	590	590	-	-	-	570
		Air-Dried		-	540	580	550	550	580	-	-	-	560
	538	As-Cast	75	-	600	590	-	550	490	-	-	-	560
			150	-	600	550	-	620	610	-	-	-	600
		Air-Dried	75	-	760	740	-	650	690	-	-	-	710
			150	-	660	580	-	610	660	-	-	-	630

* Batch C tested at 83 days.

** Only one sample used.

INSTANTANEOUS STRAINS AND ELASTIC PROPERTIES

The instantaneous or elastic strains due to the applied load were determined by taking readings just prior to loading and immediately after the maximum load had been applied. Since the four gages could not be read simultaneously, there was a delay in obtaining some of the readings. The instantaneous strains were estimated by extrapolating the strain-time relationships to obtain the strains at time zero. These estimated strains generally were one to five microunits less than the measured values.

Moduli of elasticity and Poisson's ratios were calculated from theory of elasticity; values for each specimen are contained in Ref 2. The moduli of elasticity and Poisson's ratios of uniaxially and biaxially loaded specimens were satisfactory, while values for the triaxially loaded specimens were not consistent, probably because the relationships used to calculate the values are sensitive to small errors for a hydrostatic loading condition.

Excluding hydrostatically loaded specimens, the average moduli of elasticity for the as-cast and air-dried specimens loaded at 75° F were 5.86×10^6 and 5.50×10^6 psi, respectively. Specimens loaded at 150° F had lower modulus values, with the average values for the as-cast and air-dried specimens being 5.74×10^6 and 4.87×10^6 psi, respectively.

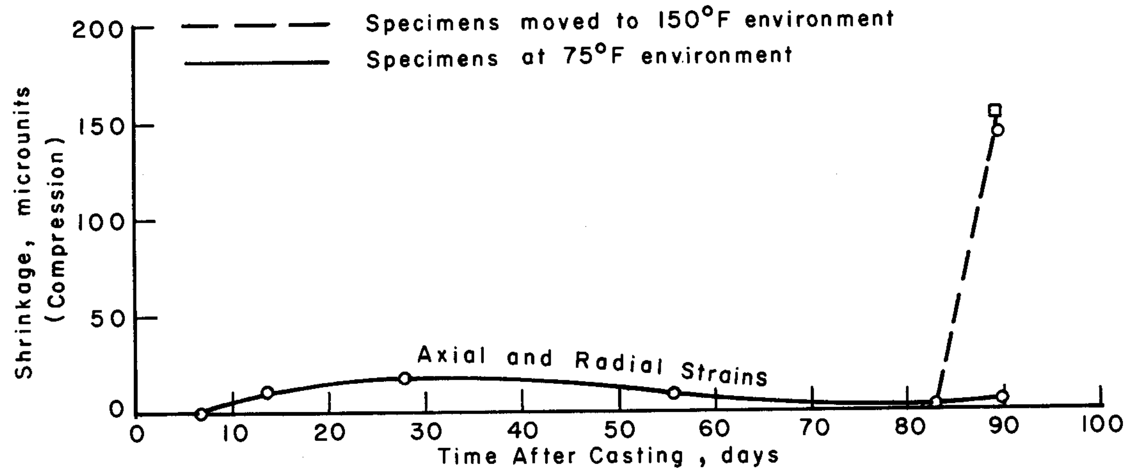
Poisson's ratio was not significantly affected by curing history or temperature although the average value was slightly smaller at 150° F than at 75° F. The average Poisson's ratio was 0.25.

SHRINKAGE STRAINS

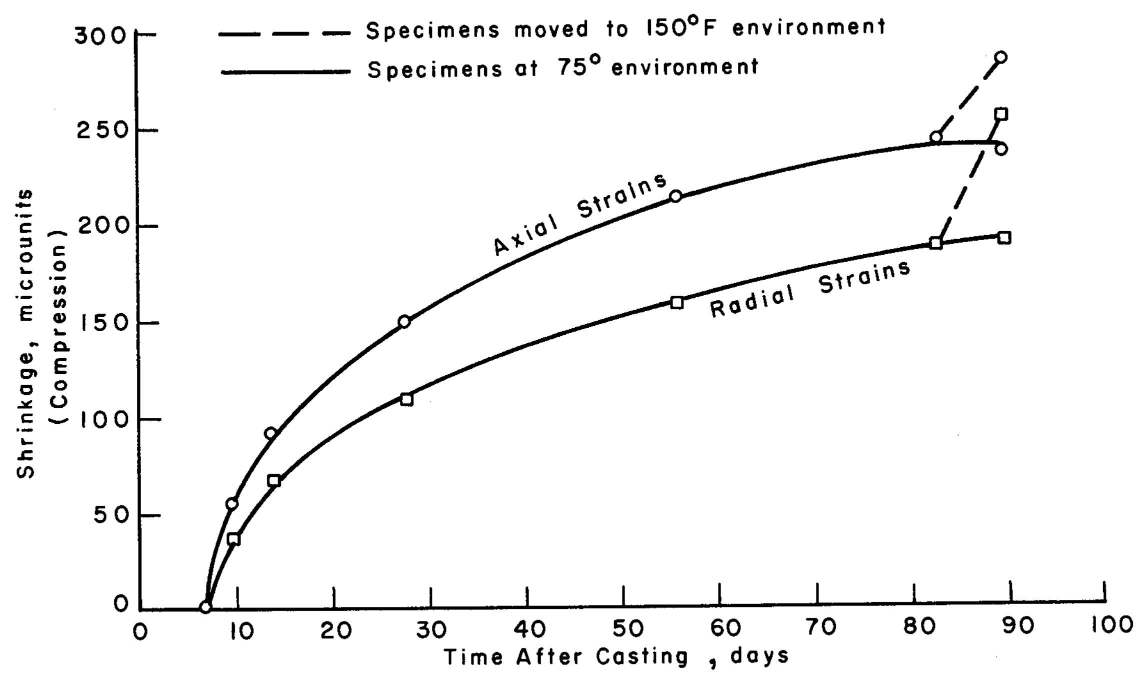
To estimate creep strains it was necessary to measure shrinkage strains during the creep and the recovery periods. In order to interpret these shrinkage strains, it was necessary to evaluate shrinkage strains during the curing period.

During the Curing Period

Estimates of the relationships between shrinkage strain and time for the as-cast and air-dried specimens during the curing period were obtained by averaging the shrinkage strains in both the shrinkage and creep specimens from Batches A through G (Fig 5). In these relationships the seven-day reading was considered as the initial reference point, since the curing and handling procedures during the first seven days were different.



(a) As-cast specimens.



(b) Air-dried specimens.

Fig 5. Average shrinkage strains for as-cast and air-dried specimens during the 90-day curing period.

The average axial and radial strains of the as-cast specimens were essentially zero throughout the curing period (Fig 5a) and these specimens did not show any significant loss of water during the curing period. On the other hand, the average strains of the air-dried specimens showed a continuous increase (Fig 5b) accompanied by continuous loss of water during the first 82 days, at the end of which the specimens were sealed in copper. At that time, the average axial and radial shrinkage strains for the air-dried specimens were approximately 240 and 190 microunits respectively, and the loss of water was between 8 and 11 ounces. The apparent increase in strains between 83 and 90 days for as-cast and air-dried specimens subjected to 150° F was due to a difference in thermal characteristics of the gage and concrete and is discussed in Ref 7.

During the Testing Period

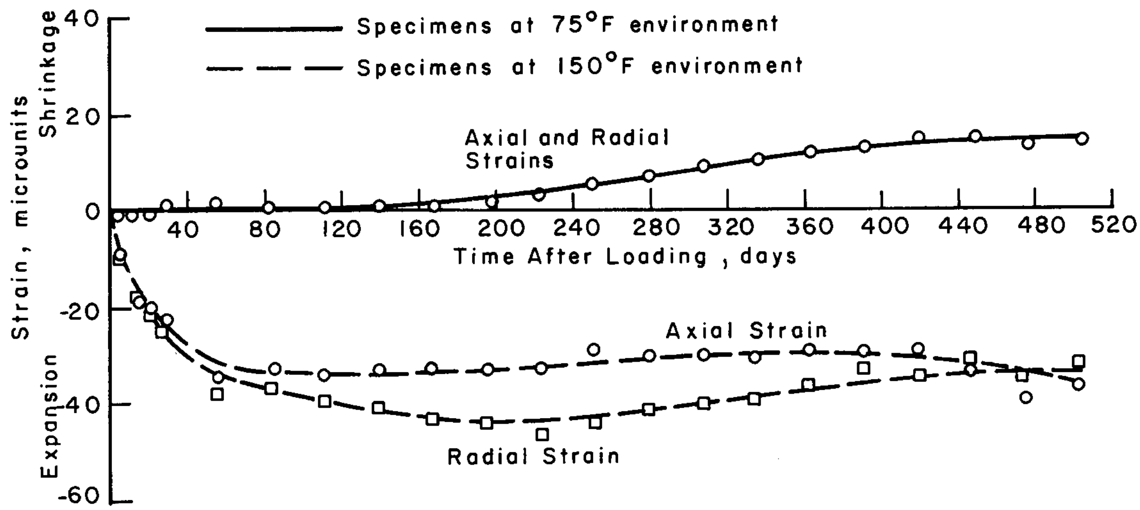
Shrinkage strains were measured during the loading period in order to estimate creep strain, by separating the total time-dependent strain into that due to moisture loss and that due to load. Average shrinkage curves for the as-cast and air-dried shrinkage specimens from Batches A through G are shown in Fig 6.

Essentially no shrinkage occurred in the as-cast specimens (Fig 6a) at 75° F; however, at 150° F the specimens exhibited expansion rather than shrinkage. Most of this expansion occurred during the first 84 days of the loading period, at the end of which the axial and radial gages indicated tensile strains of 33 and 37 microunits, respectively. During the remainder of the loading period, very little additional strain was detected.

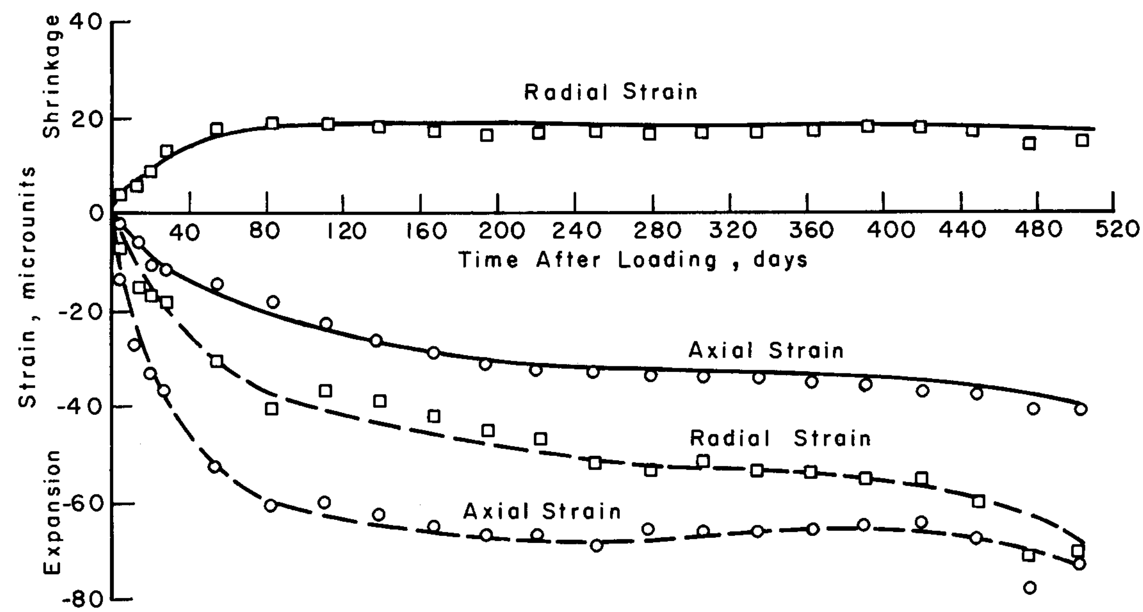
The shrinkage behavior associated with specimens subjected to the 150° F temperature is attributed to the fact that the gage and the concrete are not compatible when subjected to temperature change. This effect is discussed in detail in Ref 7.

The axial and radial shrinkage strains in the air-dried specimens at 75° F (Fig 6b) increased at a decreasing rate throughout the entire loading period. However, the radial strains were compressive (shrinkage) while the axial strains were tensile (expansion). Nevertheless, the magnitudes of the strains after 12 months were relatively small, with the axial gage indicating 34 microunits (tension) and the radial gage 18 microunits (compression).

The shrinkage strain relationships for the air-dried specimens at 150° F were similar to those of the as-cast specimens at the same temperature, although the strains were larger. These specimens expanded continuously at a decreasing



(a) As-cast specimens.



(b) Air-dried specimens.

Fig 6. Average shrinkage strains during the loading and unloading periods for specimens loaded at 90 days.

rate. At the end of the 12-month loaded period the axial and radial strains were 67 and 53 microunits (expansion), respectively.

CREEP STRAINS

Creep strains were estimated by subtracting the instantaneous strains and the shrinkage strains from the total strains. Thus it was assumed that the instantaneous (elastic) strain for each specimen was constant and did not vary with time and that the time-dependent strains, i.e., shrinkage and creep, were not interrelated. The creep strain-time relationships for the specimens loaded at 90 days are shown in Figs A.1 through A.19 in Appendix A of Ref 1 and the data are summarized in Appendix G of Ref 7.

The creep rate was much larger during the early portion of the loading period, but about three months after loading the creep strain became relatively constant and no significant change occurred during the remaining nine months of the loaded period.

A more comprehensive evaluation of the effects of moisture condition and testing temperature is contained in Ref 7. The findings, however, can be briefly summarized as follows:

(1) At a constant temperature, air-dried specimens had higher creep strains than as-cast specimens.

(2) Both as-cast and air-dried specimens tested at 150° F exhibited higher creep strains than those tested at 75° F.

(3) In uniaxially and biaxially loaded specimens at both temperatures, creep strains occurred in the direction perpendicular to the direction of the applied stress, indicating a creep Poisson's effect.

CREEP POISSON'S RATIOS

Excluding specimens subjected to hydrostatic stress conditions, creep Poisson's ratio averaged about 0.16, which was approximately 30 percent less than the average instantaneous (elastic) Poisson's ratio. Creep Poisson's ratio for air-dried specimens was approximately 30 percent less than for as-cast concrete. Values 84 days after loading ranged from 0.10 to 0.28 and averaged 0.17; values 364 days after loading ranged from 0.11 to 0.41 and averaged 0.23.

CHAPTER 4. EVALUATION OF CURING TIME AND LONG TERM CREEP

This chapter contains a discussion of the findings of an analysis of the instantaneous and time-dependent strains obtained from the 12 creep specimens associated with the portion of the overall investigation to evaluate the effects of curing time and long term creep behavior.

These 12 specimens included both the as-cast and air-dried curing histories; two uniaxial stress levels (600 and 2400 psi); and three curing times (90, 183, and 365 days). Specimens loaded after 90 days of curing were unloaded after 12 months; the 183 and 365-day specimens were not unloaded and to date have been subjected to load for periods of 5 and 4.5 years, respectively.

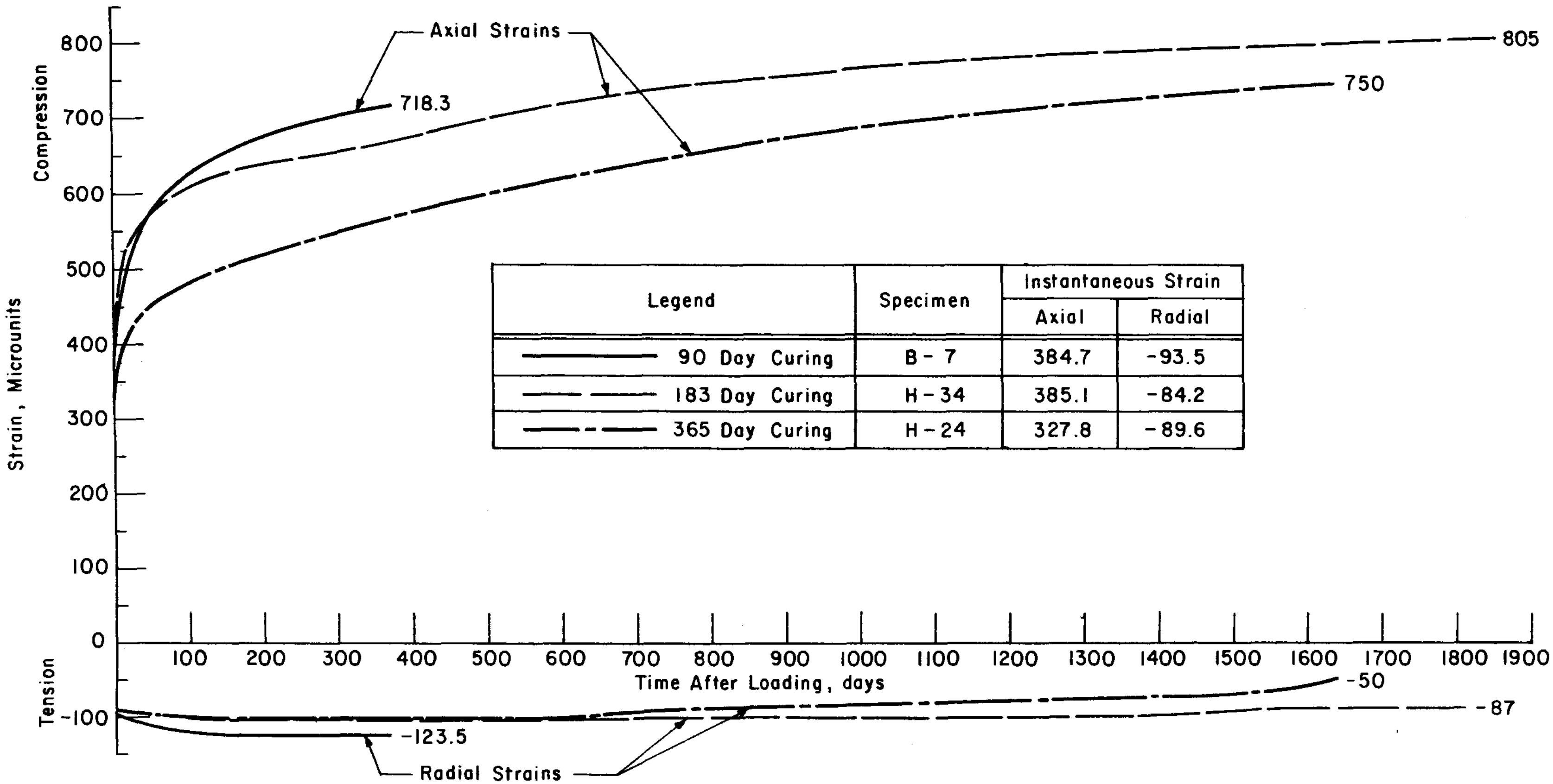
TOTAL STRAIN-TIME RELATIONSHIPS

The total strain-time relationships for the 12 specimens involved in the portion of the study to evaluate long term creep behavior are shown in Figs 7 through 10.

These relationships are typical of strain-time relationships for concrete with the possible exception of the relationships for the specimens loaded with a uniaxial stress of 600 psi. In some of these low stress relationships strain decreases rather than increases with time. This is attributed to the shrinkage which probably occurred and which would have been large relative to the creep strain due to load. The total axial strains and, in most cases, the total radial strains were found to be still increasing after 4.5 to 5 years in the specimens loaded with a uniaxial stress of 2400 psi.

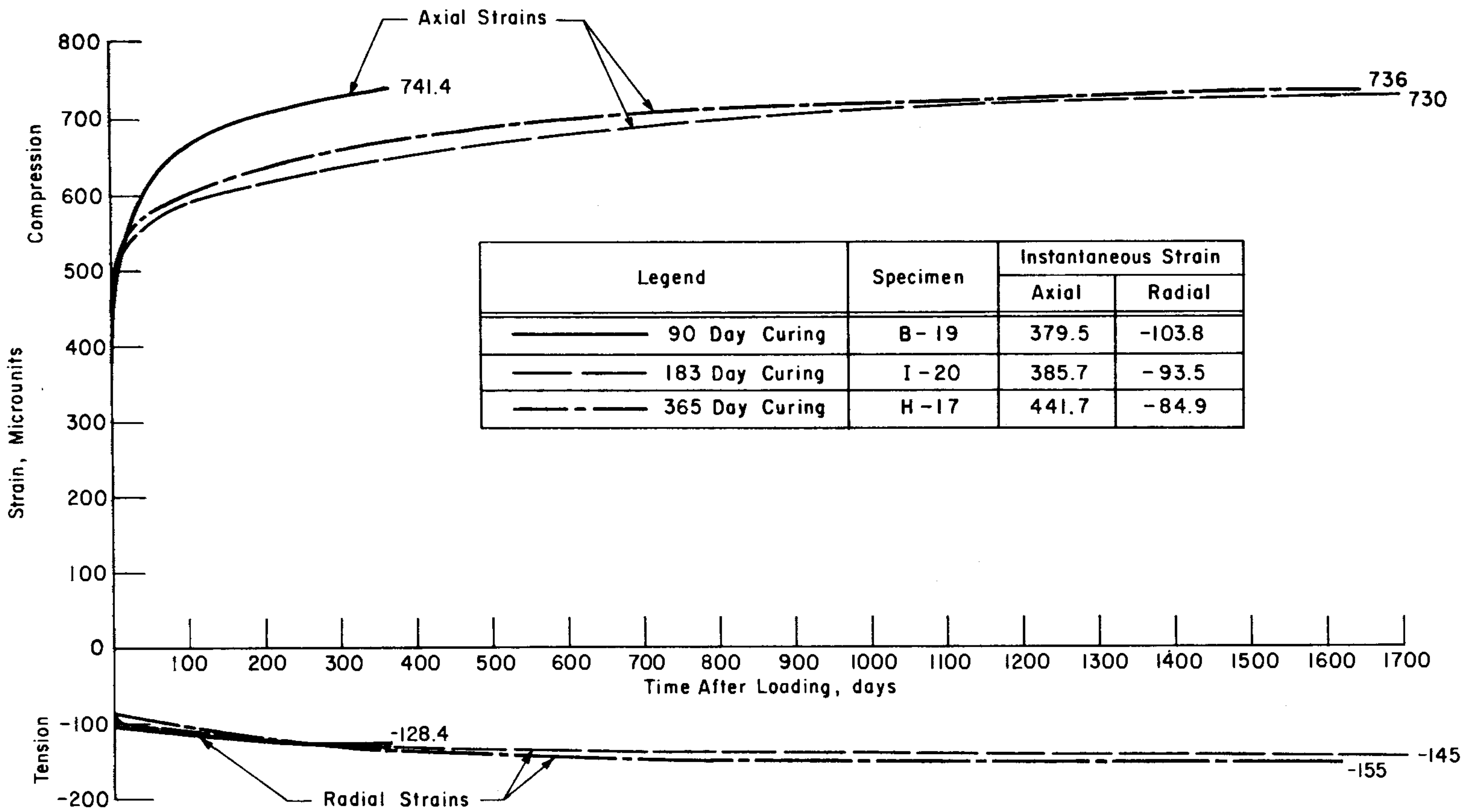
SHRINKAGE STRAINS

The strain-time relationships for the shrinkage specimens associated with the 183-day and 365-day creep specimens are shown in Figs 11 and 12. Specimen H-28 served as the shrinkage specimen for both the 183-day and 365-day creep specimens. Unfortunately this specimen apparently began to lose moisture approximately 400 days after casting, since the shrinkage strains began to



Legend	Specimen	Instantaneous Strain	
		Axial	Radial
90 Day Curing	B - 7	384.7	-93.5
183 Day Curing	H - 34	385.1	-84.2
365 Day Curing	H - 24	327.8	-89.6

Fig 7. Total axial and radial strain relationships for as-cast specimens with uniaxial stress of 2400 psi.



Legend	Specimen	Instantaneous Strain	
		Axial	Radial
———— 90 Day Curing	B-19	379.5	-103.8
— — — 183 Day Curing	I-20	385.7	-93.5
—— - —— 365 Day Curing	H-17	441.7	-84.9

Fig 8. Total axial and radial strain relationships for air-dried specimens with uniaxial stress of 2400 psi.

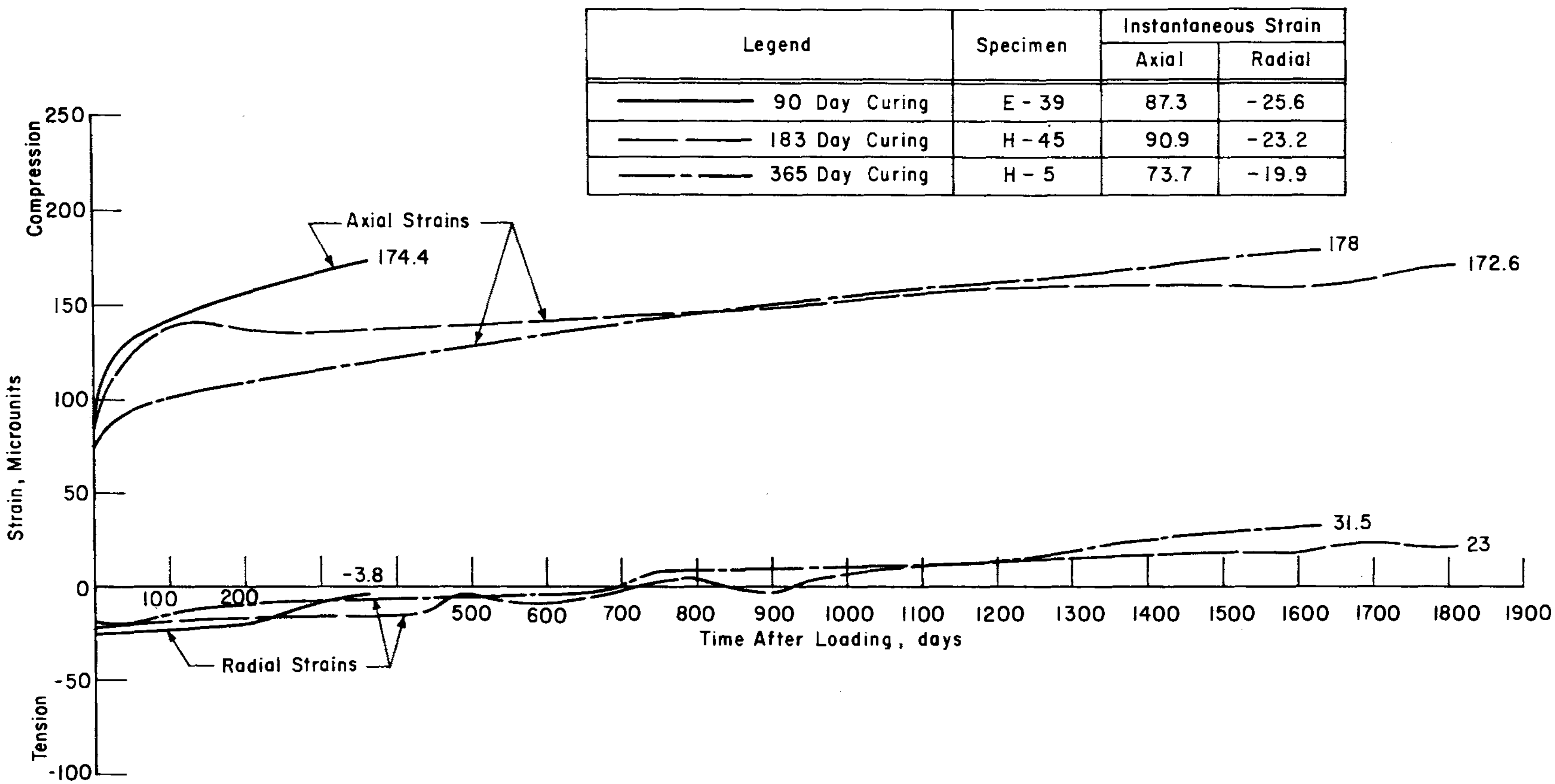
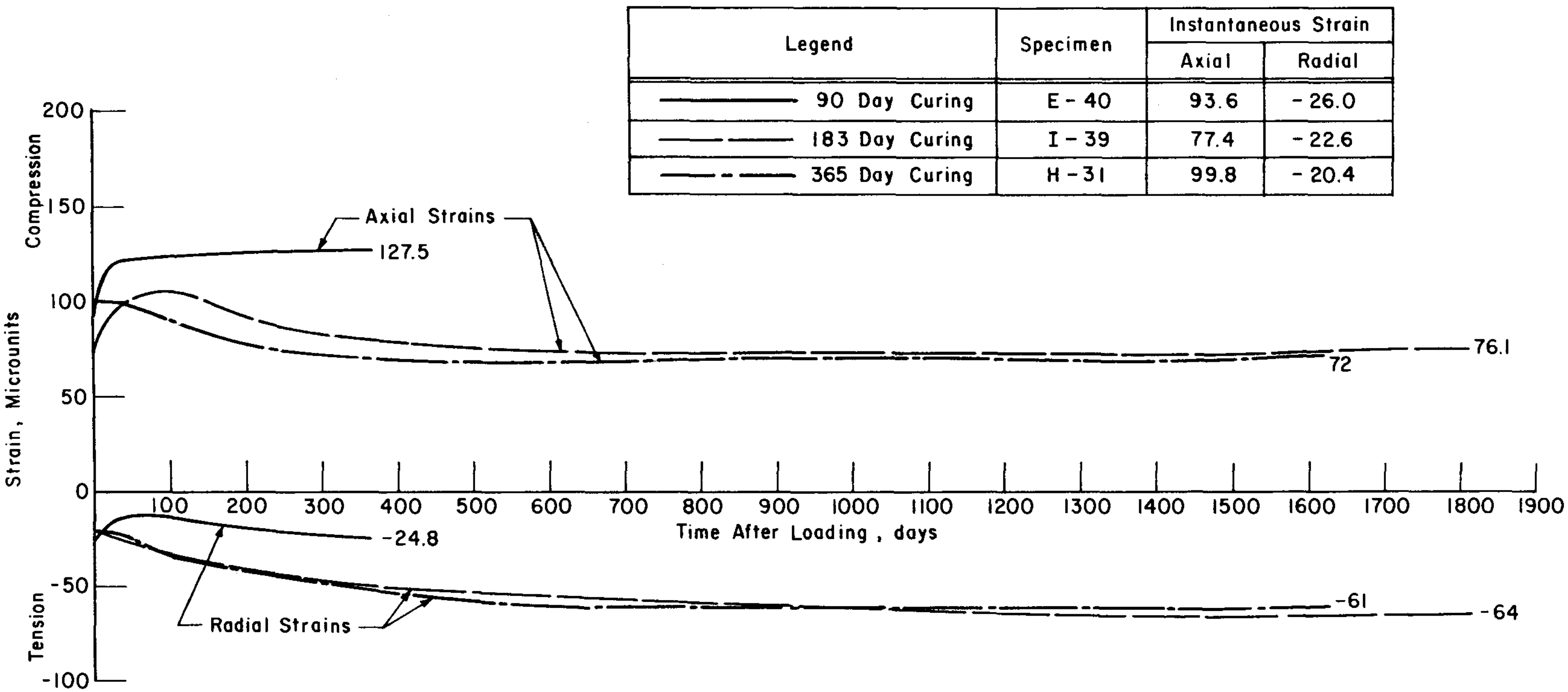


Fig 9. Total axial and radial strain relationships for as-cast specimens with uniaxial stress of 600 psi.



Legend	Specimen	Instantaneous Strain	
		Axial	Radial
——— 90 Day Curing	E-40	93.6	-26.0
— — 183 Day Curing	I-39	77.4	-22.6
—-— 365 Day Curing	H-31	99.8	-20.4

Fig 10. Total axial and radial strain relationships for air-dried specimens with uniaxial stress of 600 psi.

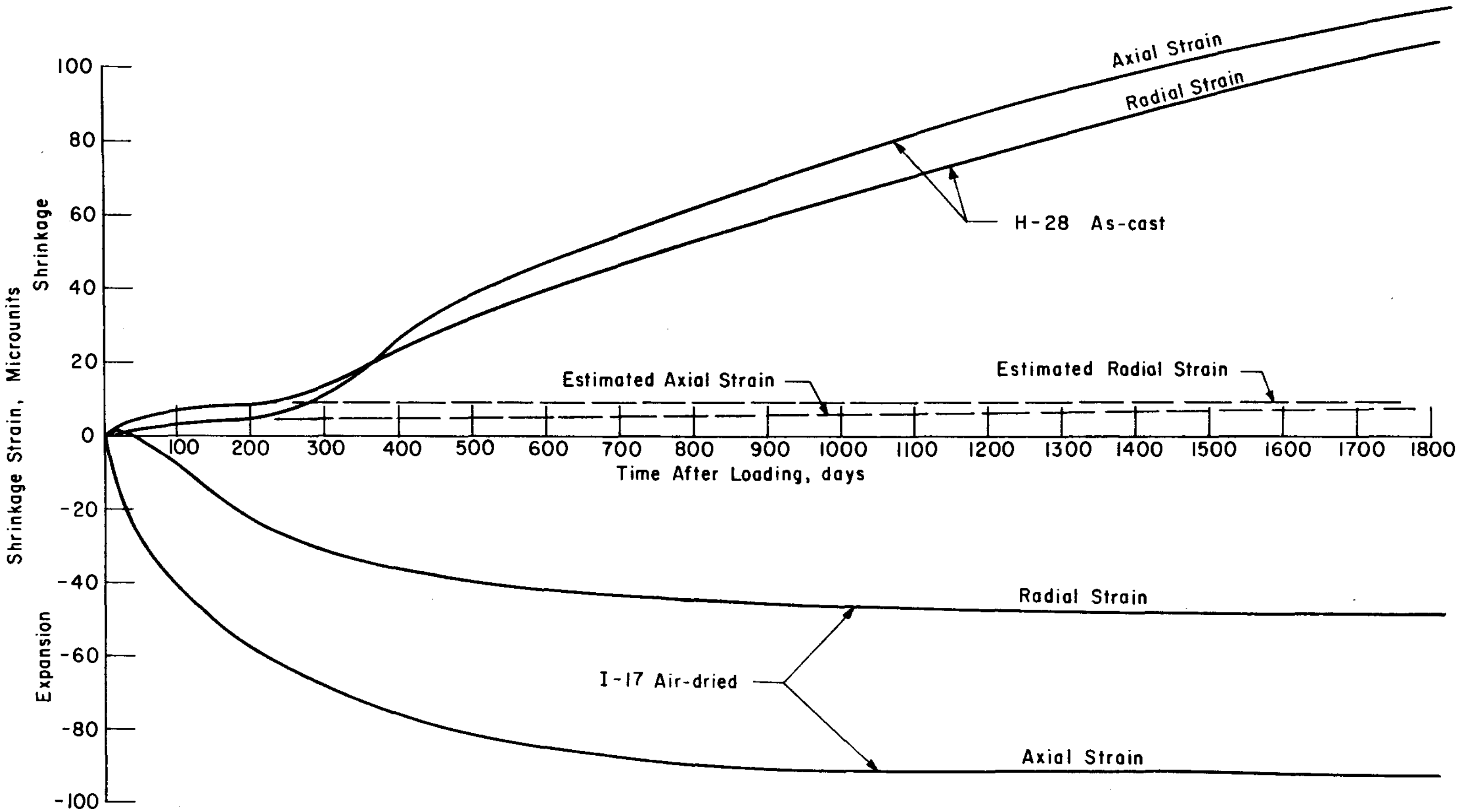


Fig 11. Shrinkage strains during the loaded periods for creep specimens cured 183 days.

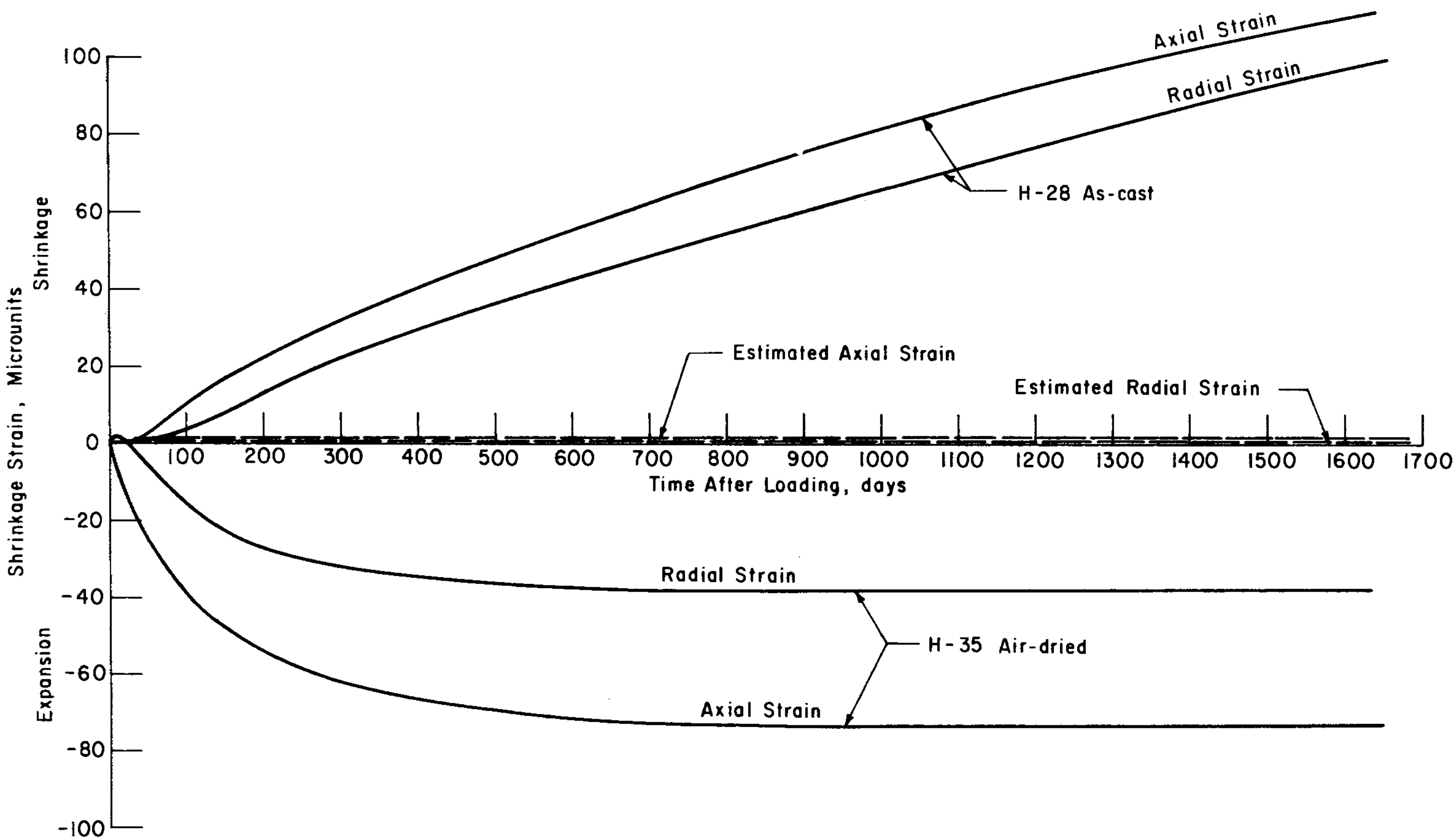


Fig 12. Shrinkage strains during the loaded periods for creep specimens cured 365 days.

increase significantly at about that time. In the portion of the experiment devoted to the evaluation of the creep behavior of concrete cured 90 days prior to loading, the as-cast shrinkage specimens at 75°F exhibited very little shrinkage strain during the entire creep (loaded) and recovery (unloaded) period (Fig 6a). Therefore, a shrinkage curve was constructed by extrapolating the shrinkage strain-time relationship prior to about 400 days after casting and assuming that essentially no additional moisture was lost (Fig 11).

Another difference between the behavior of the shrinkage specimens in this portion of the experiment and those used in the portion involving a 90-day curing period is the fact that the radial strains for the air-dried specimens (I-17 and H-35) were negative, indicating expansion, while previously the average radial strain relationship was positive, indicating shrinkage.

Thus, the shrinkage relationships are subject to question and additional specimens would be needed in order to estimate shrinkage. Nevertheless, the error in the analysis of the creep behavior of specimens subjected to a uniaxial stress of 2400 psi is probably small, since the strains resulting from this load are relatively large. However, the error will have a significant effect on the estimated creep behavior of the specimens loaded with a uniaxial stress of 600 psi. Therefore, emphasis will be placed on the creep behavior of the specimens subjected to a stress of 2400 psi.

INSTANTANEOUS STRAINS AND PROPERTIES

The instantaneous radial and axial strains for the 12 specimens were estimated by taking a reading just prior to loading and immediately after loading and are shown in Table 4. It appeared that the magnitude of the instantaneous strains was not affected by the length of curing time prior to loading nor by the curing history, although the instantaneous axial strains of the air-dried specimens loaded 365 days after casting were substantially larger than the instantaneous axial strains in the other 10 specimens. The average instantaneous axial and radial strains for specimens at 600 psi were 87.1 and -23.0 microunits respectively; at 2400 psi the corresponding values were 383.9 and -91.6 microunits.

Moduli of elasticity and Poisson's ratios for all 12 specimens were calculated from these instantaneous strains and the average axial stress for all of the uniaxial test units used in the experiment, 545 and 2185 psi. These

TABLE 4. INSTANTANEOUS AXIAL AND RADIAL STRAINS (Ref 9)

(a) Axial Strains, Microunits

Stress,* psi	Curing Time and History						Average
	90 days		183 days		365 days		
	As-cast	Air-dried	As-cast	Air-dried	As-cast	Air-dried	
600	87.3	93.4	90.9	77.4	73.7	99.8	87.1
2400	384.7	378.6	385.1	385.7	327.8	441.7	383.9
Average	236	236	238	231.6	207.5	270.8	
	236		234.8		239.2		

(b) Radial Strains, Microunits

Stress,* psi	Curing Time and History						Average
	90 days		183 days		365 days		
	As-cast	Air-dried	As-cast	Air-dried	As-cast	Air-dried	
600	-25.6	-26.0	-23.2	-22.6	-19.9	-20.4	-23.0
2400	-93.5	-103.6	-84.2	-93.5	-89.6	-84.9	-91.6
Average	-59.5	-64.8	-53.7	-58.0	-54.6	-52.6	
	-62.2		-55.8		-53.6		

*The average stresses were 545 psi and 2185 psi.

TABLE 5. INSTANTANEOUS MODULUS OF ELASTICITY, 10^6 PSI (Ref 9)

Stress,* psi	Curing Time and History					
	90 days		183 days		365 days	
	As-cast	Air-dried	As-cast	Air-dried	As-cast	Air-dried
600	6.24	5.83	5.99	7.04	7.39	5.46
2400	5.67	5.77	5.67	5.66	6.66	4.95
Average	5.95	5.80	5.83	6.35	7.02	5.20
	5.87		6.09		6.10	

*Values were calculated using average stresses of 545 and 2185 psi

TABLE 6. INSTANTANEOUS POISSON'S RATIO (Ref 9)

Stress,* psi	Curing Time and History					
	90 days		183 days		365 days	
	As-cast	Air-dried	As-cast	Air-dried	As-cast	Air-dried
600	0.293	0.278	0.255	0.292	0.270	0.204
2400	0.243	0.274	0.219	0.242	0.273	0.192
Average	0.268	0.276	0.237	0.267	0.272	0.198
	0.272		0.252		0.235	

*Values were calculated using average stresses of 545 and 2185 psi properties are summarized in Tables 5 and 6. Since the strains were not significantly different for the various conditions, the moduli and Poisson's ratios did not vary. The average modulus of elasticity and Poisson's ratio were 6.03 x 10^6 psi and 0.23, respectively, which were essentially equal to the average values obtained from the 90-day creep specimens.

CREEP STRAINS

The creep strain-time relationships for the 12 specimens, shown in Figs 13 through 16, were obtained by subtracting the instantaneous strain and the estimated shrinkage strain from the total strain at any given time. The axial creep strain-time relationships for specimens subjected to 2400 psi are shown in Fig 17.

Effect of Loading Age

A comparison of the creep strain-time relationships for specimens loaded with a nominal uniaxial stress of 2400 psi (Figs 13 and 14) indicates a definite effect of curing time prior to loading. Specimens subjected to load after a longer curing period exhibited smaller axial and radial creep strains. In one case, however, this effect diminished with time. In fact, the creep strains for the 365-day specimen exceeded the creep strains for the 183-day specimen. A similar effect is also evident for the specimens loaded at 600 psi although it is not as pronounced, possibly due to the magnitude of the strains and the error introduced by the shrinkage relationships.

A summary of the ratio of the creep strains in the 183-day and 365-day specimens to the creep strains in the 90-day specimens is contained in Table 7. During the first year under load, the creep strains in the specimens cured for 183 days and 365 days were approximately 85 and 68 percent of the creep strains in the specimens cured for 90 days.

Effect of Curing History

A comparison of the axial creep strains during the first 2.5 years under a load of 2400 psi (Table 8) indicates that the air-dried specimens exhibited larger axial creep strain than the as-cast specimens regardless of the age at loading (Ref 9). The ratios of the as-cast strains to the air-dried strains were fairly consistent. The average values for the 90, 183, and 365-day specimens were 0.80, 0.86, and 0.81, respectively, with an overall average

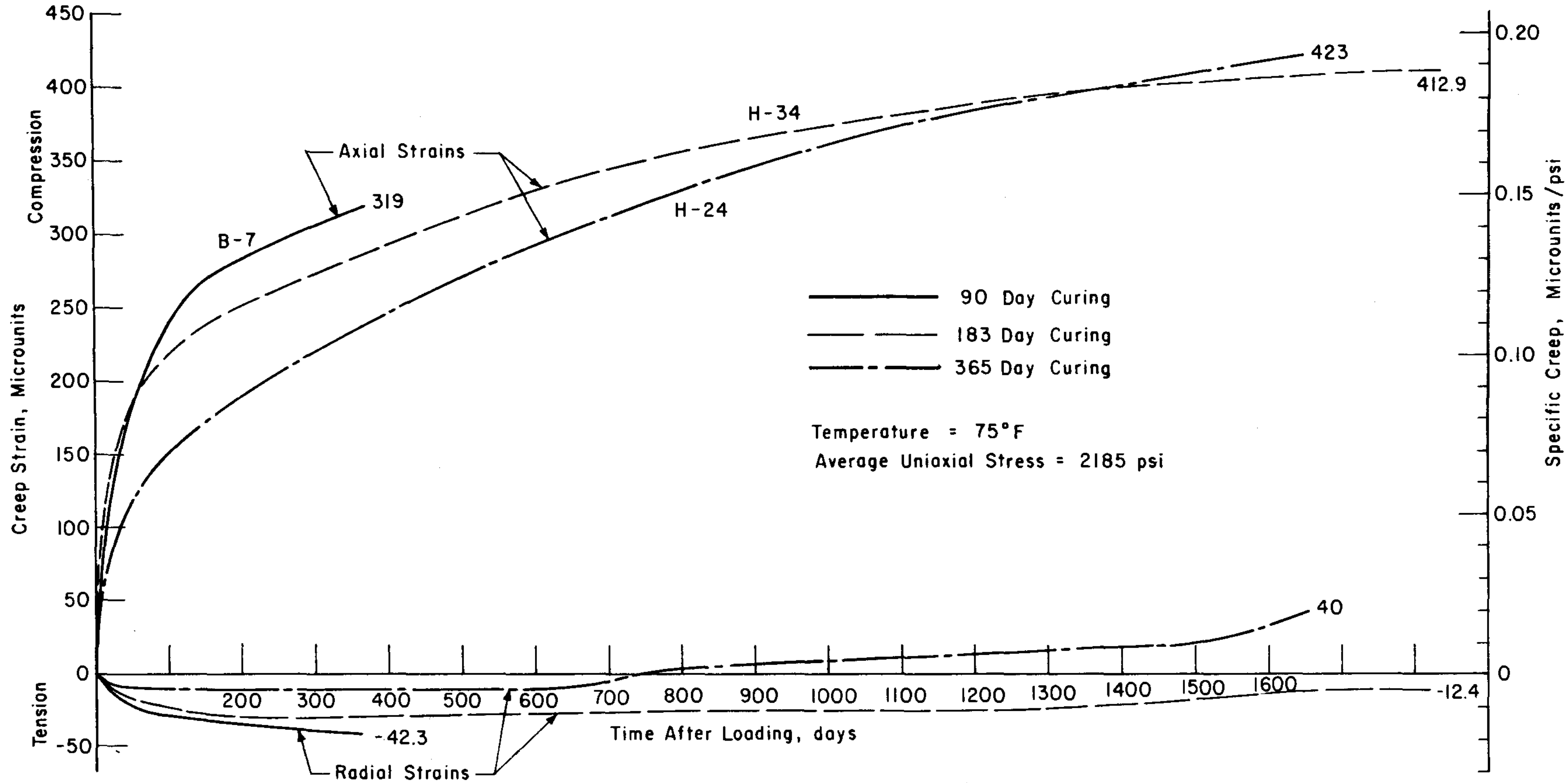


Fig 13. Axial and radial creep strain relationships for as-cast specimens with uniaxial stress of 2400 psi.

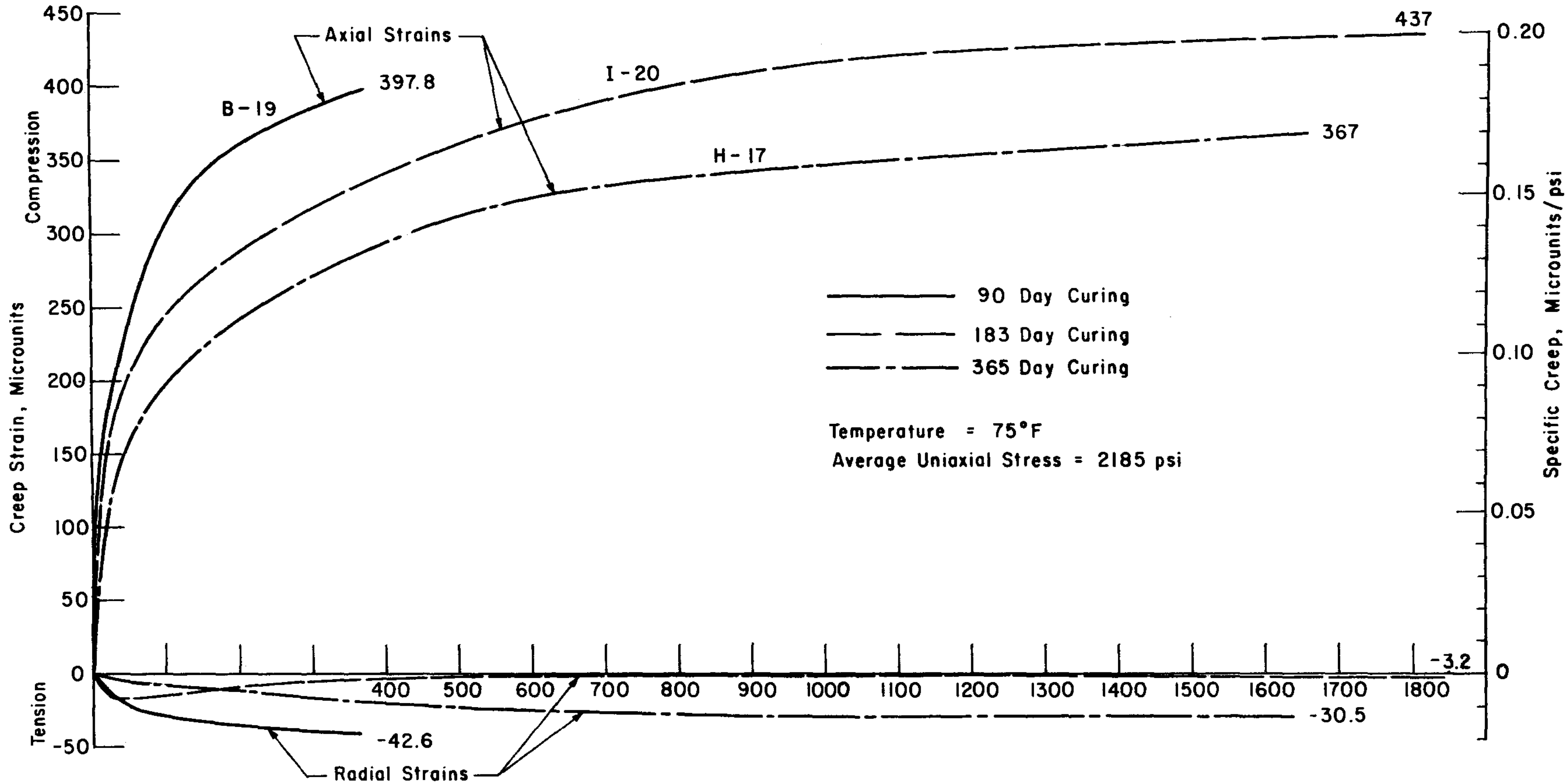


Fig 14. Axial and radial creep strain relationships for air-dried specimens with uniaxial stress of 2400 psi.

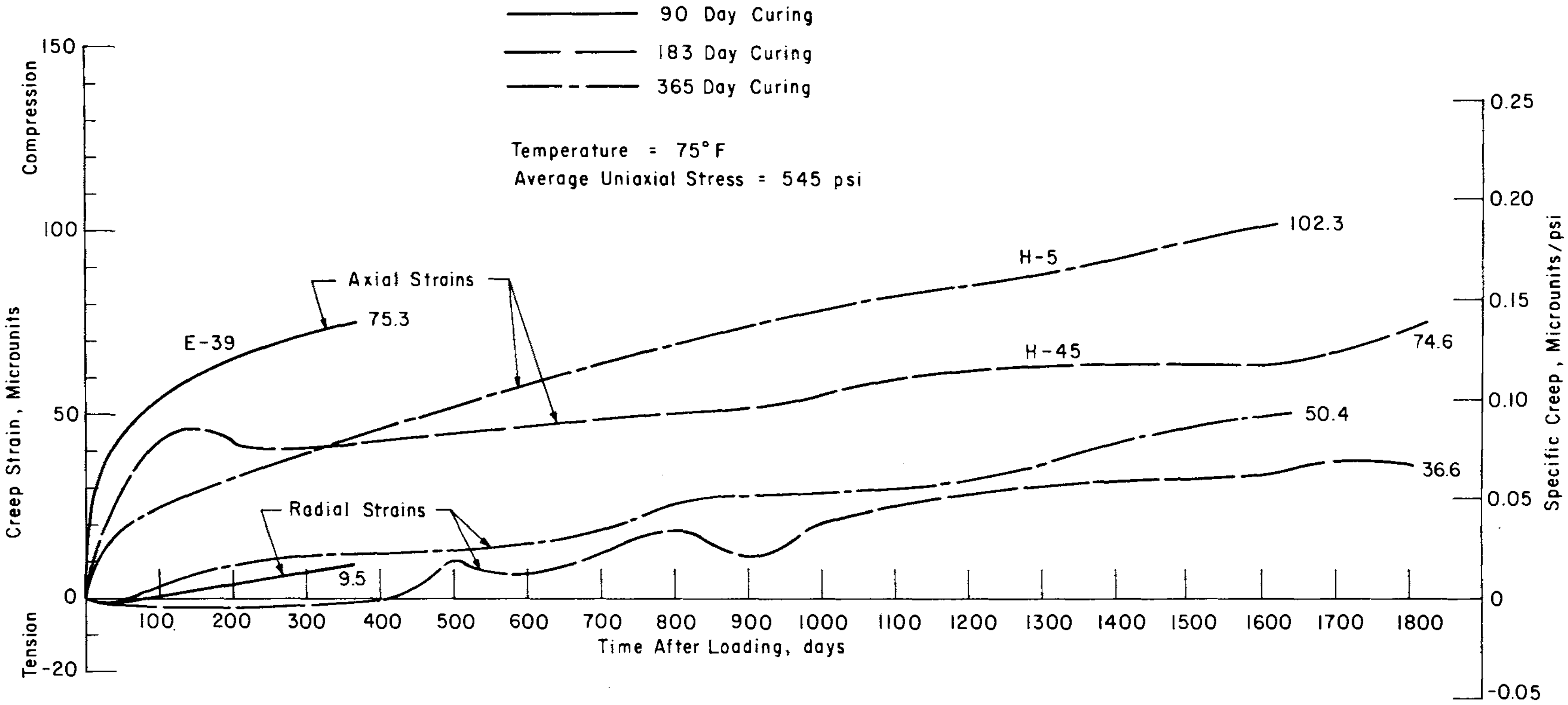


Fig 15. Axial and radial creep strain relationships for as-cast specimens with uniaxial stress of 600 psi.

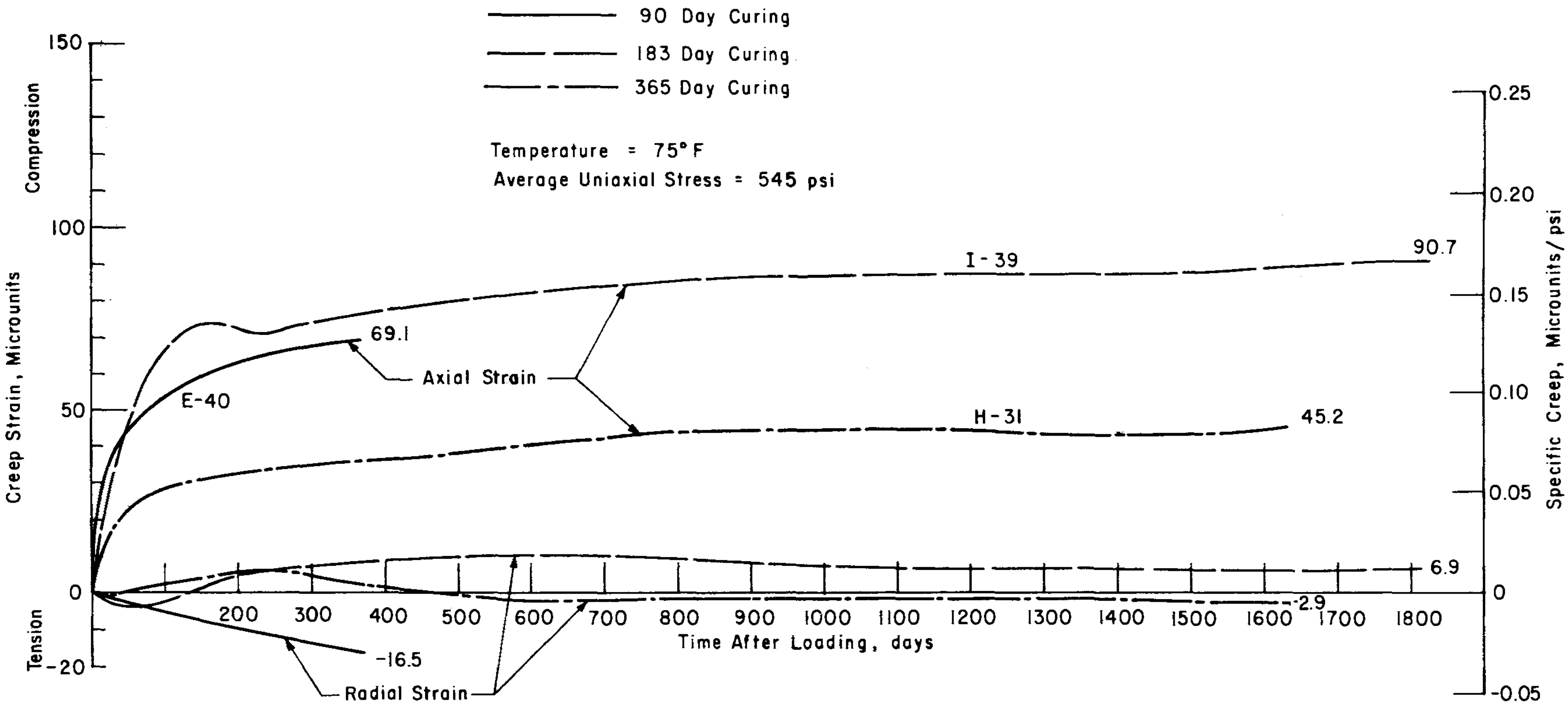


Fig 16. Axial and radial creep strain relationships for air-dried specimens with uniaxial stress of 600 psi.

TABLE 7. RATIO OF AXIAL CREEP STRAINS FOR 183- AND 365-DAY SPECIMENS TO CREEP STRAINS FOR 90-DAY SPECIMENS (Ref 9)

Days after Loading	Curing Time and History					
	183 days			365 days		
	Air-dried	As-cast	Average	Air-dried	As-cast	Average
28	0.97	1.00	0.98	0.70	0.66	0.68
56	0.83	0.91	0.87	0.64	0.62	0.63
84	0.81	0.90	0.85	0.64	0.61	0.63
168	0.81	0.86	0.84	0.67	0.65	0.66
252	0.83	0.88	0.86	0.71	0.71	0.71
364	0.83	0.88	0.85	0.73	0.75	0.74
Average	0.85 (0.82)*	0.91 (0.89)*	0.88 (0.85)*	0.68	0.67	0.68

* Excluding value 28 days after loading.

TABLE 8. EFFECT OF CURING HISTORY ON AXIAL CREEP STRAINS, MICROUNITS*

Days after Loading	Curing Time and History								
	90 days			183 days			365 days		
	(B-7) As-cast	(B-19) Air-dried	Ratio**	(H-34) As-cast	(I-20) Air-dried	Ratio**	(H-24) As-cast	(H-17) Air-dried	Ratio**
28	155	185	0.84	155	180	0.86	102	130	0.78
56	203	261	0.78	186	216	0.86	125	167	0.75
84	233	295	0.79	209	239	0.87	143	190	0.75
168	275	348	0.79	238	280	0.85	179	232	0.77
252	290	368	0.79	255	306	0.83	206	260	0.79
365 (1 yr)	319	398	0.80	280	330	0.85	239	290	0.82
547 (1.5 yrs)	--	--	--	321	371	0.86	290	329	0.88
730 (2 yrs)	--	--	--	351	400	0.88	315	340	0.93
924 (2.5 yrs)	--	--	--	364	413	0.88	351	343	1.02
1096 (3 yrs)	--	--	--	382	421	.91	374	350	1.07
1279 (3.5 yrs)	--	--	--	394	426	.92	392	356	1.10
1461 (4 yrs)	--	--	--	403	430	.94	407	362	1.12
1643 (4.5 yrs)	--	--	--	409	436	.94	423	367	1.15
1826 (5 yrs)	--	--	--	413	437	.95	--	--	--
Average (from Ref 9)	--	--	0.80#	--	--	0.86##	--	--	0.81###

*Uniaxial stress = 2400 psi
Temperature = 75°F
**Ratio of as-cast to air-dried strains

#Average for first year
##Average for first 2.5 years
###Average for first 2 years

of 0.82. Thus, it was concluded that the creep strains in as-cast specimens at any given time were approximately 82 percent of the creep strains in air-dried specimens subjected to the same stress level.

During the next 2.5 years, however, the ratios of the as-cast creep strains to the air-dried creep strains increased indicating that the magnitudes of the as-cast and air-dried creep strains were approaching the same value. This may indicate that the air-dried specimens initially deformed at a much higher rate because moisture was free to move quickly and easily into the partially dry capillary voids and therefore the maximum creep strain was approached more quickly. Given time, however, the moisture in the more saturated as-cast specimens was able to migrate, allowing creep to continue. The ultimate creep strain may be approximately the same for both as-cast and air-dried specimens, or the ultimate creep strain may actually be greater for the as-cast specimens because of the greater quantity of water involved. The observed behavior may also suggest that the specimens are leaking moisture since loss of water would be expected to have a greater effect on the as-cast specimens.

CREEP POISSON'S RATIO

Estimates of creep Poisson's ratio at periodic times after loading are summarized in Table 9. Because of the apparent errors associated with estimating shrinkage and the effect on the radial strains, which are relatively small, it was difficult to obtain a reliable value for creep Poisson's ratio. The as-cast specimens, H-34 and H-24, exhibited a gradual decrease in creep Poisson's ratio with the values for specimen H-24 becoming negative approximately 2.5 years after loading. The creep Poisson's ratio for air-dried specimen I-20 was essentially zero throughout the test period while creep Poisson's ratio for the air-dried specimen H-17 remained essentially constant at 0.08. Nevertheless, it is felt that a definite Poisson's effect did occur throughout the loading period.

At best, the values shown in Table 9 are probably on the low side since previous evaluations of the data associated with the specimens cured 90 days prior to loading indicated that creep Poisson's ratio averaged about 0.16 with values 364 days after loading ranging from 0.11 to 0.28. Specimens B-7 and B-19 exhibited values in the lower portion of this range and it is

TABLE 9. CREEP POISSON'S RATIOS*

Days after Loading	Curing History and Time					
	As-cast			Air-dried		
	(B-7) 90 days	(H-34) 183 days	(H-24) 365 days	(B-19) 90 days	(I-20) 183 days	(H-17) 365 days
28	0.09	0.12	0.10	0.08	0.10	0.07
56	0.11	0.12	0.08	0.10	0.08	0.08
84	0.12	0.12	0.07	0.10	0.07	0.09
168	0.12	0.13	0.06	0.09	0.04	0.09
252	0.13	0.12	0.05	0.10	0.02	0.08
365 (1 yr)	0.13	0.11	0.04	0.11	0.01	0.08
547 (1.5 yrs)	--	0.09	0.03	--	0.00	0.08
730 (2 yrs)	--	0.09	0.03	--	0.00	0.08
924 (2.5 yrs)	--	0.08	-0.02	--	0.00	0.09
1096 (3 yrs)	--	0.06	-0.03	--	0.00	0.08
1279 (3.5 yrs)	--	0.06	-0.04	--	0.00	0.08
1461 (4 yrs)	--	0.04	-0.05	--	0.00	0.08
1643 (4.5 yrs)	--	0.03	-0.09	--	0.00	0.08
1826 (5 yrs)	--	0.03	--	--	0.00	--
Average	0.12	0.09	--	0.10	--	0.08

*Uniaxial stress = 2400 psi
Temperature = 75°F

these two specimens which were used in this analysis. The evaluation of data obtained from the 90-day specimens also showed that creep Poisson's ratio was approximately 65 percent of the elastic Poissons' ratio and that the value for the air-dried specimens was approximately 30 percent less than that for the as-cast specimens. It was also concluded that creep Poisson's ratio was not time-dependent.

LONG TERM CREEP BEHAVIOR

The majority of the overall experiment involved specimens which were cured for 90 days, loaded for one year, and then unloaded; however, since reactor vessels and other types of structures are subjected to loads for indefinite periods of time, the specimens cured for 183 or 365 days prior to loading were subjected to load for an indefinite period of time. The purpose of this limited experiment was to determine whether the long term creep behavior was essentially the same as the behavior indicated during the first 12 months under load.

The eight specimens cured for 183 and 365 days have been under a sustained uniaxial stress of 600 or 2400 psi for 5 and 4.5 years, respectively. Examination of the total strain relationships (Figs 7 through 10) and the creep strain and specific creep relationships (Figs 13 through 16) indicates that after the instantaneous deformation, the concrete continued to deform at a decreasing rate, with the magnitude of the strain approaching a constant value. However, even after 5 years under load the specimens were still continuing to creep.

Table 10 summarizes the ratios of creep strain at any given time to the creep strain at one year for specimens subjected to 2400 psi. In addition, predicted ratios based on previous work involving the specimens loaded 90 days after casting (Ref 1) and ratios summarized by Neville (Ref 8) are shown for purposes of comparison.

For the specimens loaded with a uniaxial stress of 2400 psi, an average of 81 percent of the creep strain exhibited at two years occurred during the first year and an average of 70 percent of the creep strain exhibited at 4.5 years occurred during the first year. This ratio was slightly higher for the air-dried specimens than for the as-cast specimens throughout the test period, probably due to the fact that the air-dried specimens tended to creep at a much more rapid rate initially with the magnitudes of the creep strains for the air-dried and as-cast specimens becoming essentially equal with time (Table 8).

For the specimens cured for 183 days, it was found that the axial creep strains for the as-cast and air-dried specimens after 5 years under load was 1.48 and 1.32 times that which occurred during the first year. These values are essentially equal to the values predicted from the 90-day specimens from this project. This would indicate that the previously reported method (Ref 1) of estimating long term behavior from short term testing is relatively accurate. If this is true then it can be assumed that only 78 to 87 percent of the ultimate creep strain for the 183-day specimens has occurred during the first 5 years. The relationships between axial creep strain and the logarithm of time for the specimens subjected to a uniaxial stress of 2400 psi are shown in Fig 17. From this figure it would appear that no radical change in the creep behavior occurred during the 4.5 to 5-year loading period; however, this observation is based on a limited amount of data. Specific axial creep values at about 5 years were in the range of 0.17 to 0.20 microunits per psi and were continuing to increase.

TABLE 10. RATIO OF LONG TERM AND ONE-YEAR CREEP

Time after Loading, Years	Measured*				Estimated (Ref 1)**				From Neville and Meyers (Ref 8)***
	183-Day Curing		365-Day Curing		75° F		150° F		
	As-cast	Air-dried	As-cast	Air-dried	As-cast	Air-dried	As-cast	Air-dried	
1.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.5	1.15	1.12	1.21	1.13	--	--	--	--	--
2.0	1.25	1.21	1.32	1.17	1.17	1.15	1.15	1.06	1.14
2.5	1.30	1.25	1.47	1.18	--	--	--	--	--
3.0	1.36	1.28	1.56	1.21	--	--	--	--	--
3.5	1.41	1.29	1.64	1.23	--	--	--	--	--
4.0	1.44	1.30	1.70	1.25	--	--	--	--	--
4.5	1.46	1.32	1.77	1.27	--	--	--	--	--
5.0	1.48	1.32	--	--	1.40	1.32	1.31	1.11	1.20
Infinite	--	--	--	--	1.89	1.51	1.52	1.13	--

*Measured from axial strains from specimens loaded with a uniaxial stress of 2400 psi.
**Estimated from uniaxially loaded specimens cured 90 days before loading; 75°F and 60 percent relative humidity.
***70°F and 50 percent relative humidity.

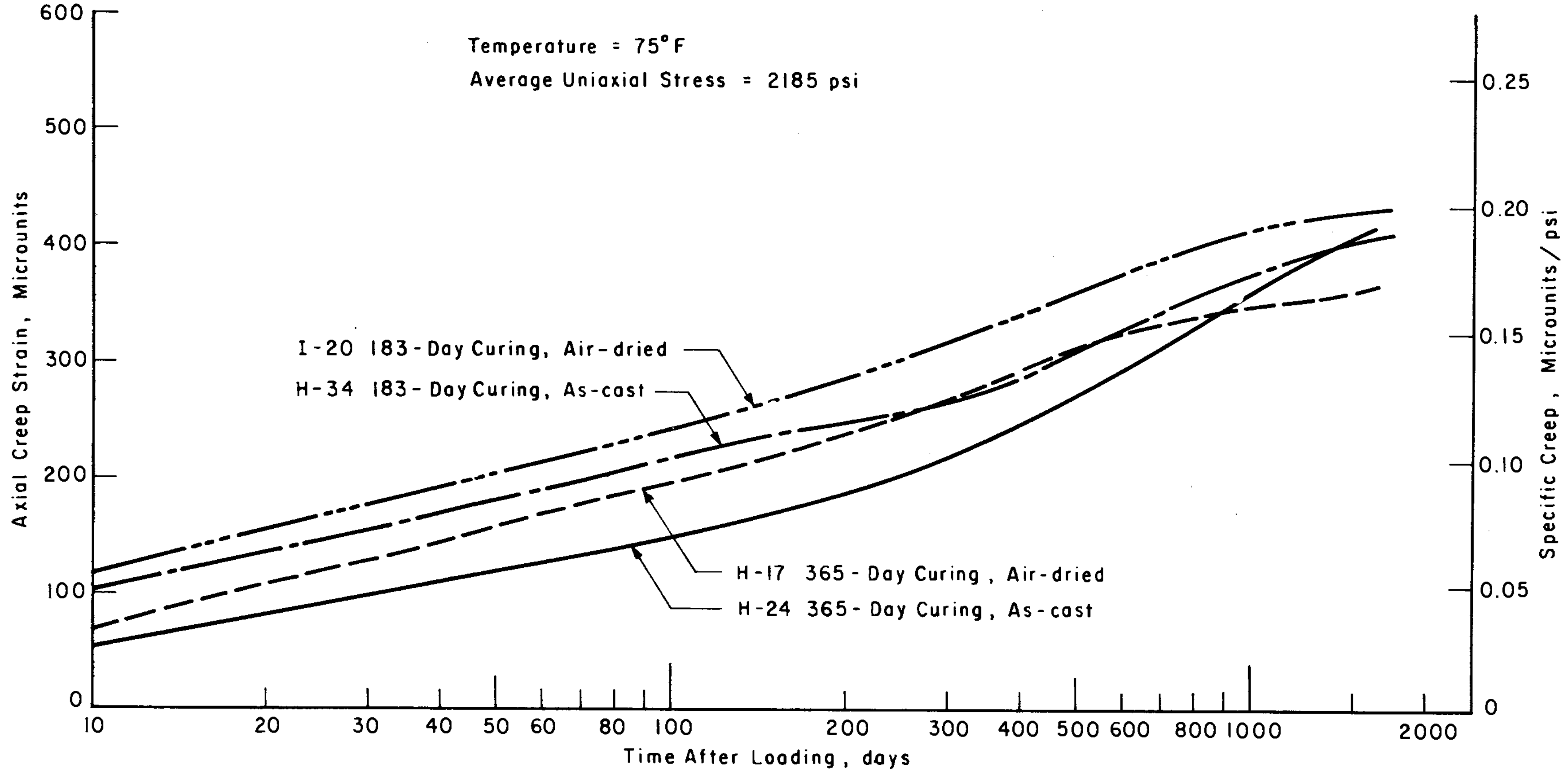


Fig 17. Relationship between axial creep strain and logarithm of time for specimens with uniaxial stress of 2400 psi.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the findings and conclusions of the evaluation of the long term creep behavior of concrete for specimens subjected to uniaxial stresses for 1, 4.5, and 5 years. These conclusions are based on measurements made on only 12 specimens, which were subjected to various combinations of uniaxial compressive stresses (600 and 2400 psi), two curing histories (as-cast and air-dried), and three curing times (90, 183, and 365 days). All specimens were cured and loaded at 75°F. A previous report summarized the findings for the specimens after 1, 2, and 2.5 years under load.

CONCLUSIONS

Instantaneous Behavior

(1) Instantaneous axial and radial strains were not affected by curing time and curing history. The average instantaneous axial and radial strains for specimens at 600 psi were 87 and -23 microunits respectively; at 2400 psi the corresponding values were 384 and -92 microunits.

(2) Likewise, moduli of elasticity and Poisson's ratios were not affected by curing history. The average modulus of elasticity and Poisson's ratio were 6.03×10^6 psi and 0.23.

Creep Behavior

(3) Creep strains were affected by both curing time prior to loading and curing history.

(4) For a 2400-psi uniaxial stress, creep strains were larger for specimens subjected to shorter curing periods prior to loading. During the first year under load, the creep strains in the specimens cured for 183 days and 365 days were approximately 85 and 68 percent of the creep strains in the specimens cured for 90 days. This difference, however, diminished with time during the early portion of the loading period.

(5) Creep strains were larger for air-dried specimens than for as-cast specimens. During the first 2 to 2.5 years of loading, the creep strain in the as-cast specimens was approximately 82 percent of the creep strain in the air-dried specimens at a stress level of 2400 psi. During the last 2.5 years of loading, however, the ratios of the as-cast to air-dried creep strains approached a value of one.

(6) During the first 2 to 2.5 years the average creep Poisson's ratio for the specimens loaded with a stress of 2400 psi was 0.09. The values for the various specimens were fairly consistent; however, based on previous evaluations in this project, it was concluded that the above average value was probably low. During the last 2.5 years of the loading period there was a decrease in creep Poisson's ratio, which was attributed to shrinkage errors.

(7) The creep behavior of the 183-day and 365-day specimens which have been under load for 5 and 4.5 years, respectively, indicated that throughout the loaded period, the creep strains continued to increase at a decreasing rate, with the magnitude of the strains approaching a constant value. After 4.5 to 5 years under load specific creep values were in the range of 0.17 to 0.20 microunits per psi and the specimens were continuing to creep.

(8) No radical change in the creep behavior was observed throughout the loading period.

(9) Approximately 81 percent of the creep strain exhibited at two years occurred during the first year for specimens loaded with a uniaxial stress of 2400 psi. For specimens cured 183 days, approximately 78 percent and 96 percent of the creep strain exhibited after 2.5 years occurred during the first year and first two years, respectively.

(10) After 5 years under load it was found that the axial creep strains for the as-cast and air-dried specimens were 1.48 and 1.32 times that which occurred during the first year; these values are essentially equal to the values predicted from the 90-day specimens (Ref 1).

RECOMMENDATIONS

In the investigation summarized in this report, the author was forced to rely primarily on the creep data obtained from the specimens loaded with a uniaxial stress of 2400 psi. The information obtained from the shrinkage specimens was questionable, and errors caused by poor estimates of shrinkage would have a significant effect on the estimated creep behavior of specimens loaded with a uniaxial stress of 600 psi and to a certain extent on the radial strains for specimens loaded with 2400 psi.

Because of the limited number of creep and shrinkage specimens, a more extensive investigation should be conducted to evaluate the long term creep behavior of concrete and the effects of curing. This investigation should involve duplicate specimens for both the creep and shrinkage specimens. In addition, it is felt that a low stress level, e.g., 600 psi, should not be used since the strains are small and difficult to interpret.

In addition, an evaluation of the specimens, experimental technique, and equipment should be conducted in order to determine the reliability of the data obtained from the total test program. The 183 and 365-day specimens should be unloaded and their recovery behavior observed. Subsequently the specimens should be destructively evaluated to determine the reliability of the long term behavior summarized in this report.

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