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Shrinkage and Creep in Prestressed Concrete

Perry H. Petersen and David Watstein

Building Research Division
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CONTENTS

Shrinkage and Creep in Prestressed Concrete

Perry H. Petersen* and David Watstein**

The loss of prestress resulting from creep and shrinkage in concrete was investigated for concrete specimens made with Type I portland cement and with Type III portland cement. The primary variables in this study were:

1. Relative humidity at which the concrete was maintained while under observation.
2. Age of the concrete at the time it was prestressed.
3. Ratio of prestress to strength; variation of this parameter required that the ratio of reinforcement be a variable.
4. Mass ratio factor defined as the ratio of the cross-section area of concrete specimen to its surface area per unit length.

Forty-nine sets of specimens were fabricated and tested; each set consisted of a prestressed specimen and an otherwise identical companion specimen without reinforcement.

The length changes with time were observed at intervals up to an age of 500 days. These observations were made for concretes subjected to different levels of prestress, and for concretes prestressed at different ages. Length changes in nonreinforced companion specimens were also obtained. Thus this study is concerned with elastic deformation occurring at time of stress transfer, shrinkage or swelling, and creep.

Key Words: Creep, relaxation, prestressed concrete, shrinkage, loss of prestress, variable prestress.

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1. Introduction

The advantages of prestressed concrete over conventional reinforced concrete are well known and have been amply demonstrated by numerous projects both in the United States and abroad. As is true of all relatively new materials, however, some properties of prestressed concrete remain to be fully explored. One of these is that loss of prestress in pretensioned concrete elements wherein the steel wire or cable is prestressd beforehand and the concrete is placed around the steel and bonded to it. Many investigators have studied the strains in concrete subjected to constant stress, and in one instance, observations were continued past the 20-year mark [1][1]. One investigator was concerned in part with stress relaxation in concrete at *constant strain* [2]. Thus it may be that new data reported herein have much significant value to the researcher as well as to the designer and engineer inasmuch as this study encompasses creep in the concrete coupled with the loss of prestress in bonded wires.

This investigation was carried out at the National Bureau of Standards with concrete specimens made with normal (Type I) Portland cement and with high-early strength (Type III) portland cement. Loss of prestress with age was obtained from the observed strains for different intensities of prestress. The study was carried out with symmetrically reinforced test specimens of various sizes having different ratios of cross-sectional area to surface area per unit of length, herein designated as mass ratio.

[1] Figures in brackets indicate the literature references at the end of this paper.

2. Materials

2. 1. Concrete

The concrete was proportioned 1:1.5:2.0 by dry weight of cement, sand and pea gravel. A normal Type I cement and a Type III cement meeting the requirements of federal specifications for their respective types were used. The sieve analysis, absorption, and specific gravities were determined for the sand and the pea gravel; these data are given in table 1.

Table 1. *Sieve analyses, absorptions and specific gravities of concrete aggregates*

U. S. standard sieve sizes	Sand percent passing	Gravel percent passing
½ in	100	99.0
⅜ in	100	98.7
No. 4	94.7	31.1
No. 8	69.8	6.0
No. 16	47.9	3.0
No. 30	28.0	2.0
No. 50	7.6	1.3
No. 100	.8	.8
No. 200	.3	.5
Absorption, percent by weight	.9	1.1
Bulk specific gravity, saturated surface dry	2.61	2.6

The concrete was mixed in a 6-cu ft rotary drum mixer for about 4 minutes and then placed in the wood forms and vibrated in place. After several hours, the top was screeded level and the concrete covered with wetted burlap. The forms were removed at 2 days and the specimens were stored under wet burlap until time for transfer of prestress.

The water-cement ratios, slump, and the compressive strengths of the concretes in the various specimens are given in table 2.

Table 2. *Water-cement ratio, slump, compressiv e strength and modulus of elasticity of concretes*

Type I cement concretes

Group No.	Set No.	Water-cement ratio by weight	Compressive strength of 6- by 12-in cylinders: Slump	7 day 100%RH [f]	28 day 100%RH [f]	28 day 50%RH [f]	1 year 100%RH [f]	1 year 50%RH [f]	Modulus of elasticity [e]
			in	*psi*	*psi*	*psi*	*psi*	*psi*	*psi*
1	1 through 6	0.53	7.5	3360	5200	----	7500	[b] 6150	3,690,000(28 da)
2	21 through 26	.52	7.0	3600	5150	[a] 5530	7020	[a] 5550	2,720,000(7 da)
5A	73, 74	.55	7.2	3960	5710	----	6910	[b] 6220	3,770,000(28 da)
5B	71, 72	.57	7.2	3770	5960	[a] 5740	6950	[a] 5180	2,850,000(7 da)
6	101 through 106	.53	7.2	4450	5990	----	8270	[b] 7000	3,860,000(28 da)
7	121 through 126	.51	7.6	3230	5470	[a] 5640	7360	[a] 4840	2,800,000(7 da)

Type III strength cement concretes

Group No.	Set No.	Water-cement ratio by weight	Compressive strength of 6- by 12-in cylinders: Slump	3 day 100%RH [f]	12 day 100%RH [f]	12 day 50%RH [f]	1 year 100%RH [f]	1 year 50%RH [f]	Modulus of elasticity [e]
			in	*psi*	*psi*	*psi*	*psi*	*psi*	*psi*
3A	42 through 45	0.54	5.5	3800	5600	----	5730	[d] 5700	3,400,000(12 da)
3B	41, 46	.54	5.5	3770	5810	[c] 5600	7760	[c] 6170	2,670,000(3 da)
4A	61, 62	.57	6.0	3920	5140	----	6760	[d] 6390	3,330,000(12 da)
4B	63	.57	6.0	3370	5580	[c] 5470	6800	[c] 6370	3,170,000(3 da)
8	141 through 146	.56	5.5	3330	4970	----	7200	[d] 6230	3,270,000(12 da)
9	161 through 166	.55	5.7	3490	5910	[c] 5920	8340	[c] 6480	2,390,000(3 da)

[a] Cured at 100% RH first 7 days.
[b] Cured at 100% RH first 28 days.
[c] Cured at 100% RH first 3 days.
[d] Cured at 100% RH first 12 days.
[e] The modulus was the secant value obtained at the age corresponding to transfer of prestress for a stress level equal to the average initial prestress.
[f] Storage condition after initial moist cure.

2.2. Steel Reinforcement

The reinforcement consisted of steel spring wire 0.1125 inches in diameter having a modulus of elasticity of 28,000,000 psi and a tensile strength of 233,000 psi.

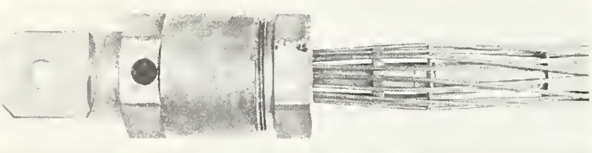


Figure 1a. *View of prestressing unit showing a close-up of the wires and spacers.*

In fabricating the smallest specimens, the six square molds were placed in line on a common axis, and external anchorages were used in tensioning the four wires extending through the molds in series. Steel spreaders were used to obtain the necessary alinement of the four wires in the prisms of three different sizes. However, in larger prisms requiring 16, 48, or 64 wires, one, three, or four symmetrically placed self-contained units were used. These were designed by the late H. Schorer, Borsari Tank Co., New York City. A short section of a unit is shown in figures 1a and 1b. Each unit consisted of two groups of eight wires each, wound over a center member in a clockwise and counter-clockwise direction, respectively, so as to balance the torsional moments. The individual wires were held in position by stamped

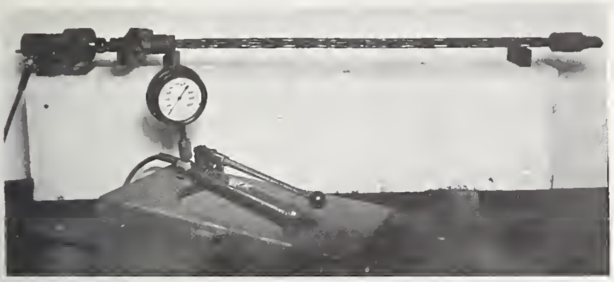


FIGURE 1b. *Complete self-contained fabricated 16-wire prestressing unit 52 in long and hydraulic jack.*

spacer discs located at regular intervals. The core of the unit consisted of a precisely centered ½-in diameter cold-drawn and heat-treated steel rod which served as the temporary compression member. It was enclosed within a paper tube to prevent bond to the concrete thereby facilitating subsequent removal of the rod. All wires in one unit were connected rigidly at one end to a gripping member while at the other end, the wires were held by a loading device which permitted them to be stressed in tension while the compressive reaction was borne by the center rod.

3. Specimens

A list of sets of specimens is given in table 3 for those made with Type I cement, and in table 4 for those made with Type III cement. In all, there were 49 sets of prisms, each set consisting of a pair of identical specimens, except that one of each set was reinforced and one was not. The unreinforced specimens served as controls to determine the shrinkage or swelling. In addition, 6- by 12-in. cylinders were made from each batch of concrete for determination of compressive strength and elastic properties at the required ages; these stress-free cylinders were cured and stored under the same environmental conditions as the prisms. Specimens were arranged in groups identified by numerals given in tables 3 and 4. The molds for reinforced specimens of a given group were arranged in line and the specimens were cast around the same set of tensioned wires. Specimens in a given group but cast on different dates are further identified by letters following the group numbers. The specimens were in the form of square prisms in the smaller sizes, and octagonal or hexagonal prisms in the larger sizes. The number of wires, dimensions of the specimens, gage lengths, type of cement, and curing conditions subsequent to prestressing are all given in table 3 and 4. *Mass ratio* as used here and elsewhere in this paper is defined as the ratio of the net cross-sectional area of concrete to the surface area of the specimen per unit of length. All the specimens were wet cured up until the age at which the prestress force was transferred to the concrete. The ends of prisms were coated with asphalt to eliminate moisture transfer at the ends.

The wires were pretensioned at least a week in advance of placing concrete so as to eliminate as far as possible all effects of creep of steel or readjustment of the pretensioned units that might

TABLE 3. *Specimens made from Type I cement concrete*

Group No.	Set No.	Shape	Gross area of concrete	Net area of concrete	Mass ratio	No. of wires	Ratio of reinforcement	Length	Gage length	Age of concrete at time of transfer of prestress	Relative humidity [a]
			sq in	sq in			Percent	in	in	Days	Percent
1	1	Octag	17.22	16.69	1.14	16	0.94	67	20	28	100
1	2	do	17.37	16.84	1.15	16	.94	67	20	28	50
1	3	do	10.73	10.20	0.90	16	1.53	52	20	28	100
1	4	do	10.55	10.02	.89	16	1.56	52	20	28	50
1	5	do	7.45	6.92	.75	16	2.25	45	20	28	100
1	6	do	7.25	6.72	.74	16	2.31	45	20	28	50
2	21	Octag	17.44	16.91	1.15	16	0.93	67	20	7	100
2	22	do	17.52	16.99	1.15	16	.93	67	20	7	50
2	23	do	10.97	10.44	0.91	16	1.50	52	20	7	100
2	24	do	10.61	10.08	.90	16	1.55	52	20	7	50
2	25	do	7.55	7.02	.75	16	2.21	45	20	7	100
2	26	do	7.25	6.72	.74	16	2.31	45	20	7	50
5B	71	Hex	31.91	30.32	1.52	48	1.55	72	20	7	50
5B	72	do	31.70	30.11	1.51	48	1.56	72	20	7	100
5A	73	do	30.87	29.28	1.49	48	1.60	72	20	28	50
5A	74	do	31.70	30.11	1.51	48	1.56	72	20	28	100
6	101	Square	4.08	4.04	0.50	4	0.97	32	10	28	100
6	102	do	4.14	4.10	.50	4	.96	32	10	28	50
6	103	do	2.54	2.50	.39	4	1.56	32	10	28	100
6	104	do	2.53	2.49	.39	4	1.57	32	10	28	50
6	105	do	1.76	1.72	.32	4	2.26	32	10	28	100
6	106	do	1.79	1.75	.32	4	2.22	32	10	28	50
7	121	Square	4.09	4.05	.50	4	0.97	32	10	7	100
7	122	do	4.18	4.14	.50	4	.95	32	10	7	50
7	123	do	2.50	2.46	.39	4	1.59	32	10	7	100
7	124	do	2.48	2.44	.39	4	1.60	32	10	7	50
7	125	do	1.74	1.70	.32	4	2.28	32	10	7	100
7	126	do	1.72	1.68	.32	4	2.31	32	10	7	50

[a] Storage conditions after transfer of prestress.

Table 4. *Specimens made from Type III cement concrete*

Group No.	Set No.	Shape	Gross area of concrete	Net area of concrete	Mass ratio	No. of wires	Ratio of reinforcement	Length	Gage length	Age of concrete at time of transfer of prestress	Relative humidity[a]
			sq in	*sq in*			*Percent*	*in*	*in*	*Days*	*Percent*
3B	41	Octag	10.43	9.90	0.89	16	1.58	52	20	3	100
3A	42	do	17.60	17.07	1.15	16	0.92	67	20	12	50
3A	43	do	10.97	10.44	0.91	16	1.50	52	20	12	100
3A	44	do	10.79	10.26	.90	16	1.53	52	20	12	50
3A	45	do	7.60	7.03	.76	16	2.21	45	20	12	50
3B	46	do	10.14	9.61	.88	16	1.63	52	20	3	50
4A	61	Octag	40.69	38.57	1.75	64	1.62	96	20	12	100
4A	62	do	41.27	39.15	1.76	64	1.60	96	20	12	50
4B	63	do	41.27	39.15	1.76	64	1.60	96	20	3	50
8	141	Square	4.13	4.09	0.50	4	0.96	32	10	12	100
8	142	do	4.08	4.04	.50	4	.97	32	10	12	50
8	143	do	2.53	2.49	.39	4	1.57	32	10	12	100
8	144	do	2.56	2.52	.39	4	1.55	32	10	12	50
8	145	do	1.80	1.76	.33	4	2.21	32	10	12	100
8	146	do	1.73	1.69	.33	4	2.30	32	10	12	50
9	161	Square	4.06	4.02	.50	4	0.98	32	10	3	100
9	162	do	3.95	3.91	.50	4	1.00	32	10	3	50
9	163	do	2.47	2.43	.39	4	1.61	32	10	3	100
9	164	do	2.45	2.41	.39	4	1.62	32	10	3	50
9	165	do	1.75	1.71	.33	4	2.27	32	10	3	100
9	166	do	1.79	1.75	.33	4	2.22	32	10	3	50

[a] Storage conditions after transfer of prestress.

tend to decrease the initial tension in the reinforcement. An initial steel tensile stress of 125,000 psi on each wire was recorded at the time the prestress was transferred to the concrete, except for specimens in sets No. 1-6, inclusive, for which the steel tensile stress was 119,000 psi. The wires were thoroughly cleaned with solvent before placing concrete in order to facilitate bonding throughout their length.

The gage lines in the prismatic specimens were either 5, 10, or 20 in. long. The gage points consisted of ½-in. long ¼-20 flat-headed brass screws embedded in the concrete surface merely by having the flat top surfaces lightly glued to the inside of the form faces prior to concreting. Upon removal of the forms, the flat surfaces were cleaned and gage lines established by drilling holes suitable for accommodating 5-, 10, or 20-in. Whittemore strain gages, this drilling being done during the period of moist curing with wetted burlap.

4. Procedure in Making Observations

When each of the prisms had reached the age at which the prestress was to be transferred to the concrete, initial readings were taken using the appropriate Whittemore strain gage (5-, 10-, or 20-in.). Then immediately upon the transfer of prestress further readings were taken, and these were continued at regular intervals of time up to an age of 500 days. Readings were taken on the nonstressed specimens every time they were made on the prestressed ones.

5. Efficiency of Stress Transfer, Steel to Concrete

In order to validate the basis upon which all the computations were made, it was necessary to determine that the change in strain gage readings on the concrete at midlength of prisms was indeed indicative and equal to that occurring in the embedded steel. The sets of specimens smallest in cross section were only 32 in. long. With these specimens in particular, it was especially questionable whether sufficient length had been allowed to fully develop the required anchorage outside of the center 10-in. gage length in order to assure that the concrete and steel did not slip relative to each other within that gage length. To check the development of bond between the wires and the concrete, 5-in gage lines were installed throughout the length on two faces of several of the shorter specimens; see figure 2, specimen No. 162.

Figures 3a and 3b graphically depict strain observations made along the length of Type I cement specimens; figures 4a and 4b are concerned with the Type III cement specimens. Since it was

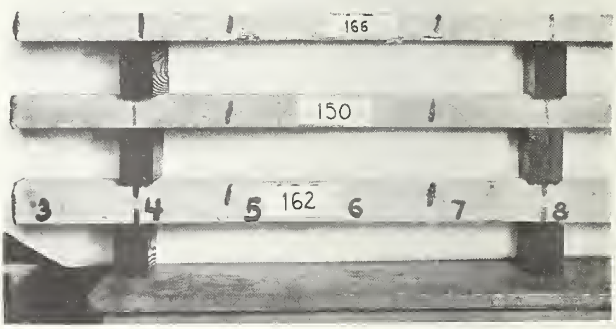
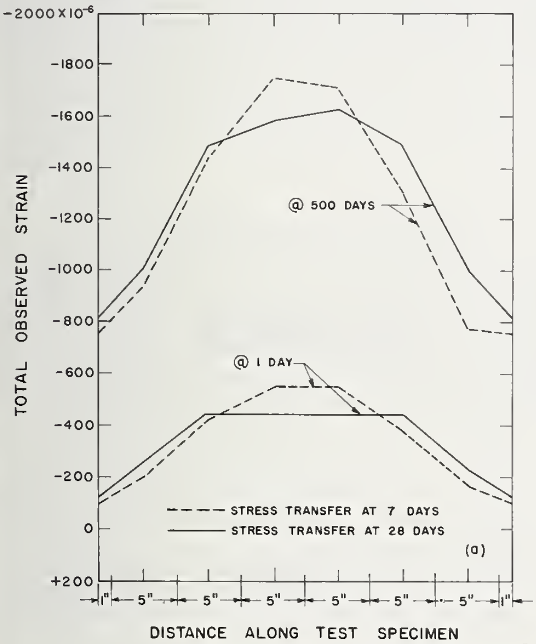


Figure 2. *Smaller specimens depicting detailed 5-in gage length on specimen No. 162 and typical center-spaced 10-in gage length on specimens No. 150 and 166.*

impractical to determine strain at the extreme end of each specimen, values for shrinkage or swelling from the nonstressed companion specimens were assumed to apply; this assumption introduces a slight error at the ends due to the restraint by the steel wires and their time-delay effect on strain and stress. First to be considered, figures 4a and 4b depict essentially a constant value of strain along the center 15 in of each specimen. Further consideration of the curves indicates that the constant deformation may indeed be applicable for more than the indicated 15-in gage line; note that the second gage line in from each end includes strains which occur within 6 in of the end of the specimen. Assuredly, the specimens made with Type III cement in all cases developed full bond within 8½ in of the end if not in a lesser distance. This conclusion is born out by G. Marshall [3] who measured development lengths in highly stressed wires 0.08 inches in diameter.

Figures 3a and 3b do not give the same assurance for specimens made with Type I cement. Here the specimens loaded at 28 days indicate that the required anchorage is developed in 6 to 8 in of length one day after stress transfer, whereas the required length increases with age up to 500 days. As mentioned previously, the strains are those based on gage lines 5 in long. It is clear that if the gage were shorter, the average strain indicated by each gage could be more nearly indicative of the true strain at the midpoint of each gage line. It is therefore reasonable to suppose that the length of the constant strain zone near the midsection of the specimens is longer than indicated in figures 3a and 3b since the points showing the "breaks" must of necessity lie below a smooth



(a) Specimens cured at 50 percent RH.

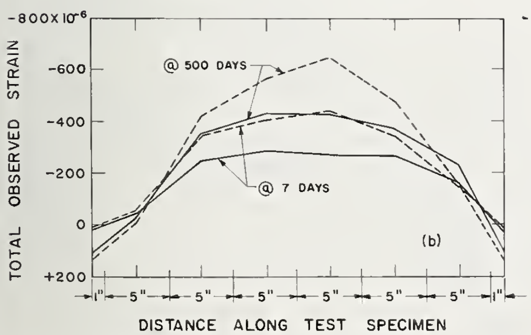
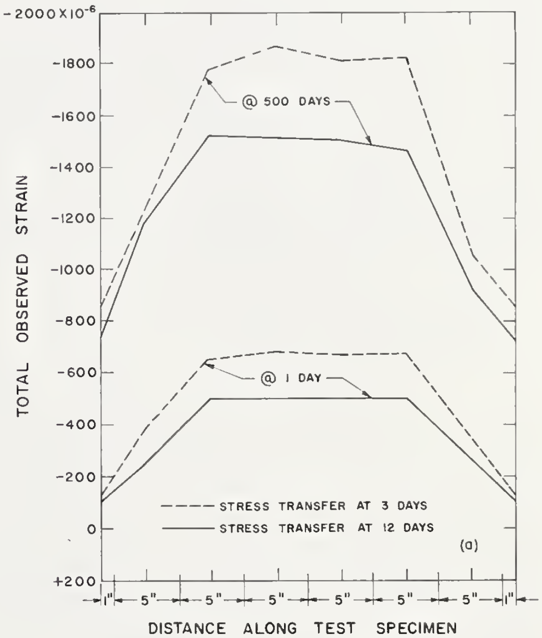


FIGURE 3. *Variation of compressive strain on surface of concrete along the length of 32-in specimens made with Type I cement.*

Times on graphs indicate age after stress transfer.

(b) Specimens cured at 100 percent RH.



(a) Specimens cured at 50 percent RH.

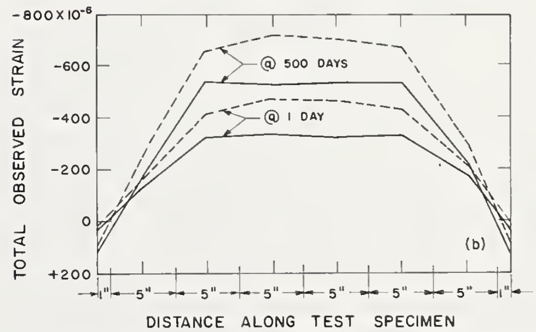


FIGURE 4. *Variation of compressive strain on surface of concrete along the length of 32-in specimens made with Type III cement.*

Times on graphs indicate age after stress transfer.

(b) Specimens cured at 100 percent RH.

curve based on a very large number of short gages. Therefore, it seems probable that the center 10-in gage length does represent true strains of fully bonded concrete and steel. Also, whereas these prestressed wires were 0.1125 inches in diameter and stressed to 125,000 psi, another investigator [3] has shown that 0.08-in wires prestressed to 200,000 psi developed end anchorage in less than 5 in initially, and in 7.5 in of length one year after stress transfer.

6. Basis of Computations

Immediately prior to transfer of the prestress load to the concrete, a check was made as previously mentioned to be certain that the magnitude of stress in the steel wires had not changed from the original level. With this assurance, initial strain gage readings were made on all the specimens in the group prestressed with the same unit. Upon release of prestress to the concrete, any change in gage length on the concrete was assumed to denote the same change in length in the steel. Thus, it was simple to compute the residual total load still imposed by the steel wires, and from this, the concrete compressive stress based on net area of concrete.

Whereas the deformation in the steel was taken as purely elastic, the deformation in the concrete was assumed to consist of three parts:

a. Elastic deformation
b. Shrinkage or swelling deformation.
c. Creep or plastic flow.

The elastic deformation upon transfer of the prestress to the concretes was assumed to follow closely the stress-strain curves obtained on the 6- by 12-in cylinders. Stress-strain curves were actually obtained on five sets of cylinders representing ages of 7 days, 28 days, and 1 year for each concrete made with Type I cement, and 3 days, 12 days, and 1 year for each concrete made with Type III cement. Cylinders cured at relative humidities of both 50 and 100 percent were included in each set for all but the earliest ages for each concrete.

The graphs in figures 5 and 6 illustrate the method by which the strain in the concrete was analyzed. The straight line in figure 5 passing through points A and B was constructed to represent the relationship between the observed strain ϵ_c and the residual stress in the concrete computed from the remaining tensile force in the prestressing unit. Point A was obtained from the strain on the surface of concrete observed immediately after stress transfer and the stress in the concrete computed from the remaining tension in the steel at that time; point B was obtained from the observed total strain ϵ_c at some chosen age of specimen and the similarly computed residual stress in the concrete. The value of ϵ_c is equal to the summation of elastic strain, creep, and shrinkage or swelling in the concrete.

Although Washa and Fluck [4] reported an increase in the moduli of elasticity associated with sustained loading, the authors made use of the moduli of previously unloaded specimens in analyzing their test results. In order to determine the magnitude of elastic strain included in ϵ_c, stress-strain curves were plotted, as in figure 6, for several ages, covering at intervals the entire range of ages in the creep measurements. When a particular specimen was being analyzed, the residual stresses were computed at ages for which the stress-strain curves were available. These values of residual stresses were then entered on the stress axis of figure 6 and points on the corresponding stress-strain curves were plotted. These points formed the locus of a generalized stress-strain curve (fig. 6) which permitted a determination of the elastic strain in a specimen at any age. The creep could thus be computed from the observed value of total deformation, the elastic

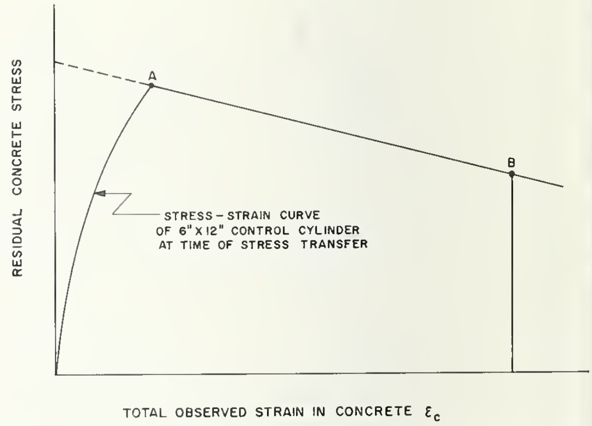


FIGURE 5. *A schematic relationship between total observed strain and the residual stress in the concrete.*

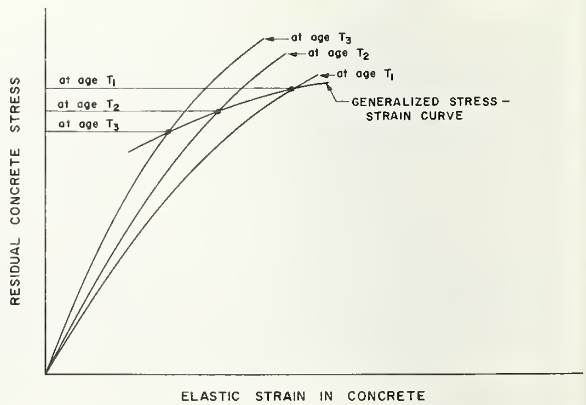


FIGURE 6. *Schematic diagram illustrating method for determination of the generalized stress-strain curve.*

strain at any age, and the observed shrinkage or swelling at that age.

The shrinkage or swelling of the concrete is determined by measuring the unstressed companion specimens. The creep strain is then computed by substracting the elastic strain and the shrinkage from ϵ_c; in case of swelling, the deformation is added to ϵ_c.

7. Test Results

Data pertinent to the concrete specimens made with Type I cement are given in table 5 and 6; those with the Type III cement in tables 7 and 8. Each table is divided into the two ages at which the prestress forces were transferred to the concrete. Creep, shrinkage or swelling, initial concrete prestress (allowing for elastic deformation only), and subsequent stress in the concrete at ages 1, 10, 100, and 500 days (reckoned from the time of transfer of prestress) were all determined as previously outlined. Also given is the prestress-strength ratio defined as the ratio of initial prestress at time of transfer of prestress to the actual strength of the concrete at that same age; see table 6 and 8.

8. Analysis and Discussion

Figure 7 depicts on semilog paper the data obtained on 6 of the 14 sets of specimens made with Type I cement and in which stress transfer was accomplished at age 28 days. Three of these (Nos. 1, 3, and 5) were stored at 100 percent relative humidity (RH), the other three (Nos. 2, 4, and 6) at 50 percent R.H. The top curves show the residual stress up to an age of 500 days. The center curves depict shrinkage of the 50 percent RH specimens and the swelling which occurred in the 100 percent RH specimens. The lower curves indicate the amount of creep. Figure 8 indicated corresponding data for comparative specimens loaded at 7 days of age. In comparing the 7-day and 28-day data; it is readily noted that loss of stress and creep are higher for the 7-day specimens. The primary reason for this behavior is that the concrete prestress-strength ratio is greater in the 7-day specimens than in the 28-day specimens. This relationship is also true of the 3-day and 12-day release specimens made with Type III cement (data not shown graphically). Other investigators [56] observed a roughly linear relationship between creep and prestress-strength ratio.

The loss of prestress as indicated by the top set of curves for a limited number of specimens in figures 7 and 8 can be depicted better by the relationships indicated in figures 9 and 10. The graphs in these figures are of particular interest inasmuch as they include *all* specimens. Figure 9 includes all the specimens of Type I cement (stress transfer at 7 and 28 days), while figures 10 shows all specimens of Type III cement (stress transfer at 3 and 12 days). In both these figures the loss of prestress after 500 days has been plotted against the prestress-strength ratio.

Inasmuch as the loss of prestress plotted in figures 9 and 10 was obtained on the basis of the

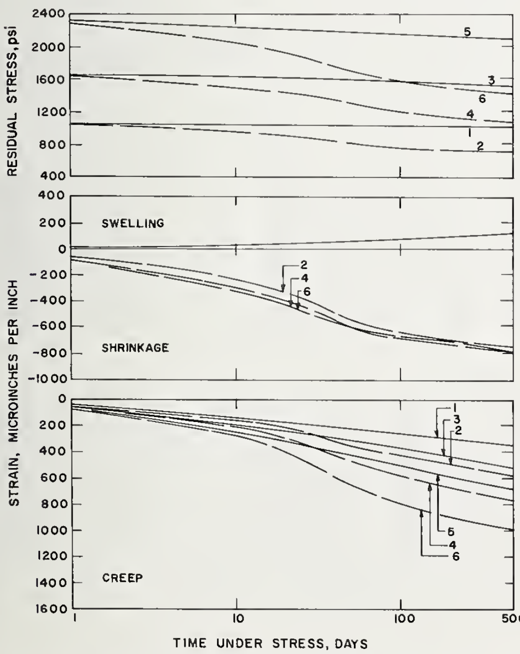


Figure 7. *Typical curves for residual stress, shrinkage or swelling and creep versus time under stress, for Type I cement concretes and stress transfer at 28 days.*

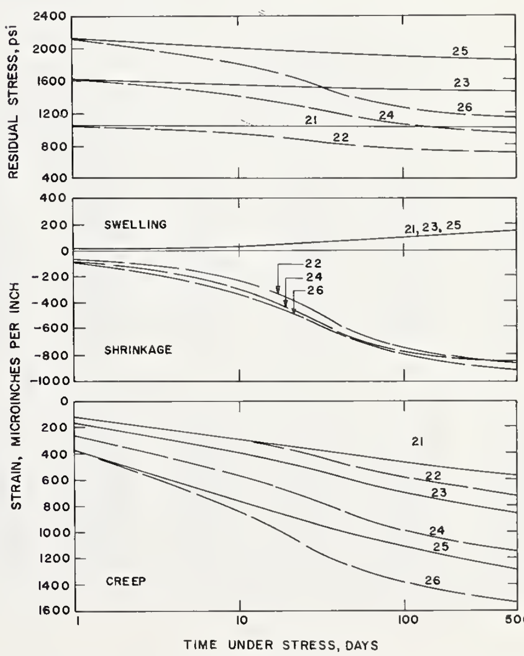


Figure 8. *Typical curves for residual stress, shrinkage or swelling and creep versus time under stress, for Type I cement concretes and stress transfer at 7 days.*

Table 5. *Values of creep and shrinkage or swelling for specimens made of Type I cement concrete*

Set No.	Mass ratio	Relative humidity	Creep				Shrinkage or swelling [a]			
			1 day	10 day	100 day	500 day	1 day	10 day	100 day	500 day
		Percent	*Microinches per inch*				*Microinches per inch*			
			Prestress transferred at 28 days							
101	0.50	100	22	82	200	305	+14	+17	+50	+102
102	.50	50	40	203	500	580	−122	−470	−750	−820
103	.39	100	30	110	280	420	+18	+25	+53	+100
104	.39	50	94	348	720	840	−145	−500	−710	−755
105	.32	100	11	150	380	590	+18	+30	+50	+100
106	.33	50	90	410	780	910	−150	−520	−720	−780
1	1.14	100	45	140	258	340	+10	+40	+83	+133
2	1.15	50	54	150	420	575	−70	−230	−645	−780
3	0.90	100	64	190	370	517	0	+14	+80	+130
4	.89	50	64	200	570	750	−90	−290	−680	−780
5	.75	100	67	250	500	675	+13	+33	+80	+130
6	.74	50	70	265	775	968	−90	−320	−670	−740
73	1.49	50	50	180	475	680	−47	−173	−360	−755
74	1.51	100	20	104	270	440	+4	+16	+35	+75
			Prestress transferred at 7 days							
121	0.50	100	50	210	380	460	+10	+25	+75	+132
122	.50	50	128	380	690	780	−100	−390	−695	−760
123	.39	100	110	365	618	745	+12	−25	+80	+120
124	.39	50	240	600	907	1015	−130	−445	−670	−718
125	.32	100	115	500	800	933	+25	+30	+75	+108
126	.32	50	260	775	1158	1270	−130	−440	−600	−658
21	1.15	100	102	283	465	560	+18	+35	+100	+150
22	1.15	50	103	295	580	714	−65	−233	−735	−867
23	0.91	100	170	400	685	850	+15	+30	+105	+160
24	.90	50	255	570	985	1130	−80	−290	−790	−903
25	.75	100	382	754	1100	1286	+12	+29	+102	+145
26	.74	50	356	830	1365	1530	−90	−330	−763	−845
71	1.52	50	185	507	940	1150	−58	−200	−655	−870
72	1.51	100	120	405	680	830	+1	+15	+50	+100

[a] Swelling is indicated by positive values.

Table 7. *Values of creep, and shrinkage or swelling for specimens made of Type III cement concrete*

Set No.	Mass ratio	Relative humidity	Creep				Shrinkage or swelling [a]			
			1 day	10 day	100 day	500 day	1 day	10 day	100 day	500 day
		Percent	*Microinches per inch*				*Microinches per inch*			
			Prestress transferred at 12 days							
141	0.50	100	6	130	283	400	+51	+62	+102	+150
142	.50	50	70	235	483	566	−95	−366	−652	−720
143	.39	100	38	198	413	570	+52	+58	+97	+126
144	.39	50	110	375	664	765	−112	−385	−560	−610
145	.33	100	5	195	470	700	+51	+57	+100	+130
146	.33	50	19	297	570	705	−119	−350	−515	−550
42	1.15	50	53	148	320	435	−43	−216	−650	−790
43	0.91	100	45	147	315	445	+19	+40	+72	+106
44	.90	50	100	288	625	758	−62	−280	−693	−795
45	.76	50	130	356	790	945	−81	−343	−740	−812
61	1.75	100	124	256	450	667	+14	+17	+37	+70
62	1.76	50	66	243	580	798	−50	−145	−480	−735
			Prestress transferred at 3 days							
161	0.50	100	136	322	490	560	+37	+62	+111	+135
162	.50	50	184	436	716	802	−114	−410	−754	−830
163	.39	100	260	575	844	960	+22	+43	+88	+117
164	.39	50	297	703	1020	1115	−136	−422	−650	−728
165	.33	100	209	677	980	1125	+43	+65	+110	+130
166	.33	50	430	890	1200	1345	−138	−440	−642	−740
41	.89	100	213	543	770	890	+30	+54	+112	+146
46	.88	50	340	668	1000	1128	−100	−300	−750	−852
63	1.78	50	250	470	781	970	−52	−130	−512	−752

[a] Swelling is indicated by positive values.

TABLE 6. *Compressive strength, initial and residual prestress, and unit creep strain*[a] *for Type I cement concrete*

Set No.	Mass ratio	Relative humidity	Strength at prestress transfer	Stress at prestress transfer	Residual stress in concrete				Ratio: initial prestress to comp. str.	Loss of prestress at 500 day	Unit creep strain, μ[a]
					1 day	10 day	100 day	500 day			
		Percent	*psi*	*psi*	*psi*	*psi*	*psi*	*psi*	*Percent*	*Percent*	10^{-6}/*psi*
					Prestress transferred at age 28 days						
101	0.50	100	5990	1155	1152	1140	1120	1110	19.3	3.9	0.264
102	.50	50	5990	1140	1100	970	820	780	19.0	31.6	.509
103	.39	100	5990	1790	1790	1766	1730	1680	29.8	6.1	.235
104	.39	50	5990	1800	1650	1480	1200	1150	30.0	36.1	.467
105	.32	100	5990	2480	2480	2430	2350	2250	41.4	9.3	.238
106	.33	50	5990	2440	2320	1970	1620	1530	40.7	37.3	.373
1	1.14	100	5200	1064	1060	1050	1040	1025	20.5	3.7	.320
2	1.15	50	5200	1057	1030	960	790	720	20.3	32.0	.544
3	0.90	100	5200	1664	1645	1620	1580	1540	32.0	7.4	.311
4	.89	50	5200	1692	1630	1500	1210	1085	32.5	35.8	.443
5	.75	100	5200	2325	2305	2240	2155	2100	44.7	9.7	.290
6	.74	50	5200	2382	2280	2050	1575	1425	45.8	40.1	.406
73	1.49	50	5710	1828	1790	1680	1400	1230	32.0	32.8	.372
74	1.51	100	5710	1783	1780	1750	1710	1675	31.2	6.1	.247
					Prestress transferred at 7 days						
121	0.50	100	3230	1131	1120	1100	1080	1070	35.0	5.4	.407
122	.50	50	3230	1106	1060	930	775	735	34.2	33.5	.705
123	.39	100	3230	1750	1725	1650	1602	1575	54.3	10.0	.426
124	.39	50	3230	1762	1650	1380	1160	1085	54.7	38.5	.576
125	.32	100	3230	2338	2310	2200	2110	2065	72.3	11.7	.399
126	.32	50	3230	2362	2200	1815	1500	1400	73.3	40.7	.538
21	1.15	100	3600	1082	1068	1038	1020	1010	30.0	6.7	.518
22	1.15	50	3600	1080	1050	970	775	705	30.0	34.7	.661
23	0.91	100	3600	1660	1630	1552	1505	1480	46.1	10.8	.521
24	.90	50	3600	1710	1610	1420	1060	955	47.5	44.1	.661
25	.75	100	3600	2280	2130	2000	1900	1850	63.4	18.9	.564
26	.74	50	3600	2300	2120	1800	1285	1150	64.0	50.0	.665
71	1.52	50	3770	1715	1650	1490	1130	960	45.5	44.1	.671
72	1.51	100	3770	1720	1690	1620	1560	1520	45.6	11.6	.483

[a] μ is defined as unit creep strain at 500 days based on stress at time of transfer.

TABLE 8. *Compressive strength, initial and residual prestress, and unit creep strain*[a] *for Type III cement concrete*

Set No.	Mass ratio	Relative humidity	Strength at prestress transfer	Stress at prestress transfer	Residual stress in concrete				Ratio: initial prestress to comp. str.	Loss of prestress at 500 day	Unit creep strain, μ[a]
					1 day	10 day	100 day	500 day			
		Percent	*psi*	*psi*	*psi*	*psi*	*psi*	*psi*	*Percent*	*Percent*	10^{-6}/*psi*
					Prestress transferred at age 12 Days						
141	0.50	100	4970	1132	1136	1118	1099	1080	22.8	4.6	0.353
142	.50	50	4970	1145	1102	1000	860	825	23.0	27.9	.494
143	.39	100	4970	1767	1772	1730	1670	1630	35.6	7.8	.323
144	.39	50	4970	1748	1670	1490	1290	1230	35.2	29.6	.438
145	.33	100	4970	2363	2363	2305	2236	2136	47.7	9.6	.296
146	.33	50	4970	2450	2277	2085	1890	1800	49.4	26.5	.288
42	1.15	50	5600	1090	1065	998	845	783	19.4	28.2	.399
43	0.91	100	5600	1703	1690	1650	1600	1565	30.4	8.1	.261
44	.90	50	5600	1724	1660	1500	1210	1110	30.8	35.6	.440
45	.76	50	5600	2275	2160	1880	1440	1325	40.6	41.7	.415
61	1.75	100	5140	1830	1805	1760	1700	1635	35.6	10.7	.364
62	1.76	50	5140	1800	1760	1650	1390	1190	35.0	33.9	.443
					Prestress transferred at age 3 Days						
161	0.50	100	3490	1132	1115	1085	1061	1048	32.4	7.4	.495
162	.50	50	3490	1155	1087	960	796	750	33.1	35.1	.694
163	.39	100	3490	1737	1677	1595	1530	1490	49.8	14.2	.553
164	.39	50	3490	1750	1603	1355	1150	1070	50.2	38.8	.637
165	.33	100	3490	2267	2235	2110	2012	1945	65.0	14.2	.496
166	.33	50	3490	2233	2020	1660	1410	1295	64.0	42.0	.602
41	.89	100	3770	1722	1685	1605	1540	1510	45.6	12.3	.517
46	.88	50	3770	1682	1570	1365	1050	950	44.5	43.5	.670
63	1.78	50	3370	1760	1670	1550	1290	1140	52.2	35.3	.551

[a] μ is defined as unit creep strain at 500 days based on stress at time of transfer.

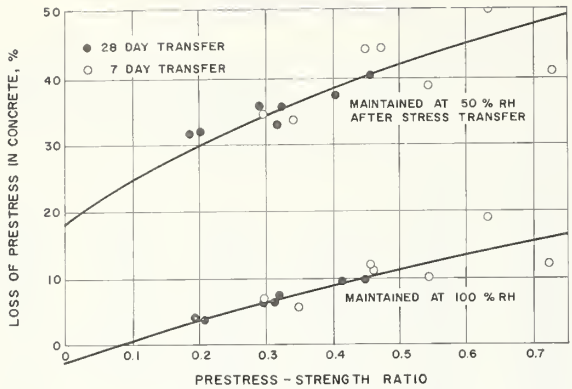


FIGURE 9. *Loss of prestress at 500 days versus prestress-strength ratio; Type I cement concretes.*

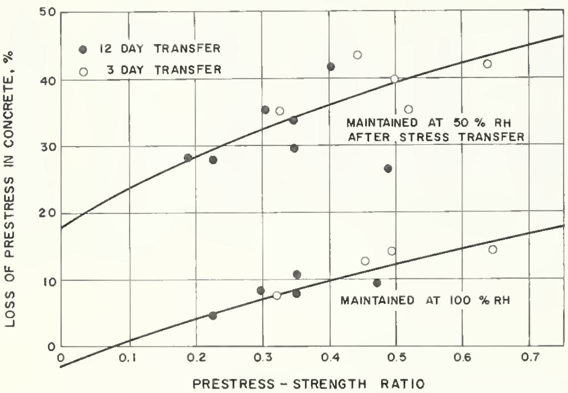
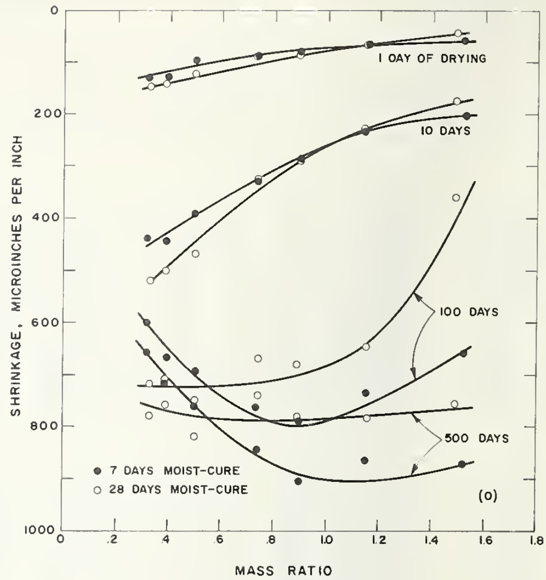


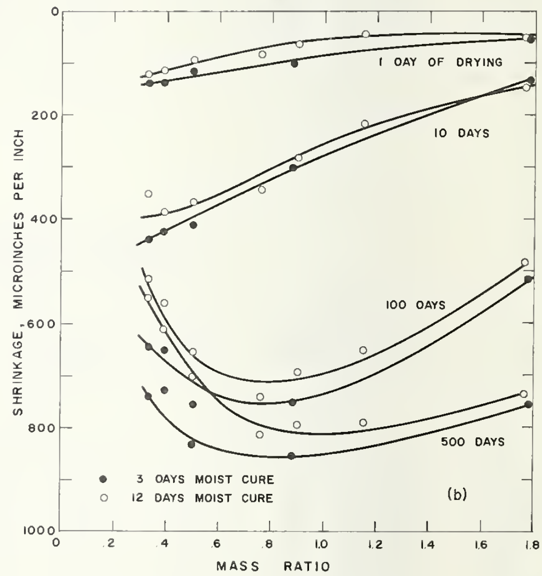
FIGURE 10. *Loss of prestress at 500 days versus prestress-strength ratio; Type III cement concretes.*

total observed time-dependent deformation in concrete, a portion of the loss of prestress represents that due to drying shrinkage. Although it is not known how the drying shrinkage of concrete is affected by the stress level, it is generally assumed that it is independent of the magnitude of the compressive stress. This assumption was also made here and the curves shown in figures 9 and 10 were faired through the experimental points so as to give intercepts of an 18-percent loss and a 3-percent gain for specimens subjected to 50 percent RH and 100 percent RH, respectively. Thus, it was assumed that as the prestress-strength ratio approaches zero, the loss of prestress in specimens maintained at 50 percent RH would approach 18 percent, i.e., the loss associated with a drying shrinkage of 800×10^{-6} in/in. Similarly, for specimens maintained at 100 percent RH the *gain* in prestress would be of the order of 3 percent, corresponding to a swelling of concrete of about 130×10^{-6} in/in.

The influence of mass ratio on shrinkage seems to change considerably with drying time. This relationship may be noted in figure 11 wherein



(a) Type I cement concretes.



(b) Type III cement concretes.

FIGURE 11. *Shrinkage versus mass ratio after drying for 1, 10, 100 and 500 days at 50 percent RH.*

shrinkage at 50 percent RH for given periods of drying are plotted against mass ratios; each of the two cements and the two ages at which drying was initiated are separately plotted in figures 11a and 11b. There appears to be a marked difference, up to the observed age of 500 days, between the Type I cement concrete specimens wet-cured for 28 days and those cured for only 7 days. Also, it appears that at 1 and 10 days of drying the large specimen had less shrinkage than did the smaller specimens. However, at 500 days, the 28-day cured Type I cement specimens all shrank about the same amount independently of mass ratio; this was also the case for specimens wet-cured for 7 days, and having mass ratios in excess of 0.7.

Creep per unit of stress has been variously called: unit creep, creep under unit of stress, unitary-deferred deformation, unit creep strain and the like [7] and [8]. Lorman [9] employs in his study a term *m* defined or designated as "the creep coefficient in millionths of an inch per inch per psi which is assumed to be numerically equal to the ultimate creep strain per unit of stress." There are indications by Lorman and others that this *m* is constant up to some ratio of stress-to-strength of concrete; all of these studies have been concerned with creep under constant stress. The breakover point beyond which *m* increases appreciably has been variously given as being in the range of 1500 psi stress [9], at stress-strength ratios of 0.20 to 0.26 [10], or as high as 0.50 [2]. In this report, stress was not maintained constant but was allowed to decrease as creep and shrinkage took place. With considerable shrinkage and creep occurring in some instances, the stress level decreased appreciably. Because all the specimens were under a stress which varied with time, an alternate definition of *unit creep strain* designated as μ will be introduced. It is defined as the creep occurring at 500 days per unit of stress, the stress being the initial prestress at the time of transfer.

Values of μ, unit creep strain at 500 days as defined above, are plotted against the prestress-strength ratios in figures 12 and 13. It appears to be reasonable to assume that these plots are straight lines; these were obtained by method of least squares. The specimens subjected to 50 percent RH (Type I and Type III cements alike) exhibit a decrease in μ with an increase in prestress-strength ratio. For constant stress conditions, it would be expected that μ would remain essentially constant for all stress-strength values up to the breakover point and then increase. For the conditions of these tests there was no indication of a breakover point up to the maximum prestress-strength ratio of 0.7 used in this investigation.

Figures 14 and 15 indicate the relationship between unit creep strain at 500 days and mass ratio; the straight lines shown were obtained by method of least squares. In general, μ increases slightly with an increase in mass ratio for all specimens and both storage conditions (50% and 100%RH). Also this effect of mass ratio on μ appears less marked than the effect of the prestress-strength ratio.

Inge Lyse [11] reported that in an atmosphere of 50 percent RH, a sustained stress of about 25 percent of the initial concrete strength will result in creep nearly equal to the shrinkage under the same ambient conditions. It is assumed that the temperature was at about 70°F. He also related that Mamillan [12] equated creep at a 15 percent stress-strength ratio to the amount of shrinkage at 85 percent RH, and creep at a 35 percent stress with shrinkage at 15 percent RH. Again these two investigators were concerned with constant stress. In this study, creep computed for the four variables (2 cements, 2 ages of stress transfer) approximately equals shrinkage (at 50% RH) for stress-strength ratios ranging from 32 to 36 percent. True, these ratio values are higher than the aforementioned 25 percent value established by Lyse. This relationship should be so since the concrete stress in this instance diminished with time because of creep and shrinkage.

9. Summary

This study involved creep and shrinkage occurring in prestressed specimens in which the steel reinforcement was bonded to the concrete. Thus, any change in linear dimension caused a change to occur in the amount of prestress force to which the concrete was subject. Creep and shrinkage in the concrete superimposed upon elastic deformation

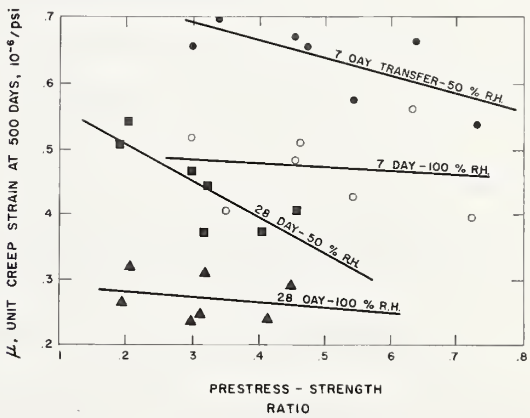


Figure 12. *Unit Creep Strain at 500 days versus prestress-strength ratio for Type I cement concretes.*

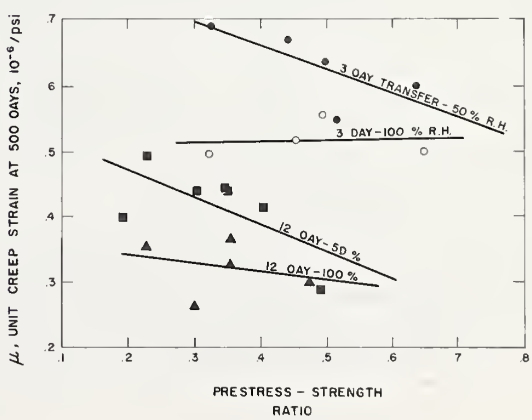


Figure 13. *Unit Creep Strain at 500 days versus prestress-strength ratio for Type III cement concretes.*

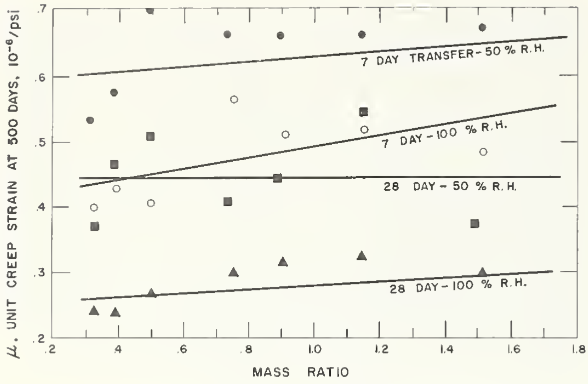


Figure 14. *Unit Creep Strain at 500 days versus mass ratio for Type I cement concretes.*

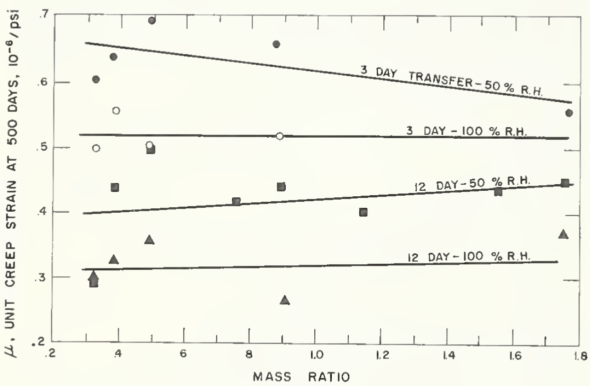


Figure 15. *Unit Creep Strain at 500 days versus mass ratio for Type III cement concretes.*

of concrete and reinforcement caused a relaxation of the initial prestress force.

Several items of note are:

1. Wires 0.1125 inches in diameter, tensioned to 125,000 psi initial prestress, require an embedment for anchorage of less than 10 inches in length when used in good quality normal portland cement concrete with an age of release of prestress as early as 7 days, or when used in high-early strength cement concrete as early as 3 days. The required length of embedment seemed independent of cure of concrete, wet or dry.

2. Early shrinkage of nonstressed specimens exposed to 70°F. and 50 percent RH seemed to be dependent upon the mass ratio. Small cross-sectional specimens exhibited more rapid shrinkage at an earlier age than the larger specimens, but the larger specimens appeared to approach the shrinkage values of smaller ones at ages of about 500 days.

3. Loss of prestress in these specimens having bonded tendons appears to vary linearly with the ratio of initial concrete prestress to initial strength, regardless of strength of concrete or age of release of prestress. There is little difference in the percentage of loss of prestress between specimens of normal portland cement and those made with high-early strength cement when storage conditions are the same.

4. Unit creep strain (i.e., creep strain at 500 days divided by initial concrete prestress) was found to be dependent upon moisture conditions during storage. Greater creep per psi of stress occurs at 50 percent RH than at 100 percent RH.

5. Unit creep strain at 500 days appears to be almost independent of the prestress-strength ratio for specimens stored at 100 percent RH. However, for specimens stored at 50 percent RH Unit Creep Strain at 500 days appears to decrease linearly with increasing prestress-strength ratios.

6. The mass ratio had little significant effect on the unit creep strain at 500 days.

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THE INSTITUTE FOR BASIC STANDARDS . . . provides the central basis within the United States for a complete and consistent system of physical measurements, coordinates that system with the measurement systems of other nations, and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. This Institute comprises a series of divisions, each serving a classical subject matter area:

—Applied Mathematics—Electricity—Metrology—Mechanics—Heat—Atomic Physics—Physical Chemistry—Radiation Physics—Laboratory Astrophysics[2]—Radio Standards Laboratory,[2] which includes Radio Standards Physics and Radio Standards Engineering—Office of Standard Reference Data.

THE INSTITUTE FOR MATERIALS RESEARCH . . . conducts materials research and provides associated materials services including mainly reference materials and data on the properties of materials. Beyond its direct interest to the Nation's scientists and engineers, this Institute yields services which are essential to the advancement of technology in industry and commerce. This Institute is organized primarily by technical fields:

—Analytical Chemistry—Metallurgy—Reactor Radiations—Polymers—Inorganic Materials—Cryogenics[2]—Office of Standard Reference Materials.

THE INSTITUTE FOR APPLIED TECHNOLOGY . . . provides technical services to promote the use of available technology and to facilitate technological innovation in industry and government. The principal elements of this Institute are:

—Building Research—Electronic Instrumentation—Technical Analysis—Center for Computer Sciences and Technology—Textile and Apparel Technology Center—Office of Weights and Measures —Office of Engineering Standards Services—Office of Invention and Innovation—Office of Vehicle Systems Research—Clearinghouse for Federal Scientific and Technical Information[3]—Materials Evaluation Laboratory—NBS/GSA Testing Laboratory.

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D. C., 20234.

[2] Located at Boulder, Colorado, 80302.

[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

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