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"CREEP RECOVERY AND CREEP OF PRESHRUNK CONCRETE"

MISSOURI STATE HIGHWAY DEPARTMENT
UNIVERSITY OF MISSOURI, COLUMBIA
BUREAU OF PUBLIC ROADS

CREEP RECOVERY AND
CREEP OF PRESHRUNK CONCRETE

Prepared for

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ACKNOWLEDGEMENTS

The study described in this report is a continuation study of a cooperative research program, "Study of the Effect of Creep and Shrinkage on the Deflection of Reinforced Concrete Bridges", undertaken by the Engineering Experiment Station of the University of Missouri in 1959 under the sponsorship of the Missouri State Highway Commission and the U.S. Bureau of Public Roads and under the administrative direction of Dean Joseph C. Hogan and Dean William M. Sangster. The program was inaugurated through the initiative of Mr. John A. Williams, former Bridge Engineer, Missouri State Highway Commission. The advice and assistance of Mr. D. B. Jenkins, Bridge Engineer and Mr. Roy Cox, Assistant Bridge Engineer, and Mr. Billy Drewell, Senior Preliminary Structural Designer, all of the Missouri State Highway Commission, Mr. R. C. Gibson, Regional Bridge Engineer and Mr. Mitchell Smith, District Bridge Engineer, both of the U.S. Bureau of Public Roads, is hereby gratefully ack-knowledged. This phase of the program was conducted by Mr. Ronald L. Hollrah, a National Science Foundation Trainee in the Department of Civil Engineering. Dr. Donald R. Buettner was Project Engineer at the time this study was completed. The study was directed by Dr. Adrian Pauw, Professor and Chairman of the Department of Civil Engineering.

SYNOPSIS

While there is extensive literature on the behavior of concrete under a sustained load, only limited test data is available on creep recovery behavior upon unloading. Inasmuch as over one hundred specimens were available from an earlier study in the program, an unusual opportunity was available to study creep behavior of specimens which had been under load for a period of over two years.

The creep recovery behavior for the specimens in this study was considerably different from that previously reported for specimens loaded for a shorter period of time. Similarly it was found that the basic, or viscous, creep appears to be a function of the age at the time of loading. Finally it was found that for the size of the specimen used in this study and for the environmental conditions of 70°F and 50% relative humidity, both the elastic modulus and the ultimate compressive strength of the concrete generally decreases with time from the values obtained 28 days after casting. These results indicate the desirability of continued studies of these phenomena to determine the reasons for this unexpected behavior.

CHAPTER I

INTRODUCTION

General

An extensive research program to study the effects of creep and shrinkage on the deflection of reinforced concrete bridges was begun on September 1, 1959. The program was conducted under the supervision of the Engineering Experiment Station at the University of Missouri in cooperation with the Missouri State Highway Commission and the United States Bureau of Public Roads. The objective of this research program was to develop design criteria which will enable the engineer to predict long-time deflections of reinforced concrete beams resulting from creep and shrinkage of the concrete. A broad program of field and laboratory testing was prepared to accomplish this objective.

The field test program consisted of a study of the effects of creep and shrinkage on the deflection of reinforced concrete bridges. Deflection and column strain readings were taken over a period of approximately two years. The results of this study were reported by Brautigam (1)*.

In conjunction with the field study, the theoretical time-dependent deflections for these bridges were obtained using an analysis based on a method developed by Pauw and Meyers (2). The

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*Numbers in parentheses refer to entries in the bibliography.

results of this analysis will be reported in a thesis under preparation by Cronister (3).

The laboratory test program consisted of two phases; a study of the effect of creep and shrinkage on the deflection of reinforced concrete beams, and a study of the effects of constituents, environment, and stress on the creep and shrinkage of plain concrete prisms.

In the beam study, six rectangular beams and two T-beams were constructed and subjected to sustained loads. Deflection and strain measurements were taken over a period of eighteen months. The results of this study are reported by Jones (4).

The second phase of the laboratory test program consisted of an extensive analysis of the effect of constituent, environment, and stress variables on the creep and shrinkage of plain concrete. This program was conducted to support previous conclusions as well as to investigate the effects of some of the variables that have not been considered in previous studies. The program was conducted over a period of eighteen months following over a year of work developing a suitable instrumentation system, selecting materials, and designing the concrete mixes to be used in the tests. The entire program consisted of testing over two hundred specimens comprising twenty-five separate studies. The results of this study will be presented in a report by Buettner (5).

Background

At the completion of the creep study conducted at the University of Missouri (5), there were approximately 100 prisms which had been under load for 2 to 3 years, and 50 prisms which had been used for shrinkage measurements and were not under load. In order to derive the maximum amount of information from these prisms, it was decided to investigate two major aspects of creep. These aspects consist of a study of creep recovery and a study of the creep of preshrunk prisms. The background information for each of these studies will be presented separately.

Creep Recovery

An examination of the literature which has been published on the subject of creep revealed that only a limited number of investigations have been conducted concerning the subject of creep recovery. The test program which was adopted for the study reported in this paper was set up to allow the collection of data which will yield conclusions of a qualitative nature, regarding the time-rate of creep recovery, the time required for creep recovery to become complete, and the amount of creep recovery which can be expected.

It was also noted that there is only a limited amount of information available regarding the effect of constituents, environment, or previous stress level on the characteristics of creep recovery. This investigation included a study of the effects of a number of variables on the creep recovery behavior of approximately thirty-five plain concrete prisms.

Most of the previous research concerning the subject of creep strain behavior of concrete specimens which were unloaded and reloaded, considered only the case when a period of several days or weeks had elapsed between the time of unloading and reloading (6), (7). These investigations indicated that upon reloading the specimen, there was an initially rapid rate of creep, but that the total creep strain did not reach the value which it would have attained, if the specimen had remained under load. Figure 1 illustrates this behavior. There was no previous information available on the creep strain behavior of plain concrete prisms which have been unloaded and immediately reloaded. This problem is currently being further investigated at the University of Missouri.

During the process of loading and unloading the prisms, the load-deflection readings obtained could be used to give an indication of the modulus of elasticity of the concrete. Load-deflection readings were also taken at the outset of the prism study at the University of Missouri (5), thus allowing a comparison of the modulus of the aged specimen to the modulus at the time the prisms were initially loaded. A companion prism was also tested to determine the ultimate compressive strength at the time the prisms were initially loaded. Ultimate strength tests were conducted at the completion of the experimental portion of this study. This permitted a comparison of the strength of the prism when it was initially loaded to the strength which existed at the completion of this study.

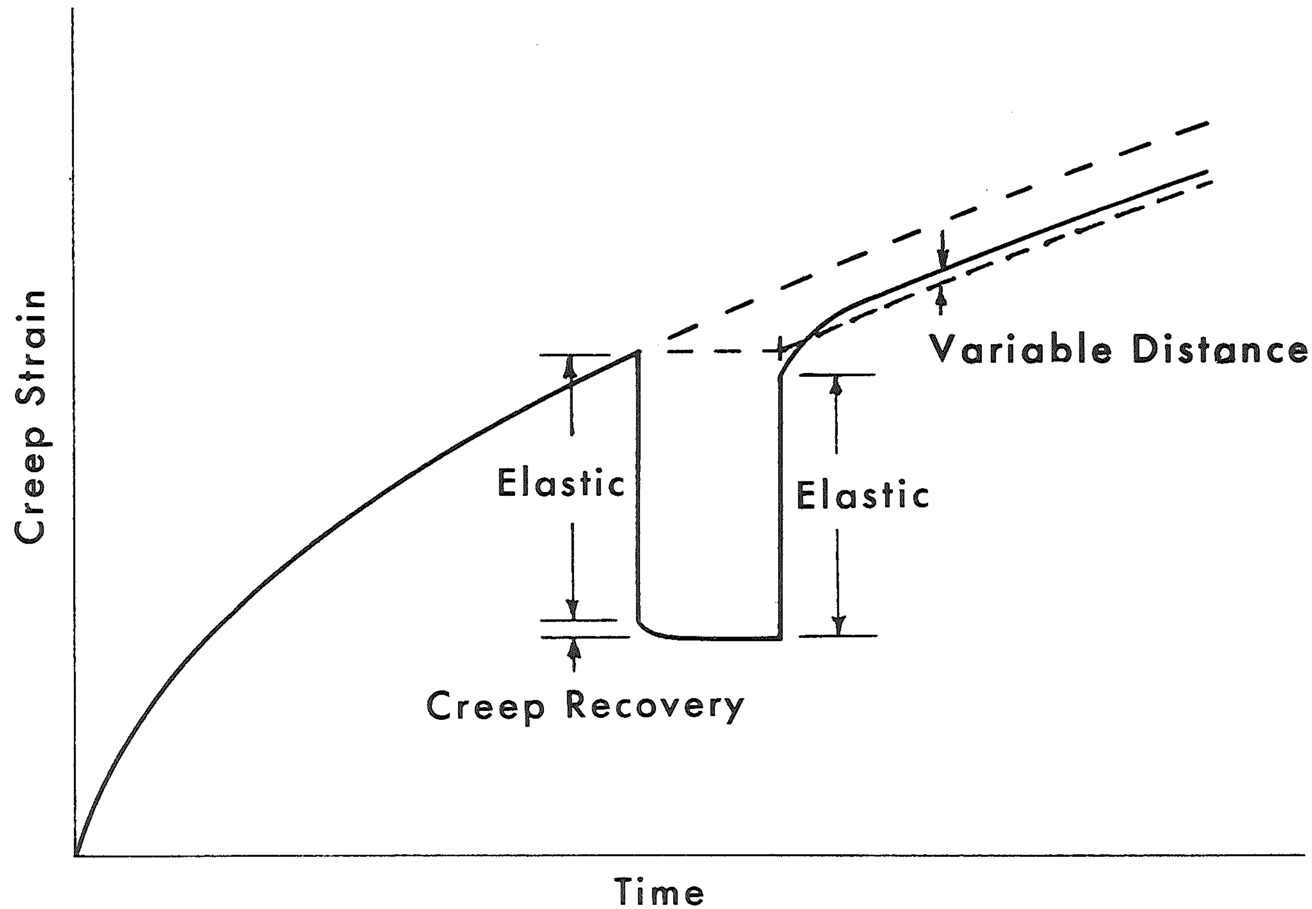

Figure 1. Typical creep strain behavior obtained from unloading and reloading plain concrete

Creep of Preshrunk Prisms

In current concrete theory, creep strain is defined as the total strain minus the sum of the shrinkage strain and the elastic strain, or

$$\varepsilon_c = \varepsilon_t - \varepsilon_s - \varepsilon_e \qquad (1)$$

However, as a result of an investigation conducted by Ali and Kesler (8) it was determined that creep and shrinkage are not independent. It was proposed by Ali and Kesler that the total creep strain is equal to the sum of the basic creep strain and the drying creep strain. These quantities are represented graphically in Figure 2.

Basic creep is defined as the creep occurring under conditions of no moisture exchange with the environment. Drying creep is defined as the creep in excess of the basic creep, resulting from concurrent loss of moisture.

Through a study of the mechanism of creep and shrinkage of plain concrete, it was proposed that basic creep could be represented by the rheological model shown in Figure 3. This model corresponds to the following mathematical equation which may be used to predict the basic creep strain:

$$\varepsilon_{bc} = \beta\sigma\{\alpha_1(1-e^{-t/\tau_1}) + \alpha_2(1-e^{-t/\tau_2}) + \phi t\} \qquad (2)$$

where:

ε_{bc} = creep strain occurring under conditions of no moisture exchange with the environment (basic creep strain).

β = gel compliance factor.

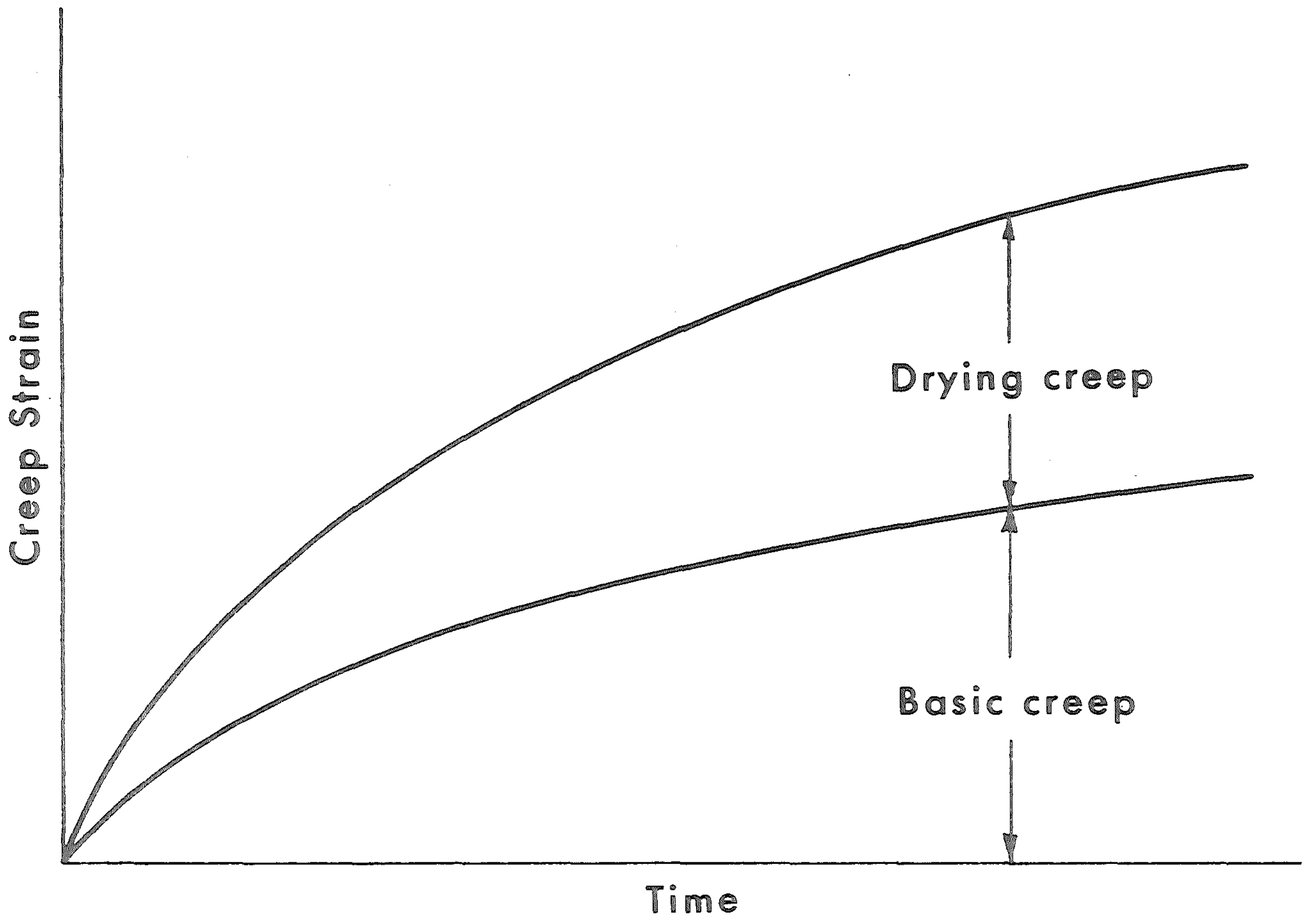

Figure 2. Composition of creep as proposed by Ali and Kesler

σ = stress level.

α_1, α_2 = compliances of the Kelvin springs.

τ_1, τ_2 = retardation times of the Kelvin elements.

ϕ = effective fluidity of the free dash pot in the Maxwell body.

t = creep time.

The gel compliance factor β, represents the ratio of the deformation of the gel component of the concrete, to the deformation of a hypothetical specimen of pure gel, subjected to the same stress as the concrete. At full hydration,

$$\beta = \frac{(1-V_a)^2}{2.20V_c}$$

where:

V_a = volume concentration of aggregate.

V_c = original volume concentration of cement.

In the tests of Ali and Kesler, the values of the coefficients corresponding to a temperature of about 70°F and a relative humidity range of 50 to 100 percent, expressed in inch-pound-day units, were found to be,

$\alpha_1 = 225 \times 10^{-9}$ $\tau_1 = 35$

$\alpha_2 = 115 \times 10^{-9}$ $\tau_2 = 2$

$\phi = 0.3 \times 10^{-9}$

These values were proposed to be the same for all concretes in environments which are within the temperature and humidity restrictions stated above.

In the prism study at the University of Missouri, there were

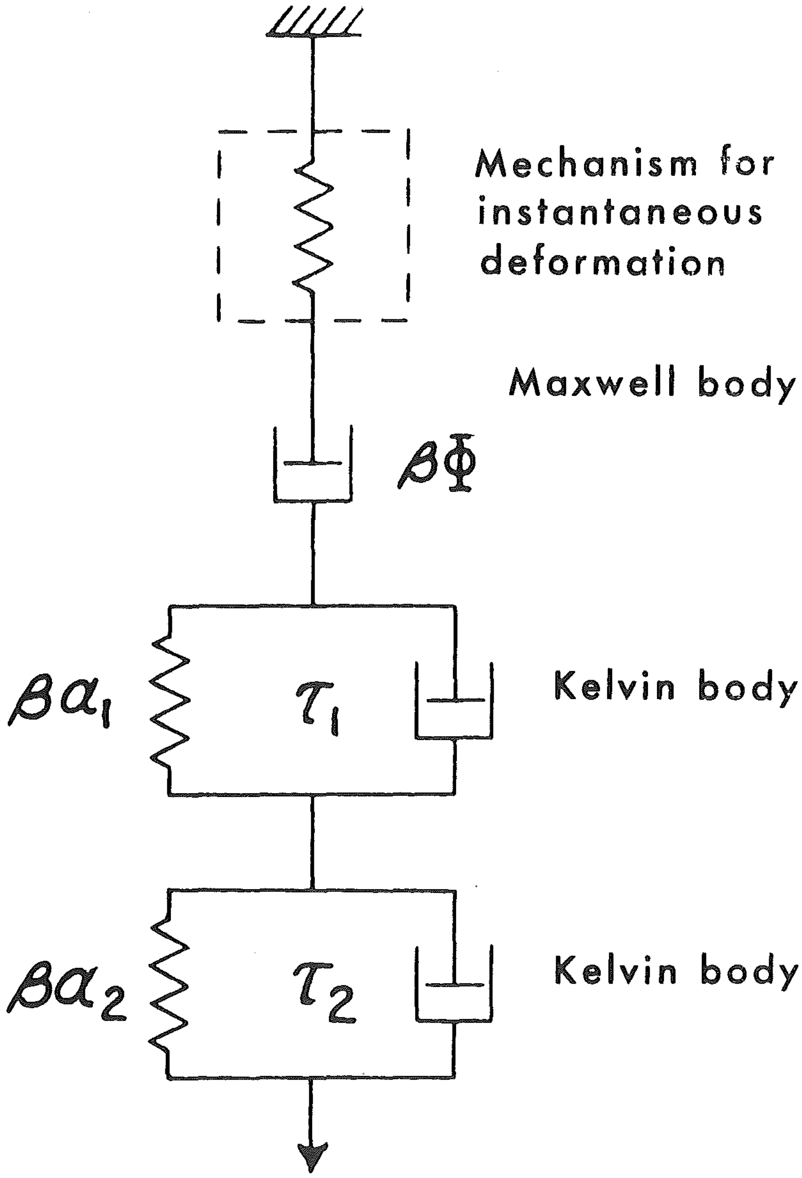

Figure 3. Kesler and Ali model for basic creep of concrete

approximately 50 unloaded shrinkage specimens stored at 50 percent relative humidity, and at a temperature of 72°F for approximately two years. Measurement of the shrinkage strains had indicated that the prisms were undergoing very little or negligible shrinkage at the time the study presented in this report was conducted. It was assumed that since the prisms were essentially preshrunk, no moisture would be exchanged with the environment. The creep exhibited upon loading the prisms should therefore be the basic or viscous creep as defined by Ali and Kesler.

Objectives

The objectives of the test program described in this paper were as follows:

1. Obtain qualitative data on the rate and amount of creep recovery of plain concrete.
2. Observe the effect of constituents, environment, age at loading, and previous stress level on creep recovery.
3. Observe the creep strain behavior of plain concrete specimens which had been under load for several years and were then unloaded and immediately reloaded.
4. Compare the creep of preshrunk specimens to the basic creep or viscous creep as predicted by Ali and Kesler (8).
5. Examine the effects of time, stress, constituents, and environment on the elastic modulus and the strength of plain concrete prisms.

CHAPTER II

EXPERIMENTAL PROGRAM

General

Information pertaining to the apparatus and instrumentation which were used in this study may be found in a report written by Meyers and Pauw (9). A detailed description of the test equipment is therefore not presented.

Specimens

The prism specimens used in this study were of two sizes. All of the prisms were 16 in. in length and 4 in. wide, and had depths of either 3 in. or 4 in. The size of each prism and the variable studied for that prism are listed in Table I. The prisms were cast horizontally in a casting bed. This system produced prisms which were initially square, thus eliminating the necessity of capping before loading. The flat surfaces also simplified the problem of applying the instrumentation. Mix quantities were weighed carefully to obtain batches of uniform quality. The specimens were cured under controlled laboratory conditions. The moist room into which the prisms were placed for curing was maintained at 70°F and 100 percent relative humidity. Except when otherwise noted in Table I, all prisms were moist cured for 28 days.

Many of the specimens used in previous creep and shrinkage studies were of the standard 6"x12" cylinder size. Prior to the selection of the rectangular prisms for this study, nine sets of

TABLE I
Prism Mix and Variable Descriptions

Series	In.xIn.	Details of Variable Studied	Mix Proportions for 1 Cubic Yard				Slump	Water Cement Ratio	Cement Paste Content	f_c' PSI
			Agg.	Sand	Cement	Water*				
2.1	3x4	Slump - 1 inch	1726	1661	496	307	1"	.608	.192	4560
2.2	3x4	Slump - 5 inches	1642	1576	559	347	5"	.611	.220	4460
2.3	3x4	Slump - 7 inches	1670	1603	397	380	7"	.944	.192	4690
3.1	3x4	Gradation-No. 1** 3/4" = 100% 1/2" = 84% 3/8" = 60% #4 = 44% #8 = 8%	1559	1501	487	303	3"	.612	.205	4790
3.2	3x4	Gradation-No. 2 3/4" = 100% 1/2" = 72% 3/8" = 40% #4 = 22% #8 = 4%	1559	1501	487	303	3"	.612	.205	5500
3.3	3x4	Gradation-No. 3 3/4" = 100% 1/2" = 84% 3/8" = 50% #4 = 29% #8 = 2%	1559	1501	487	303	3"	.612	.205	5380
4.1	3x4	Type Aggregate- Missouri Limestone	1702	1639	530	331	3"	.581	.205	5560

Series	In.xIn.	Details of Variable Studied	Mix Proportions for 1 Cubic Yard				Slump	Water Cement Ratio	Cement Paste Content	f_c' PSI
			Agg.	Sand	Cement	Water				
4.2	3x4	Type Aggregate-Missouri Limestone	1702	1639	530	331	3"	.581	.205	5630
4.3	3x4	Standard Specimen-Wisconsin Trap Rock	1685	1619	525	328	3"	.614	.205	5170
5.1	3x4	Curing Time-14 Days	1685	1619	525	328	2¼"	.614	.205	5380
5.2	3x4	Curing Time-21 Days	1685	1619	525	328	2¼"	.614	.205	5920
5.3	3x4	Curing Time-28 Days	1685	1619	525	328	2¼"	.614	.205	5460
6.1	3x4	Type Aggregate-Missouri Limestone	1703	1636	531	331	2"	.581	.205	5230
6.2	3x4	Type Aggregate-Missouri Limestone	1703	1636	531	331	2"	.581	.205	5540
6.3	3x4	Type Aggregate-Missouri Limestone	1703	1636	531	331	2¼"	.581	.205	8420
7.1	3x4	Age at loading-3 days	1685	1619	525	328	2¼"	.614	.205	3890
7.2	3x4	Age at loading-7 days	1685	1619	525	328	2-3/4"	.614	.205	2790
8.1	3x4	Age at loading-2 days	1685	1619	525	328	3"	.614	.205	2154
8.2	3x4	Age at loading-7 days	1685	1619	525	328	3"	.614	.205	2390
8.3	3x4	Age at loading-7 days	1685	1619	525	328	3"	.614	.205	2154
9.1	3x4	Water Cement Ratio	1718	1406	738	327	3"	.436	.254	8880
9.2	3x4	Water Cement Ratio	1616	1751	438	328	3"	.737	.185	3430
9.3	3x4	Age at Loading-14 days	1685	1619	525	328	3"	.614	.205	3460
12.1	3x4	Admixture-Placewell, 2-3/4 oz./sack	1685	1619	525	328	3½"	.614	.205	5420

Series	In.xIn.	Details of Variable Studied	Mix Proportions for 1 Cubic Yard				Slump	Water Cement Ratio	Cement Paste Content	f_c' PSI
			Agg.	Sand	Cement	Water				
12.2	3x4	Admixture-Retardwell, 3 fl. oz./sack	1685	1619	525	328	2-3/4"	.614	.205	4580
12.3	3x4	Curing Conditions-Preshrunk	1685	1619	525	328	3"	.614	.205	x
13.1	3x4	Admixture-Sicacrete 1½ gallon/cubic yard	1685	1619	525	328	3"	.614	.205	4410
13.2	3x4	Admixture-Calcium Chloride, 1.88 lb/sack	1685	1619	525	328	3"	.614	.205	5380
13.3	3x4	Admixture-Pozzolith, 4 oz./sack	1685	1619	525	328	3"	.614	.205	4640
15.1	4x4	Type Aggregate-Haydite #1	F= 785 M= 410 C= 541		470	358	3"	.762	.322	4734
15.2	4x4	Type Aggregate-Haydite #2	F=1090 M= 450		705	625	2-3/4"	.887	.464	4198
15.3	4x4	Type Aggregate-Haydite #3	F=1090 M= 450		705	541	3½"	.768	.447	4854
19.1	4x4	Preshrunk with 6% Air-Readymix	1967	1111	545	213	3"	.391	.198	6000
20.1	4x4	Preshrunk with 6% Air-Readymix, Haydite. Coarse aggregate gradation in accordance with Mo. Hwy. Comm. specs. for Class A concrete	1740		658	x	3"	x	x	5290

Series	In.xIn.	Details of Variable Studied	Mix Proportions for 1 Cubic Yard				Slump	Water Cement Ratio	Cement Paste Content	f_c' PSI
			Agg.	Sand	Cement	Water				
21.1	4x4	Air Content-2.6% Add Air-½ oz./sack	1847	1478	470	299	3"	.611	.188	3250
21.2	4x4	Air Content-5.2% Add Air 3/4 oz./sack	1891	1397	453	283	3"	.611	.183	2667
21.3	4x4	Air Content-7.4% Add Air 1¼ oz./sack	1936	1328	431	269	3"	.610	.177	2292
22.1	4x4	Type Aggregate-Missouri Limestone, High Stress Level (2500 psi.)	1703	1636	531	331	3"	.581	.205	4208
22.2	4x4	Type Aggregate-Missouri Limestone, High Stress Level (2500 psi.)	1703	1636	531	331	3"	.581	.205	3718
22.3	4x4	Type Aggregate-Missouri Limestone, High Stress Level (2500 psi.)	1703	1636	531	331	3"	.581	.205	4198
23.1	4x4	High Stress Level (2500 psi.)	1684	1622	525	328	3"	.614	.205	4235
23.2	4x4	High Stress Level (2500 psi.)	1684	1622	525	328	3"	.614	.205	3300

* Measured additional absorption for saturated surface dry condition: Wisconsin Trap Rock 0.32%, Missouri Limestone 1.36%. Light weight aggregates were soaked before mixing and saturated surface dry conditions were assumed.

** % Passing.

prisms and companion standard 6"x12" cylinders were cast to determine the reliability of the elastic modulus and strength tests as measured from the prisms. It was found that the results were in good agreement with results from cylinders (10).

Test Environment

The creep and shrinkage laboratory is equipped to maintain a temperature of 72^{O}F, and a relative humidity of 50 percent. Temperature and humidity were recorded continuously during the test period so that any failure of the test environment control system could be noted and corrected.

Hydraulic Loading System (9)

The hydraulic loading system permits a large number of specimens to be loaded quickly. The basic system consists of a motor, an oil-injection pump, an accumulator, a pressure control system, pressure cells and associated plumbing, and loading frames.

A loading rack can accomodate a stack of three 16-in. long specimens. The load is applied at the lower end of the rack by the floating circular plate of the pressure cell. Castings machined to finished dimensions are used for the body of the pressure cells. Oil is pumped under pressure through flexible hosing to each pressure cell and the loading pressure is transmitted to the floating plate through a rubber piston cup. The reaction is provided by high strength steel tension rods and cold-rolled flat steel plates.

A fuel-injection pump, driven intermittently by a small ¼-h.p. gear-head motor is used to pump oil under pressure to the pressure cells. A 2½-gal. hydraulic accumulator is used to maintain constant pressure between pumping cycles. The pumping system is regulated to increase the pressure when leakage causes a 10-psi drop in the static pressure of 514-psi.

Two sizes of pistons were used; 6-in. diameter, and 10-in. diameter. This provided four possible stress levels, three of which were used in this study. They were as follows:

1. 6-in. diameter piston
   a) 3x4 in. prism, = 1200-psi (1176-psi minimum)
   b) 4x4 in. prism, = 900-psi (882-psi minimum)
2. 10-in. diameter piston
   a) 4x4 in. prism, = 2500-psi (2450-psi minimum)

The stress level to which any given specimen was subjected can be deduced from Table I by assuming case 1 above unless "High Stress Level (2500-psi)" is stated as the variable studied.

<u>Test Procedure</u>

In Chapter I, it was stated that there were two basic topics to be studied, i.e., creep recovery and creep of preshrunk prisms. Although these two studies were independent of each other, there were certain laboratory procedures which were common to both. Broadly speaking, these procedures may be broken down into loading and unloading.

1. <u>Loading</u>. Using the hydraulic loading system described

above, it was possible to collect data to determine the elastic properties of the concrete while the prism was being loaded.

In the loading procedure, three prisms were stacked vertically inside the creep rack. These prisms were centered by means of scribe lines on the top and bottom plates of the creep rack. An initial strain reading was then taken for each prism. Strain readings were taken using a portable 6 in. longitudinal extensometer (9) which was referenced to a standard-length gage bar before and after taking the reading for for each prism. This allowed corrections to be incorporated into the reduced data for drift in the strain indicator or for effects of environment on the test equipment. Load was applied in 50 psi increments using a dead-weight gage tester to measure the pressure in the hydraulic line. This 50 psi pressure increment corresponded to an increment in load of 1414 pounds in the creep racks with 6 in. diameter hydraulic pistons, and 3928 pounds in racks with 10 in. diameter pistons.

After the addition of each load increment, strain readings were taken again for each prism in the same manner as described above. Gage points had been placed 6 in. apart in the center of each of the four sides of the prisms. The location of gage points on all four sides of the prisms allowed for the averaging of the effects of any eccentricities which may have been induced by positioning the prisms slightly off center in the creep rack.

In order to determine if the elastic properties obtained from loading in the creep racks were comparable to the values obtained using a hydraulic testing machine, the moduli of elasticity of 12 prisms were measured using both methods. The prisms were first taken into the materials testing laboratory and subjected to an elastic modulus test using a universal hydraulic testing machine and a mechanical compressometer (9). Each prism was cycled three times, with the upper load limit producing approximately the same stress as the stress to which the prism would be subjected in the creep rack. The prisms were then returned to the creep laboratory and reloaded using the dead-weight gage tester, and the portable longitudinal extensometer. The values of elastic modulus obtained from the two tests were within ± 7.3 percent.

2. Unloading. The procedure used to unload the prisms was basically the reverse of the loading procedure. In the loading procedure, pressure increments of 50 psi were used, and in the unloading procedure, the pressure decrement was 100 psi. An examination of the unloading stress-strain relationships of the first several prisms revealed that the relationship was not linear and that the concrete was exhibiting a hysteresis effect. It

was decided that since a plot of these relationships would not yield any significant information regarding the elastic properties of the concrete, readings would be taken in 100 psi hydraulic gage pressure increments in order to save time.

CHAPTER III

EXPERIMENTAL RESULTS

General

The results of this study will be presented and discussed in the order of the objectives listed in Chapter I.

Creep Recovery

The first two objectives of this study concerned the rate, amount, and effect of constituents, environment, age at loading, and previous stress level on creep recovery of plain concrete.

The creep recovery curves obtained in this investigation were not similar to the recovery curves which had been obtained in previous investigations (6, 11). The general shape of the creep recovery curves obtained in this study is illustrated in Figure 4. The band shown represents the upper and lower bounds of all recovery curves obtained. Specific values for each prism tested are shown in Table II.

Note that in Figure 4, the creep-time curve is shown as a horizontal line immediately preceding the time the prism was unloaded. An examination of the last several recorded creep strains prior to unloading any one prism indicated that this constant strain condition actually existed.

The general creep recovery pattern consisted of first a shortening or decrease in length. This was followed by a period of recovery (swelling) to a maximum value, and then a second

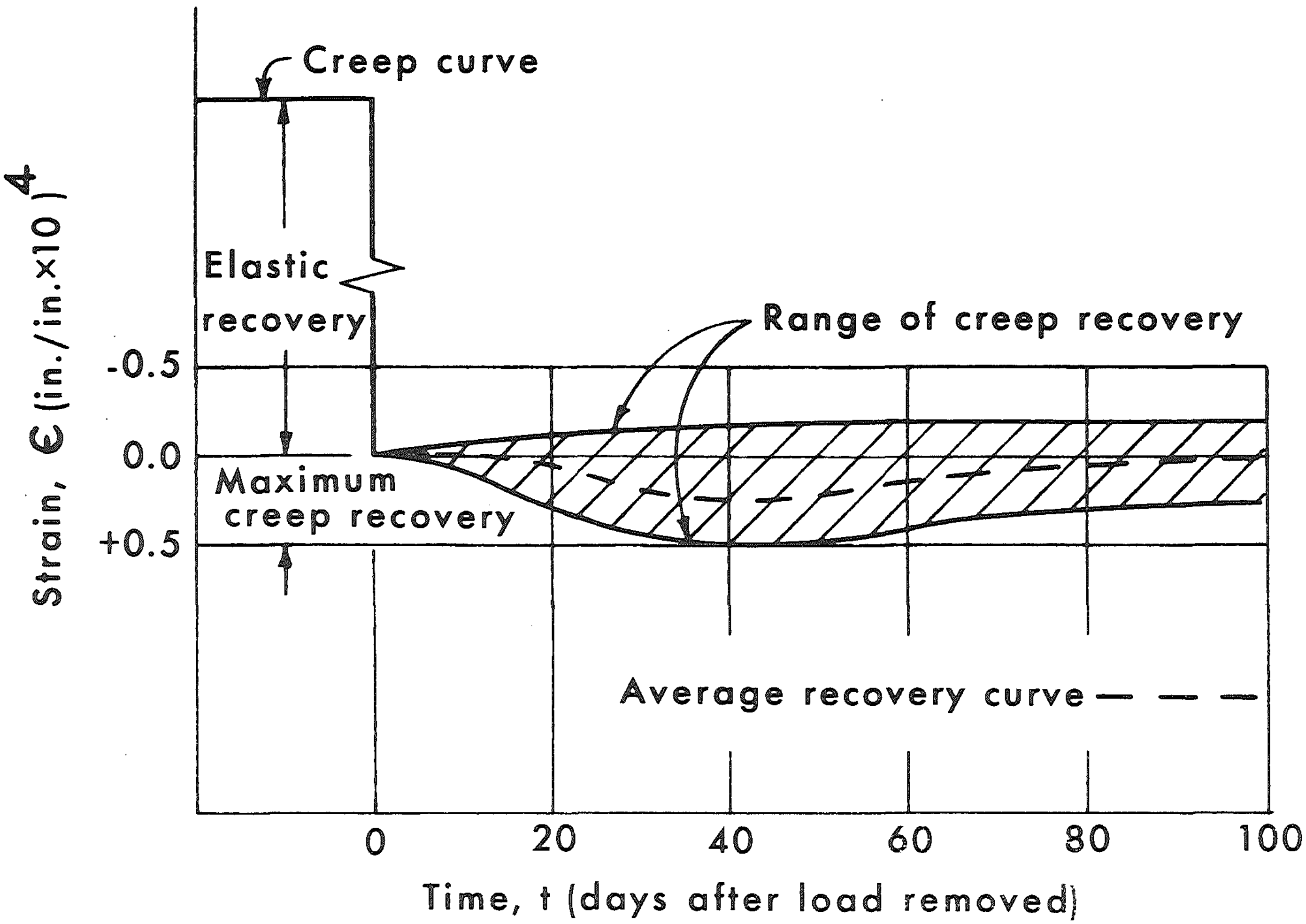

Figure 4. Observed creep recovery behavior

TABLE II
Creep Recovery Data

Specimen	Maximum Recovery (in/inx10^{-4})	Time of Max. Rec. (days)	Recovery at t=50 days (in/inx10^{-4})	Final Recorded Recovery (in/inx10^{-4})	Time of Final Read. (days)
2.13	0.50	38	0.467	0.033	128
2.23	0.25	55	0.25	-0.033	128
2.33	0.417	57	0.40	-0.017	128
3.13	0.35	37	0.167	0.00	95
3.23	0.45	37	0.25	-0.04	95
3.33	0.317	37	0.15	-0.082	95
6.13	0.467	43	0.43	0.082	74
6.23	0.267	18	0.00	-0.13	74
6.33	0.217	17	-0.10	-0.117	74
7.13	0.33	22	0.05	-0.013	77
8.12	0.00	30	-0.05	-0.10	74
9.12	0.00	45	0.00	-0.083	73
12.13	0.367	50	0.367	0.183	74
12.23	0.25	45	0.24	0.013	74
12.33	0.45	45	0.44	0.167	74
21.12	0.30	30	0.133	-0.30	128
21.13	0.35	35	0.267	-0.05	128
21.22	0.45	35	0.233	-0.283	128
21.23	0.40	33	0.317	-0.283	128
21.32	0.267	28	0.10	-0.300	128
21.33	0.45	30	0.35	-0.10	128

period of shortening. This second period of shortening appeared gradually to decrease until it eventually stopped.

Nine prisms in this study had creep strain recovery readings taken at four, nine, and fifteen days after the load had been removed. In all cases, the prisms exhibited decreases in length for approximately the first 15 days. For all the other prisms in the study, readings were not taken until 15 days after the load had been removed. Although no creep strain recovery information is available on the remainder of the prisms for the first 15 days after the load was removed, it is reasonable to assume that these prisms exhibited similar behavior.

It is important to note that there was no change in either temperature or humidity during the recovery period from conditions which had existed during the loaded period. One possible source of error in creep recovery readings could relate to variations in either temperature or humidity in different parts of the creep laboratory. An examination of the spatial variation of environmental conditions in the creep laboratory indicated that the variation could be considered negligible.

Several comments can be made regarding the observed creep strain behavior:

1. As a result of the limitations of the instrumentation and the test procedure, from 1 to 15 minutes elapsed between the time the load was removed, and the time the readings were taken. As indicated by Davies (12),

the elastic recovery which was recorded would actually include a certain amount of creep recovery due to the time lapse.

An attempt was made to find the exact amount of elastic recovery by using the elastic modulus obtained when the prisms were unloaded. However, the effect of hysteresis produced non-linear stress-strain curves which eliminated the possibility of determining an acceptable elastic modulus. A typical unloading stress-strain curve is shown in Figure 5.

2. It also appears that in previous investigations of creep recovery, the time between loading and unloading was much shorter than the 2- or 3-year time interval in this study (6,11). It is possible that the cement in the specimens in the previous investigations was not completely hydrated at the time the specimens were unloaded. However, in this study it is reasonable to assume that a 2-year period would be sufficient for the hydration process to stabilize. As the cement hydrated, and the concrete subsequently hardened while the specimen was under load, the structure of the material itself may have developed a residual stress. After the load was removed, it is possible that a certain amount of time would be required for the structure of the material to readjust and relieve this residual stress. This could account for the initially slow rate of creep recovery.

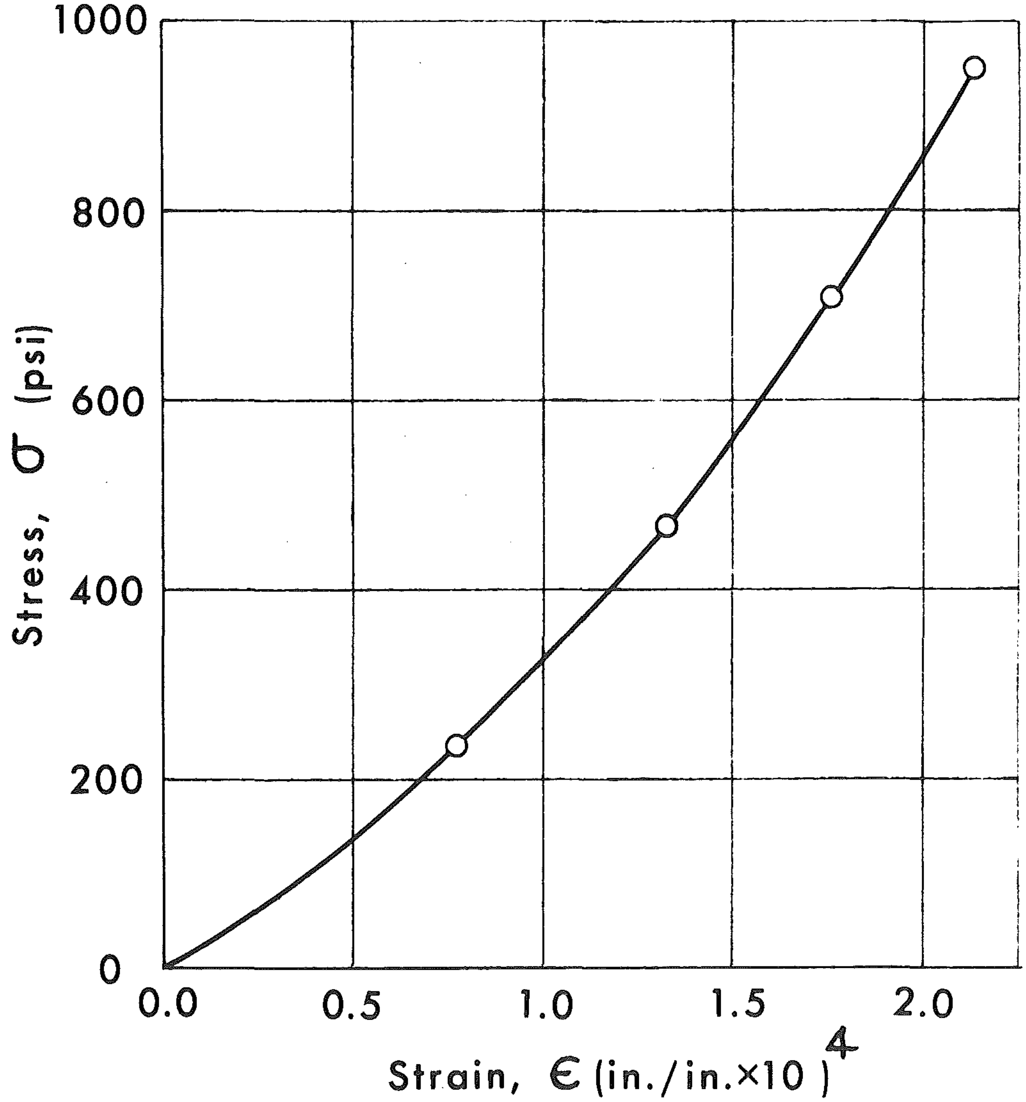

Figure 5. Unloading stress-strain curve

Specimen 4.12

3. The application of stress before the concrete was completely dry may have inhibited free moisture movement. It is believed that the application of load to a concrete specimen will squeeze water out of the pores and force it to the surface. It is possible, however, that this application of load may have prevented free moisture movement by restricting capillary action, reducing pore sizes, and creating negative pore pressures.

   After the removal of the load and the gradual relief of the residual stresses, moisture movement would become less restricted, and additional shrinkage could occur.

By superimposing the strains which would occur from the phenomena discussed in comments 2 and 3 above, the creep strain recovery behavior observed in this study would result. (See Figure 6.)

The results of previous investigations indicate that at the end of a 2- to 3-week period, the creep strain recovery is essentially complete (12, 13). The results of this study at least partially support this finding in that the process of creep recovery was observed to occur at a much faster rate than creep. Complete recovery appeared to have occurred within from 3 to 8 weeks after the load was removed. The average time required to reach the maximum recovery was 5 weeks.

If measurements taken by earlier investigators were discontinued at the time when the specimens had apparently completed recovery (see Figure 6), the subsequent decrease in creep strain recovery would not have been observed.

In addition to a qualitative study of creep strain recovery behavior, this study was also designed to provide information regarding the effects of constituents, environment, age at loading, and previous stress level on the creep strain recovery behavior. It was found, however, that the accuracy of the instrumentation was insufficient to allow the formulation of definite conclusions. The maximum amount of creep recovery recorded was 0.5×10^{-4} in./in. The average for the 23 prisms tested was 0.326×10^{-4} in./in. It can be seen that the creep recovery strains for all prisms tested, regardless of the constituents or environment, were much smaller than the total creep strains which generally ranged from 5 to 10×10^{-4} in./in.

Unloading and Immediate Reloading

The third objective of this study was to observe the behavior of specimens which had been under load for several years and were then unloaded and immediately reloaded. As mentioned in Chapter I, there appears to have been no previous research on creep strain behavior under such conditions. The results of this investigation indicate that this loading cycle produces additional creep strain above the value which would have occurred if the specimen had remained under load. A typical strain-time curve resulting from this test procedure is shown in Figure 7. Actual values

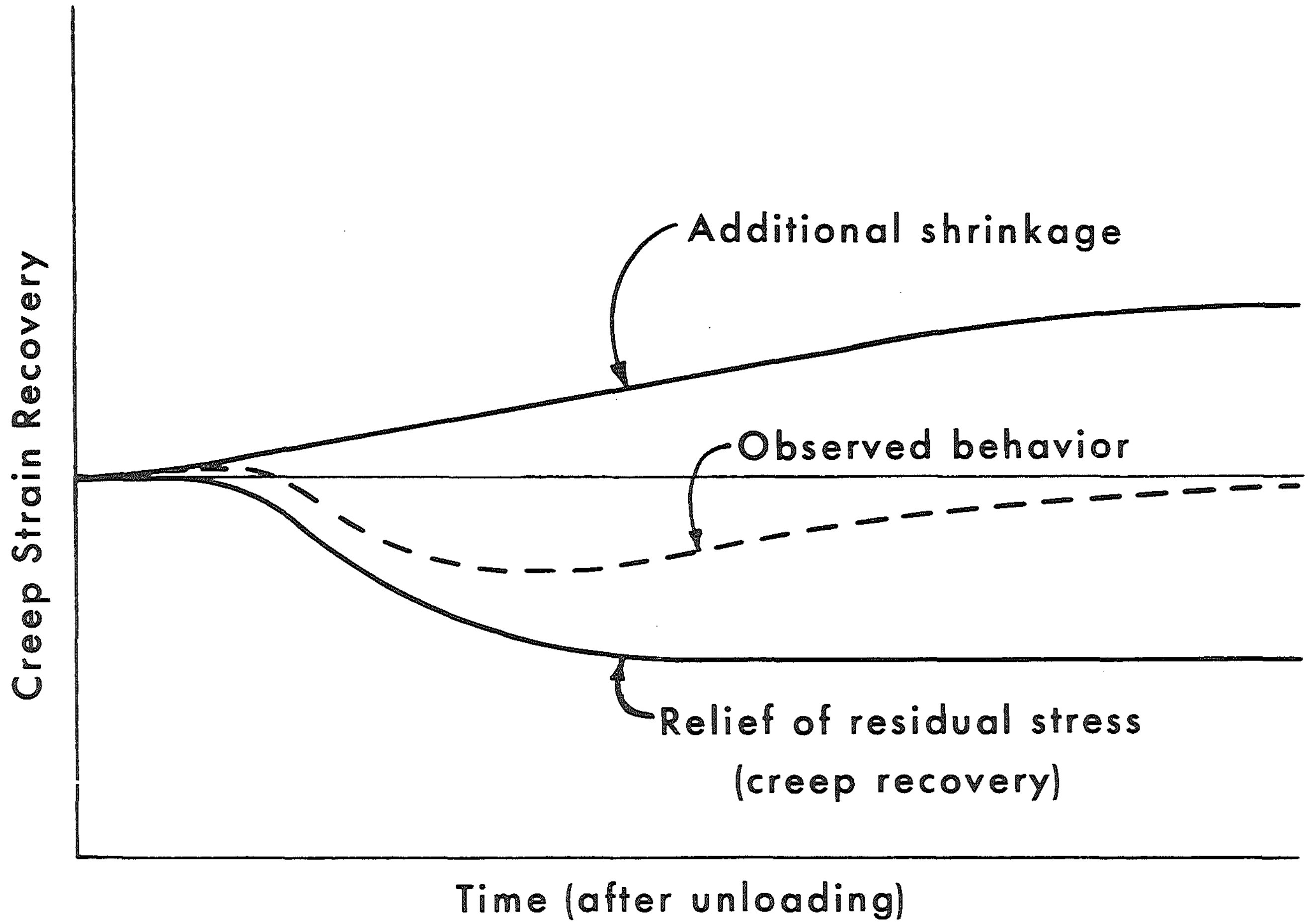

Figure 6. Postulated recovery behavior

for all specimens are presented in Table III.

As the Figure indicates, the elastic recovery is greater than the elastic strain recorded upon the reapplication of the load. It should be noted that the elastic recovery in this case would also contain some creep recovery for the same reason stated in comment 1 of the previous section.

The creep strains reached at approximately 80 days after the load cycle were from 0.017×10^{-4} in./in. to 0.983×10^{-4} in./in. greater than the creep strain of the prism prior to the load cycle. The average additional creep strain increment was 0.306×10^{-4} in./in. This would tend to indicate that a prism subjected to a fatigue condition would exhibit larger creep strains than an identical prism subjected to a sustained load.

It is of interest to note that the 4 in. by 4 in. prisms were, in general, more affected by the load cycle than were the 3 in. by 4 in. prisms. The average additional creep strain increment exhibited by the 3 in. by 4 in. prisms was 0.22×10^{-4} in./in., while the average increment exhibited by the 4 in. by 4 in. prisms was 0.733×10^{-4} in./in. A study of this observation failed to reveal any apparent explanation.

Creep of Preshrunk Specimens

The fourth objective of this study was to compare the creep of preshrunk specimens to the basic or viscous creep as predicted by Ali and Kesler (8). Basic creep, as defined in Chapter I, is the creep occurring under conditions of no moisture exchange with

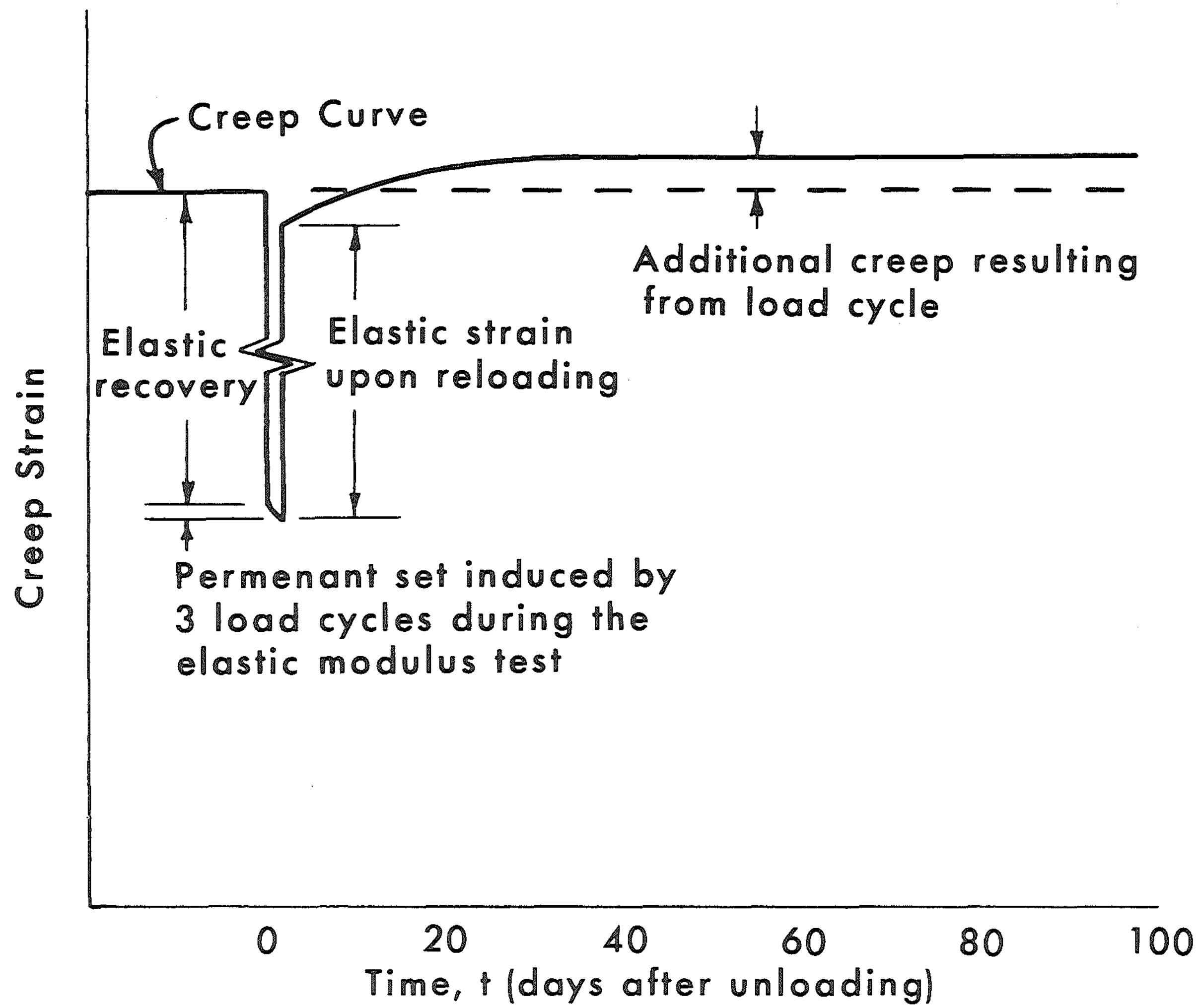

Figure 7. Typical reloading behavior

TABLE III
Unloading and Immediate Reloading Data

Spec-imen	(in x 10^{-4}) C bef. U.L.	(in x 10^{-4}) C aft. U.L.	Δ in. x 10^4	Strain Increment (in/in x 10^4)
4.12	36.5	40.3	+ 3.8	0.63
4.22	36.3	36.4	+ 0.1	0.02
4.32	54.1	55.4	+ 1.3	0.22
5.12	41.5	43.3	+ 1.8	0.30
5.13	41.5	44.9	+ 3.4	0.57
5.22	43.4	44.3	+ 0.9	0.15
5.23	41.4	41.8	+ 0.4	0.07
5.32	48.5	50.3	+ 1.8	0.30
5.33	44.9	45.0	+ 0.1	0.02
6.12	41.2	42.0	+ 0.8	0.14
6.22	30.7	31.8	+ 1.1	0.18
6.32	19.4	19.8	+ 0.4	0.07
9.13	20.5	21.4	+ 0.9	0.15
9.23	59.1	60.8	+ 1.7	0.28
9.33	64.4	67.2	+ 2.8	0.47
12.12	50.2	52.4	+ 2.2	0.37
12.22	44.8	45.9	+ 1.1	0.18
12.32	26.4	27.0	+ 0.6	0.10
13.12	38.2	39.4	+ 1.2	0.20
13.22	42.4	42.6	+ 0.1	0.02
19.12	13.9	17.8	+ 3.9	0.65
19.13	11.9	14.4	+ 2.5	0.41
20.12	44.5	50.4	+ 5.9	0.98
20.13	44.3	49.6	+ 5.3	0.88

the environment. The results of this study indicate conclusively that the creep obtained by loading preshrunk prisms is only one-half to one-third of the basic creep as predicted by Ali and Kesler. A typical comparison of the observed creep and the proposed basic creep is shown in Figure 8.

In the experimental investigations of Ali and Kesler, the rheological model constants were obtained by fitting their proposed basic creep equation to creep curves obtained by loading a number of specimens which were approximately 100 days old. All of the preshrunk specimens tested and reported in this paper were at least 1100 days old when they were loaded. Previous investigations have shown that as age at loading increases, creep decreases (7). Therefore, if two identical specimens were loaded at the age of 100 days and 1100 days respectively, the 100-day old specimen would be expected to exhibit larger creep strains than the 1100-day old specimen.

The results of this study indicate that basic creep, just as total creep, is a function of the age of the specimen at loading. It appears that the basic creep concept cannot be universally applied until some method of incorporating the age at loading is introduced. In other words, it appears that basic creep may not be simply defined as the creep occurring under conditions of no moisture exchange with the environment, but should also include some reference to the age of the specimen at loading.

It is also possible that the method of computing the gel compliance factor is not completely accurate. A reduction of

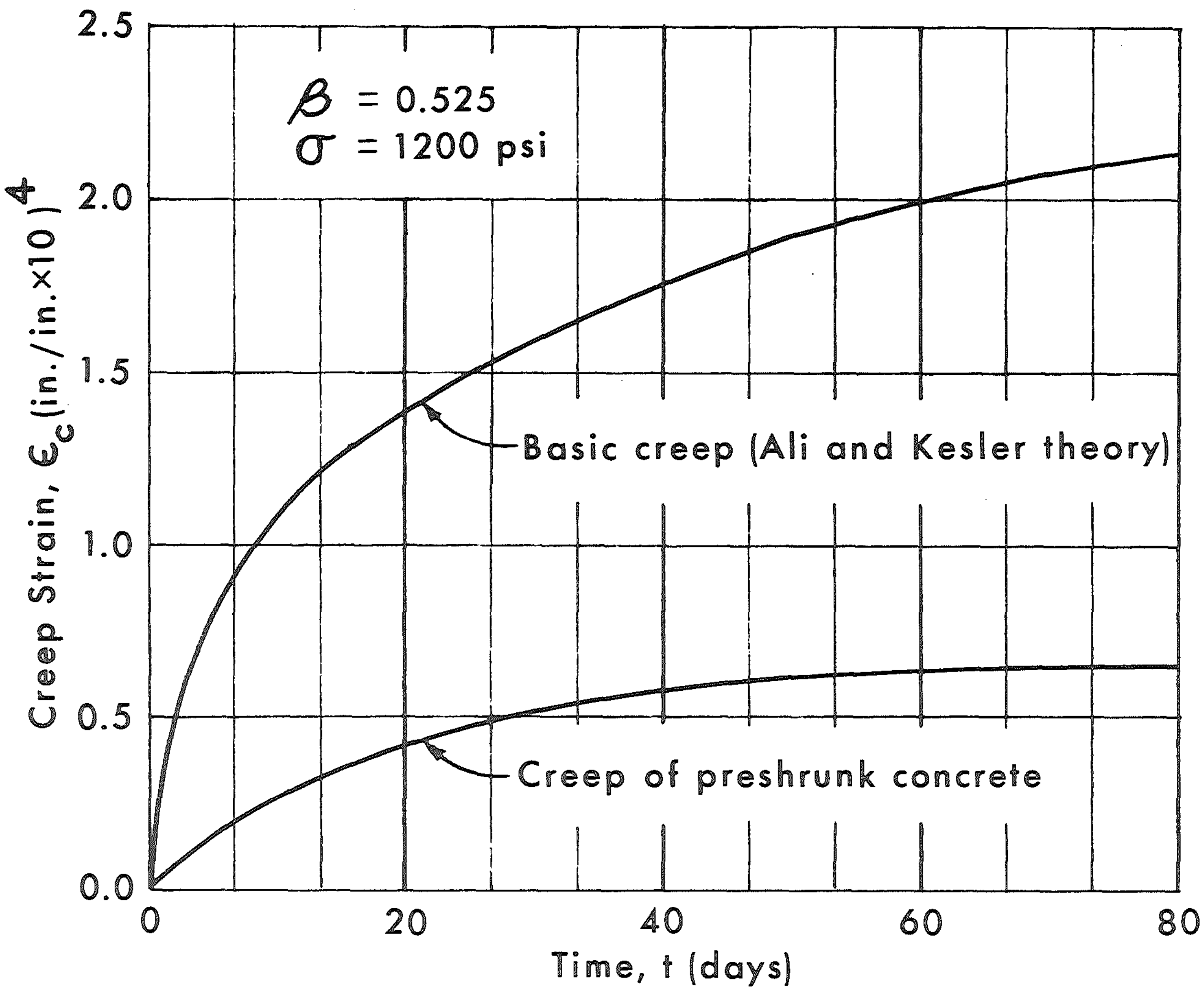

Figure 8. Basic creep and creep of preshrunk concrete

the gel compliance factor would have the effect of reducing the magnitude of the predicted basic creep strain. The results of this study indicate that this reduction of magnitude in itself would not be sufficient to correlate the observed results to the predicted creep, since the observed creep curves did not exhibit the rapid initial creep rate predicted by the basic creep strain equation.

Elastic Modulus and Strength

The fifth objective of this study was to examine the effect of time, constituents, and environment on the elastic modulus and strength of plain concrete prisms. All values of strength and elastic modulus were determined from the same specimens used in the examination of the other objectives of the report. As a result of the test procedure which was adopted, it was possible to obtain measurements, during the loading operation, to determine the elastic properties of a number of the prisms. The modulus of elasticity as defined in this paper is the value obtained by approximating the stress-strain curve with a straight line. Figure 9 shows a typical stress-strain curve and the straight line approximation.

It was standard procedure in the test program to load four creep racks (12 prisms) simultaneously. This procedure required approximately three hours to complete. As a result of the slow rate of loading and measurement, the stress strain relationship as shown in Figure 9 is nearly linear. The same loading procedure

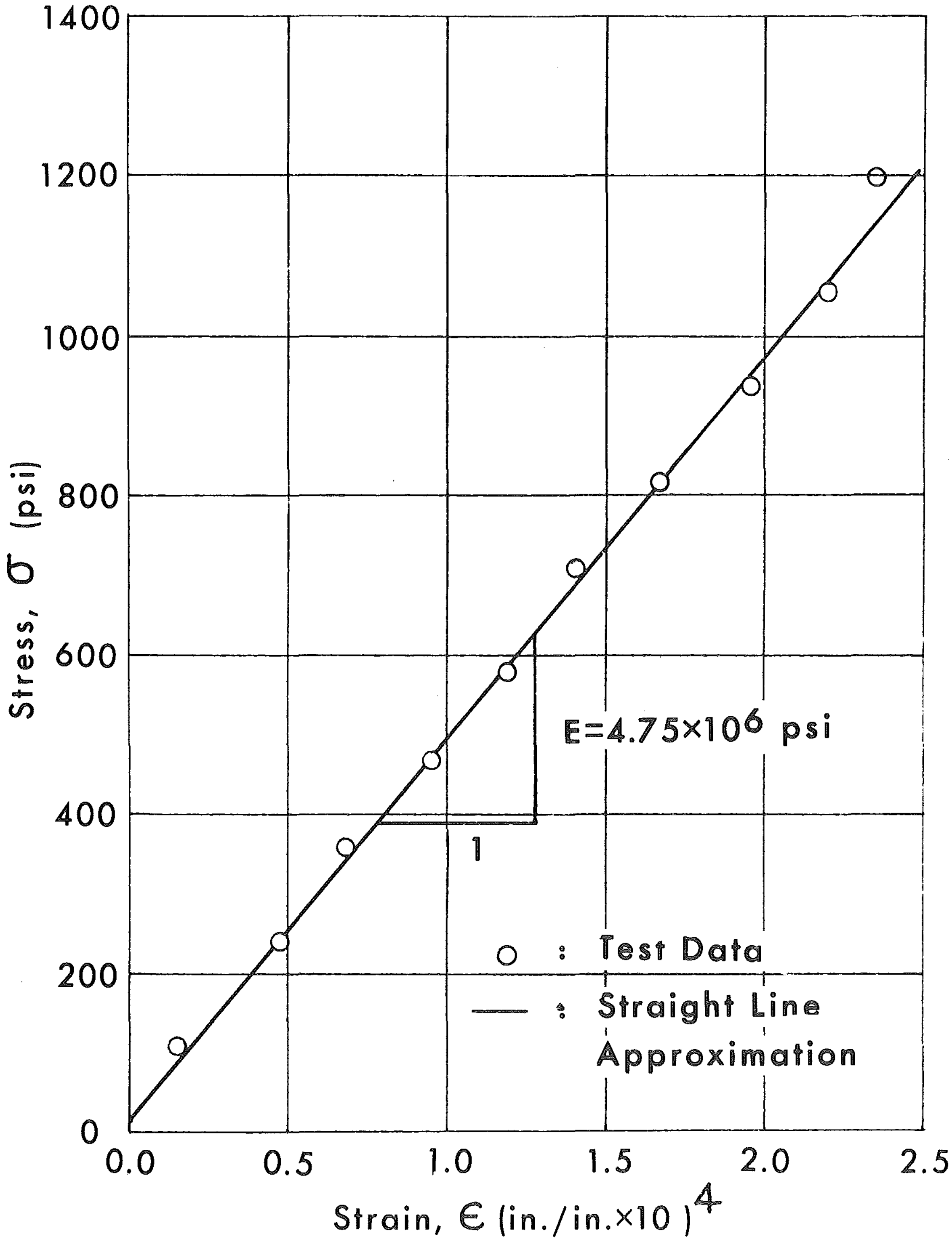

Figure 9. Loading stress-strain curve
Specimen 4.22

and elastic modulus definition was used in the previous study (5). This allowed a comparison of the original modulus of elasticity and the modulus which was found to exist at the time of this study.

In order to simplify the presentation of the experimental results of this study, the following terms will be introduced and defined for future reference:

Original modulus - modulus of elasticity existing at the time the prism was originally loaded;

Final loaded modulus - modulus of elasticity of a prism which had been under sustained load (creep prism);

Final unloaded modulus - modulus of elasticity of a prism which had not previously been subjected to any loading (shrinkage prism).

The experimental results which were obtained in this part of the study are presented in Table IV. It can be seen that the elastic modulus generally decreases with time, except in the case of those prisms which were loaded at early ages. It should be noted also that specimens which had been under load generally had a higher modulus than specimens which were unloaded for the same time period. This result is to be expected since the load would have the effect of increasing the density of the concrete. The increased density would yield a more rigid body.

The results of the ultimate compressive strength tests are also shown in Table IV. The original ultimate strength as listed

TABLE IV
Elastic Modulus and Strength Data

Spec	Modulus of Elasticity					Ultimate Strength		
	Orig $psix10^6$	Final Ldd $psix10^6$	Final Unldd $psix10^6$	Δ Ldd % Orig	Δ Unldd % Orig	Orig psi	Final psi	Δ % Orig
2.1	6.67	5.23	4.90	-21.6	-26.5	4560	4280	-6.1
2.2	6.03	5.00	4.65	-17.1	-23.0	4460	4365	-2.1
2.3	6.50	5.02	4.55	-22.8	-30.0	4690	4075	-13.1
3.1	4.85	-	4.65	-	-4.1	4790	3780	-21.1
3.2	4.89	-	4.30	-	-12.1	5500	4065	-26.1
3.3	5.63	-	4.80	-	-14.8	5380	4075	-24.2
4.1	5.88	4.76	4.95	-19.0	-15.9	5560	4305	-22.6
4.2	5.41	4.86	4.75	-10.2	-12.2	5630	4550	-19.2
4.3	6.50	5.15	5.15	-20.8	-20.8	5170	4285	-17.1
5.1	6.58	6.75	5.10	2.6	-17.5	5380	4390	-18.4
5.2	6.36	6.50	5.13	2.2	-19.3	5920	4610	-22.1
5.3	6.76	6.09	5.00	-9.9	-26.0	5460	4730	-13.4
6.1	6.81	5.32	4.70	-21.9	-31.0	5230	4680	-10.5
6.2	6.25	5.55	5.05	-11.3	-19.2	5540	4940	-10.9
6.3	6.47	-	4.95	-	-23.5	8420	7580	-10.0
7.1	5.79	-	6.28	-	11.8	3890	4760	22.4
7.2	4.63	-	5.20	-	12.3	2790	2920	4.7
8.1	4.50	-	4.65	-	3.3	2150	3740	74.0
8.2	4.37	-	5.65	-	29.2	2390	3435	47.6
8.3	5.67	-	5.40	-	-4.8	2150	3635	69.0
9.1	7.11	6.65	4.97	-6.5	-30.1	8880	6980	-21.4
9.2	5.63	4.78	4.41	-15.1	-21.7	3430	3080	-10.2
9.3	5.23	6.17	5.35	18.0	2.3	3460	3650	5.5
12.1	6.03	6.00	5.12	-0.5	-15.1	5420	4170	-23.0
12.2	5.17	5.88	5.40	11.8	4.5	4580	3730	-18.6
12.3	5.19	4.02	-	-22.6	-	-	3205	-
13.1	6.18	5.90	5.93	-4.5	-4.1	4410	5200	17.9
13.2	6.18	6.59	5.92	6.6	-4.2	4640	3860	-17.5
13.3	6.23	-	5.86	-	-	4640	4660	0.4
15.1	2.49	-	-	-	-	4730	5090	7.1
15.2	2.03	-	-	-	-	4200	4610	9.8
15.3	-	-	-	-	-	4850	6030	24.3
19.1	6.02	5.84	4.46	-3.0	-25.9	6000	5790	-3.5
20.1	2.43	2.93	2.25	21.4	-7.4	5290	5620	6.2
21.1	5.19	-	5.11	-	-1.5	3250	3210	-1.2
21.2	4.59	-	5.11	-	11.3	2760	2650	-4.0
21.3	4.29	-	4.51	-	5.1	2290	2440	6.5
22.1	4.71	-	-	-	-	4210	3920	-6.9
22.2	4.55	-	-	-	-	3720	3870	4.0
22.3	5.57	-	-	-	-	4200	4440	5.7
23.1	-	-	-	-	-	4235	3960	-6.5
23.2	-	-	-	-	-	3300	3270	-0.9

in the table is based on the result of testing one unloaded companion prism. In most cases, the final ultimate strength was found by averaging the results of testing two prisms which had been under load (creep prism), and one prism which had not been under load (shrinkage prism).

The strengths of the loaded prisms and the unloaded prisms were examined individually before they were averaged. It was found that the absence or presence of the 900 psi, 1200 psi, or 2500 psi stress had essentially no effect on the ultimate strength of the concrete. In 30 percent of the prisms tested, the strength of the shrinkage prism was greater than the strength of the creep prisms, and in the remaining 70 percent, the strength of the creep prisms were greater than the strength of the shrinkage prism. This would imply that the effect of sustained load on the compressive strength is comparatively small.

This study did reveal, however, that time has a significant effect on the strength of the concrete. Several comments can now be presented, which point out observed general trends.

1. Prisms which were loaded before they had reached their 28-day strength showed an increase in strength over the strength which existed at the time the prisms were loaded. The amount of the increase in strength was a function of the age of the prism at loading. Those prisms loaded at 2 days showed a greater increase in strength than those loaded at ages greater than 2 days.
2. Normal weight prisms which were loaded after the prisms

had reached the 28-day strength generally showed decreases in the ultimate compressive strength. The amount of this decrease was as large as 25 percent in some cases. The average amount of the decrease, without regard to the other variables involved, was about 13 percent.

3. In general, the lightweight concrete prisms showed increases in strength over the recorded 28-day strength, regardless of their age at loading. This result is to be expected because in general lightweight concrete does not reach full strength until about age 90 days. This is caused by continued hydration of cement from water absorbed by the lightweight aggregate.

CHAPTER IV

SUMMARY

The conclusions and possible explanations for the observed phenomenon were presented in the previous chapter. These may be summarized as follows:

1. The creep strain recovery which occurs in plain concrete which has been under load for several years does not behave in the same manner which was observed to occur in specimens which were under load for a shorter period of time, i.e., for less than six months.
2. The magnitude of the creep recovery is generally only about five percent of the total creep. The comparatively small magnitudes which were observed yielded no conclusions on the effect of constituents or environment on the creep strain recovery behavior.
3. The procedure of unloading and immediately reloading plain concrete prisms produces additional creep strain above the value which would have existed if the specimen had remained under load. The magnitude of this additional creep strain increment was generally only approximately five percent of the total previous creep strain. This observation would tend to indicate that concrete subjected to a fatigue condition would exhibit larger creep strains than concrete under sustained load.

4. The basic creep or viscous creep as predicted by Ali and Kesler is from two to three times the creep strain obtained by loading preshrunk concrete prisms. It appears that age at loading is an important function of the basic creep phenomenon.

5. The elastic modulus of concrete which had been loaded after the concrete had reached its 28-day strength generally decreased with time. The amount of this decrease in elastic modulus was found to be as much as 30 percent of the original value in some cases.

   It was also found that prisms which were under a sustained load generally maintained higher elastic moduli than prisms which were not under load.

6. The ultimate compressive strength of the concrete generally decreased with time from the value of the 28-day strength. Some of the prisms showed as much as a 25 percent decrease in strength.

   It was observed, however, that the absence or presence of load had essentially no effect on the strength of the concrete.

   It should be noted in items 5 and 6 above that the environment in which the specimens were studied ($70^{\circ}F$ and 50% relative humidity) is essentially a drying condition. Concrete in normal service will receive more moisture than was available in the test laboratory.

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