THE ANELASTIC BEHAVIOUR OF CONCRETE UNDER SUSTAINED LOADS

by

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B. S., National Central University, Nanking, China, 1944

A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Applied Mechanics

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1955

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INTRODUCTION

Preliminary

It is a recognized fact that time yielding, generally called creep, takes place in concrete under sustained stress. This yielding, which gradually slows down, will generally reach an appreciable magnitude. Various observations have indicated that, from this yielding, marked redistribution of stresses between the concrete and steel will result.

With increasing refinement in the design of structures, and particularly with increasing interest in pre-stressed concrete, the necessity for more complete information in this respect has become paramount.

In February of 1954, a number of concrete specimens were made in the Department of Applied Mechanics, Kansas State College. The purpose of the work was to investigate the effects of load, curing period, and storage conditions on the creep of concrete. This thesis presents the results to date of this experiment and includes a general survey of the problem.

Purpose and Scope of Investigation

The purpose of the work was to study the effect of various exposures on the magnitude and rate of creep. Six different exposures were studied: indoor air, oven, soaking, Exposure 2 (wetting and drying), Exposure 10 (heating and cooling saturated), heating and cooling dry, and flexure loading in indoor air.

In addition to the above, the effect of age at time of loading, the effect of partial prestressing, and the effect of aggregate were also studied.

Incidentally, a formula for correlating creep data was checked.

Resumé of Previous Work

Early in 1905 Woolson (62) published a paper, Some Remarkable Tests Indicating Flow of Concrete Under Pressure; this was probably the first reference to creep of concrete. It was followed in 1907 by a paper by Hatt (21) reporting his deflection tests of beams in which time yielding was evident. In 1915 McMillan (34) reported tests on beams and slabs in which the change of deformation due to combined effects of shrinkage and creep was measured. In 1916 three reports appeared. Smith (47) with the Bureau of Public Roads brought out the fact that plastic recovery after the load was removed was considerably less than the original deformation. The second report was made by Goldbeck and Smith (20), in which it was shown that the creep rate was high at first and decreased as time went on. The third report was given by Fuller and More (16) at the University of Washington on some measurements made on a concrete building under construction. In 1917 two important papers appeared in the proceedings of ACI, one by Lord (24) on one year's measurement of a flat slab panel and another by Smith (48) who reported tests on cylinders and beams and suggested the asymptote-to-certain-limit law for creep. In 1921 McMillan (36) published the results of observations made on the reinforced concrete columns of a building over a period of six years. He concluded that the unit stresses in the steel were lessened when creep occurred. In 1925 an investigation was started at the Ohio State University (Shank, 44) and eight series of tests were made. In the same year, when the Stephenson Creek Arch Dam was projected, attention was given to the creep properties of concrete and Professor R. E. Davis was commissioned to perform laboratory tests dealing with problems.

These results appeared in the proceedings of the ACI first in 1928 (5), then in 1931 (8), and also in proceedings of ASTM 1930 (6) and 1934 (9).

In 1927 Faber (15) published in England the results of tests he made on beams. The effects of shrinkage and creep were brought into the theory of mechanics by way of change with time of modular ratio. In 1930 a publication by Glanville (17) of the Building Research Station, England, set forth the results of tests in a concise and simple manner. Glanville's calculations appeared to be an improvement over those of Faber. American and British investigators such as Ross (42, 43), Shank (44), and Thomas (52) have since published their findings and suggested mathematical formulae for predicting the amount of creep.

In 1940 a remarkable paper was given by Lorman (25) in which he used a method which was originated by Ross (42) to analyze experimental results and which appeared to be very convenient to use. His method contained two parameters determined from experiment which expressed two important quantities in the creep equation.

Subsequent papers dealing with the subject have appeared in ACI and ASTM proceedings every year. A bibliography is included in this paper.

General Information Regarding Creep

<u>Definition</u> <u>of</u> <u>Creep</u>. The word "creep" means the inelastic unit-deformation of an infinitesmal concrete element caused by applied stress. In practice, it is measured by comparing the change of deformation of two concrete specimens, one under sustained load and one without load. Creep is obtained by subtracting from the total strain of the compressed specimens the strain of the unloaded control specimen, the latter quantity being called

shrinkage. Theoretically, it is assumed that the effects of shrinkage and creep are additive.

It must be pointed out here that many investigators have not agreed to this method of separation of total deformation into shrinkage and creep. Lynam (26) wrote, "Shrinkage and creep are two aspects of the same phenomenon; it is impossible to separate them and no good end is served by trying to do so." Lorman (25) wrote, "Shrinkage or swelling due to loss or gain of moisture and creep due to seepage are interrelated phenomena." Maney (29) states, "Non-uniform shrinkage is the source of all time-yield in loaded concrete members." Therefore, it is not quite justified to regard the effects of shrinkage and creep as additive.

However, in order to simplify the analysis and also to be in agreement with previous investigators the foregoing assumptions were made. Following are some important definitions:

1. Shrinkage - the strain occurring in the non-loaded control specimens caused by drying or any other causes. A positive shrinkage strain means that the gage points became closer together. The datum reading was made at the end of the curing period and all later readings were compared to this first reading to obtain shrinkage strain.

2. Gross - the strain occurring in the axially compressed specimens. Again, a positive strain indicated that the points became closer together. The datum reading was just after loading (to be exact, 45 minutes after the specimen was removed from the testing machine where it was loaded), and, therefore, this strain does not contain the instantaneous elastic strain which occurred during the loading.

3. Creep - the difference of gross and shrinkage as stated above, or

Creep = Gross - Shrinkage.

All units for strain are measured in in./in.

<u>General Theory of Creep</u>. In spite of the apparently enormous amount of work done in this field, no theory to date explains satisfactorily the nature of creep. It is generally believed that creep might take place in the following three ways:

1. Viscous Flow. This is a movement of particles, one over the other, as in the flow of oil, asphalt, glue, or wet clay.

2. Crystalline Flow. This is a movement similar to the creep of metals at elevated temperature, being a slip occurring along planes within a mass composed of crystals.

3. Seepage. The third way of yielding occurs from an actual loss of water. Water may exist within the mass of concrete in three forms: (a) as chemically combined water, (b) as water which has been absorbed by the cement colloids, and (c) as "free" water within the pore spaces or voids.

Lynam (26) has given evidence that the gain or loss of water from the colloidal mass is the fundamental cause of volume change.

An approximate explanation has been given by Davis et al (9) for this loss of water. He says that the flow of water to or from the gel takes place through minute capillary channels which permeate the mass. The flow along the capillaries, both in direction and amount, is a function of the pressure gradient along these channels, and thus is also a function of the variations in the moisture of the surrounding air and of the pressure applied to the concrete.

Changes in moisture content are accompanied by changes in volume. As moisture is lost, the gel shrinks, a process which may be thought of as the collapse of minute pore spaces within the gel. Then as moisture is gained, the gel expands as these spaces become filled with water.

When an external load is applied to a mass of concrete, the gel is placed under pressure, and moisture is expelled. The rate of expulsion would again be a function of the vapor pressure on the outside of the mass and of the friction in the capillary channels. This flow of water from the gel due to applied pressure is that which is called seepage.

While it appears that the major portion of the time-yield in concrete is caused by colloidal seepage, there is also evidence that crystalline and viscous flow may exist. The flow of rock has been observed in nature and the aggregates in the concrete are usually a crystalline material. It is reasonable to assume the same phenomena occurring in rock may occur in the aggregate. The considerable difference in creep of concrete made of different aggregates is strong support for this belief. On the other hand it is also possible that creep may be caused by, at least in part, viscous flow.

Factors That Affect Creep. In view of the causes of creep, it is evident that the following factors come into the picture:

1. Composition of cement
2. Fineness of cement
3. Type of aggregate
4. Size and gradation of aggregate
5. Water-cement ratio
6. Cement content
7. Gypsum and admixtures present
8. Curing period
9. Degree of compaction

10. Temperature prior to loading

11. Magnitude of sustained load

12. Humidity of surrounding air

13. Temperature during storage under load

14. Size of specimen

15. Nature of load

16. Age at time of loading

17. Humidity prior to loading

There are many more factors and those listed above involve more factors themselves. Therefore, it is difficult to say what conclusions can be drawn from the previous studies.

The following are several conclusions generally believed to be true and which have served as a guide in this analysis:

1. The plastic flow of plain concrete under a constant, sustained, compressive stress continues to increase, at first rapidly and then more slowly, approaching a limit asymptotically.

2. Humidity has a reverse effect on the magnitude and rate of creep. A specimen flows more rapidly and to a greater limit in an atmosphere of low humidity.

3. Creep is less for rich mixes than for lean mixtures.

4. Creep is less for concrete having a high modulus of elasticity than for one having a low modulus of elasticity.

5. High water-cement ratio concrete has greater creep.

6. Creep is greater when load is applied at an early age.

7. Creep is materially affected by the character of aggregate.

8. Creep is roughly proportional to the magnitude of sustained stress up to 1/4 to 1/3 of the ultimate strength.

TESTING PROCEDURE

Preparation of Specimens

Altogether there were 136 specimens made for observation. There were three mixes, designated CC, CH and CZ respectively. In each series there were 11 sets of specimens except for CH which had 12 sets. Each set contained four specimens, two loaded and two controls. Specimens of the same set were identical in all other respects and underwent the same kind of storage. For a detailed description of mix data, aggregate characteristics, and other information refer to Tables 1 and 2.

In addition to the above specimens, additional ones were made for strength tests. These results are tabulated in Table 3.

To prepare the specimens, the materials were mixed in a power driven, open-tub mixer. Cement, aggregates, and water were weighed out and placed in the mixer. Air entraining agent was mixed with part of the water to assure thorough mixing. The mixing operation was usually continued for about one minute. Slump and percent air tests were made. The mixture was then poured into molds on a platform type vibrator. The time of vibration, however, was carefully kept to a minimum to avoid segregation.

The molds were stored in the moistroom under 70° F. and 100 percent relative humidity for 24 hours at which time the molds were removed. Then the specimens were again placed in the moistroom for curing. The period of curing varied from 7 to 28 days as shown in Table 4.

The dimensions of the specimens are shown in Plate I. Gage pins were made of stainless steel and solidly cast into the two 3-inch sides of the specimens during placing. By taking the readings on both sides and averaging

Table 1. Mix data and properties of green concrete.

Series	Cement	Aggregate			Proportions	W/C (gal./sack)	Cement factor (bbl./cu.yd.)	Unit weight (lbs./cu.ft.)	Slump (in.)	Percent air
		Sand	Stone: Coarse	Stone: Fine						
CC-	Penn-Dixie Type I	Blue River (Pass 3/8" sieve)	Chat	Chat	1:1.5:1.5:1.5	6.04	1.70	145.1	1 1/4	0.8
CH-	Penn-Dixie Type I		Bx Haydite		1:2.8	9.17	1.59	102.5	0	4.0
CZ-	Penn-Dixie Type I	Blue River (Pass 3/8" sieve)	Limestone		1:2.5:2.5	6.05	1.63	147.8	1 3/4	0.8

Table 2. Aggregate characteristics.

	Gradation: Cumulative percent retained on sieve size: 3/4"	3/8"	#4	#8	#16	#30	#50	#100	Pan	Fineness modulus	Specific gravity	Remarks
CC (Coarse chat	0	56.8	82.7	100	100	100	100	100	100	6.40	2.59	
CC (Fine chat	0	6.4	32.4	62.3	71.0	83.9	87.5	92.5	100	4.36	2.59	
CC (Sand	0	0	13.9	39.8	62.8	77.8	94.5	97.9	100	3.87	2.65	Natural proportions & all pass 3/8" sieve
CC (Total agg.	0	21.1	43.0	67.4	77.9	87.2	94.0	96.8	100	4.67	——	
CH (Bx Haydite	0	0	15.1	44.6	63.9	77.9	86.3	91.2	100	3.79	——	Unit wt. = 60.9 #/ft^3 Percent H_2O = 1.29
CZ (Zeandale limestone	0	97.3	99.9	99.9	99.9	100	100	100	100	6.97	2.61	
CZ (Sand	0	0	2.5	10.0	32.6	57.6	89.7	96.5	100	2.89	2.65	Sand from Blue River of Kans., not in natural proportions.
CZ (Total agg.	0	48.7	51.2	55.0	66.3	78.8	94.9	98.3	100	4.92	——	

Table 3. Strength test results.

Mix	Beams	Total No. of beams	Curing period in moistroom: Age in	Curing period in moistroom: Age out	Curing period in moistroom: Days in	Age when tested	Average strength: Modulus of rupture (psi)	Average strength: Compressive strength (psi)
CC	L1,L2	2	0	7	7	7	927	5,058
	L3,L4	2	0	14	14	14	1,023	5,194
	L5,L6	2	0	28	28	28	1,029	5,894
CH	L1	1	0	8	8	8	665	3,230
	L2	1	0	14	14	14	729	3,279
	L3	1	0	28	28	28	875	3,754
	L5	1	0	36	36	36	682	3,459
CZ	L1	1	0	5	5	5	641	3,992
	L2	1	0	12	12	12	735	5,529
	L3,L4	2	0	28	28	28	814	6,161
	D4	1	0	14	14	14	—	4,437
	K1,K2	2	0	70	70	70	948	4,709
	K1	1	0	28	28	28	886	6,113

Table 4. Schedule of curing and treatment for each series.

Specimen	No. of beams of each mix	Curing in moistroom			First loading		First storage period* (days)	Final loading			Storage period where specimens under observation					
		Age in (days)	Age out (days)	Days in MR	Age (days)	Stress (psi)		Age (days)	Days after first loading	Final stress (psi)	Age in (days)	Days af. final loading	Type of storage	Total days in storage CC	CH	CZ
A	4	0	28	28	-	-	-	28	-	1,000	28	0	Lab air	329	301	303
B	4	0	14	14	-	-	-	14	-	1,000	14	0	Lab air	329	301	303
C	4	0	7	7	-	-	-	7	-	1,000	7	0	Lab air	329	301	303
CE	4	0	7	7	-	-	-	7	-	1,000	7	0	Lab air	329	301	303
D	4	0	28	28	-	-	-	28	-	500	28	0	Lab air	329	301	303
E	4	0	7	7	7	250	14	28	14	1,000	28	0	Lab air	329	301	303
F	4	0	28	28	-	-	-	28	-	1,000	37	9	Oven	329	301	303
G	4	0	28	28	-	-	-	28	-	1,000	37	9	Soaking	329	301	303
H	4	0	28	28	-	-	-	28	-	1,000	37	9	Exp. 2	329	301	303
I	4	0	28	28	-	-	-	28	-	1,000	37	9	Exp. 10	329	301	303
J	4	0	28	28	-	-	-	28	-	1,000	37	9	Wet and drying	329	301	303
K	4	0	28	28	28	1,000	9	37	9	Flexure	37	9	Lab air	189	105	273

*First storage period was in indoor air.

Notes: 1. There were 3 different mixes, CC, CH, and CZ.
2. Only CH mix has CE beams, therefore, the total number of beams under observation is 136.
3. CZ has no D4. A4 was used as one of the controls.

EXPLANATION OF PLATE

Two specimens used in the investigation. At the right is a specimen loaded in the assembly, and at the left is a control specimen. Each set of specimens was composed of two loaded and two control specimens.

PLATE I

them, the error that might come from bending of specimens was eliminated.

Loading

Specimens were loaded at prescribed dates. The sustained load was maintained by a spring assembly. Plate II shows such assembly with a specimen being loaded in a testing machine.

The procedure during loading was as follows:

1. Specimens were taken from the moistroom and gage length was measured with a Berry strain gage.

2. The loading device was assembled. Before doing this, the spring of the assembly was compressed and released several times in a testing machine in order to reduce subsequent steel relaxation in the spring.

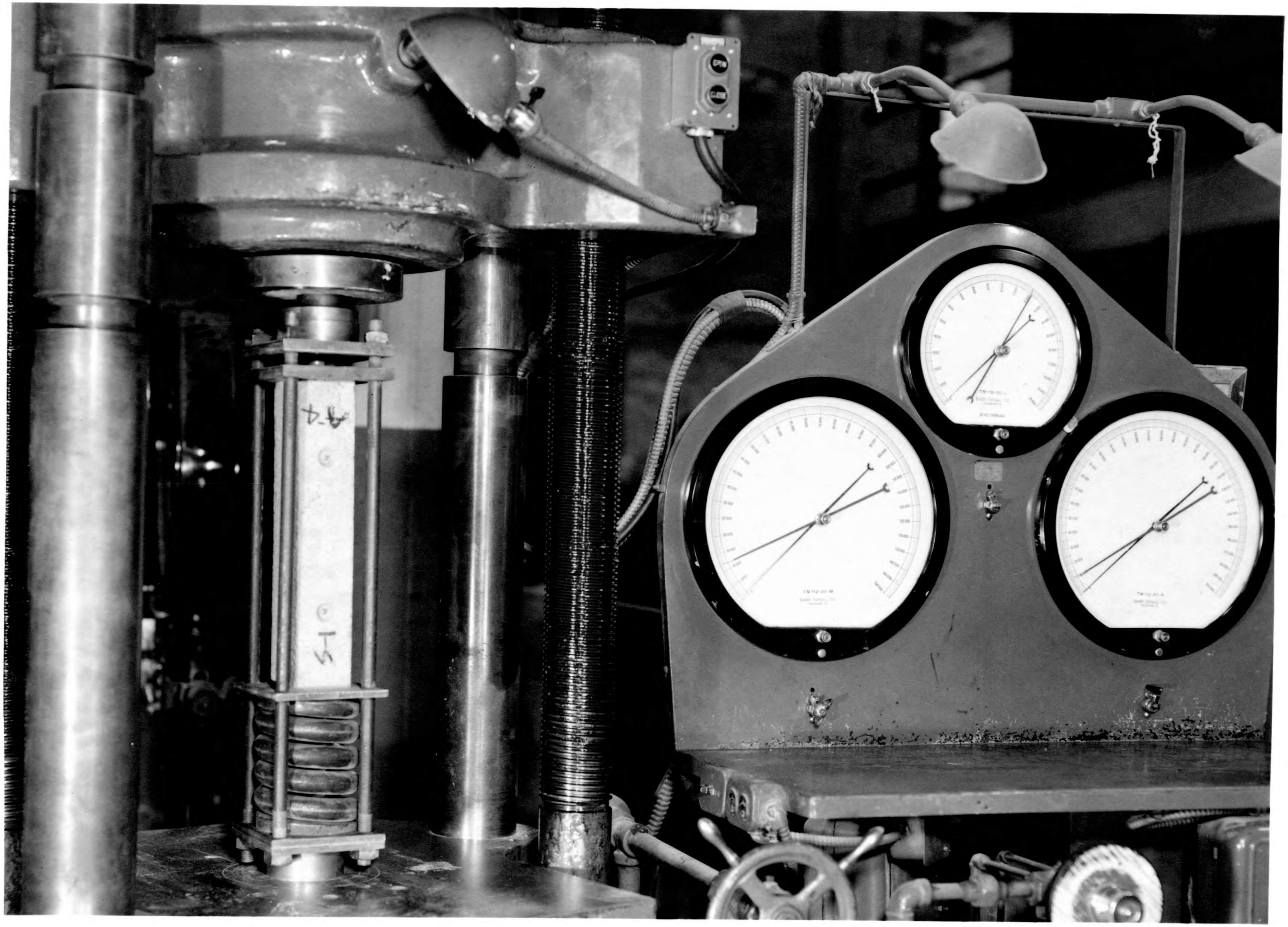
3. The specimens were loaded in a testing machine. Spring and specimen were compressed until the load indicator of the testing machine reached a little over the desired load. During compression, the four rods of the squeezer were kept free to rotate to eliminate friction between the rods and the plates. Then the nuts were tightened by hand and the loading assembly was tapped slightly until the testing machine dial read exactly the desired load. Based on the experience of former tests (4), the actual load for most of the test period on the specimens was probably 11,700 lbs. for an initial load of 12,000 lbs.

4. After 45 minutes, strain readings were again taken. This reading allowed computation of the instantaneous elastic deformation as well as obtaining a zero strain reading for future readings.

EXPLANATION OF PLATE II

Specimen being loaded in a testing machine. Nuts were set hand tight before the machine was released.

PLATE II



Storage

Seven storage conditions were provided for the tests. A brief description of each exposure is given below:

Indoor Air. Specimens were placed in racks in well-ventilated rooms. No control of temperature or humidity was obtained.

Oven. Some of the specimens were placed in an oven at 130° F. On the days when readings were to be taken, the specimens were taken out of the oven and cooled to room temperature by exposure to room air. Strain, therefore, was compared on the basis of room temperature. (Plate III)

Soaking. A tank of water was provided for continuous soaking. No attempt was made to keep the water at constant temperature. Readings were taken immediately after the specimens were removed from the tank. After reading the specimens, they were returned to the tank. Temperature was measured at each reading.

Exposure 2 (wetting and drying). The specimens were placed in the drying oven at 130° F. for five days and then immersed in water at room temperature for 2 days. Readings were made at the end of the 2-day soaking period while the specimens were still in the saturated condition.

Exposure 10 (heating and cooling saturated). The specimens were exposed to a continuous spray of water of changing temperature. During one complete cycle, the temperature of water changed from 68° to 130° F. and back to 68° F. There were 32 cycles per day. On the day when specimens were to be read, the temperature controller was switched to the cold side early in the morning so that the specimens were cooled to 68° F. for reading. (Plate IV)

EXPLANATION OF PLATE III

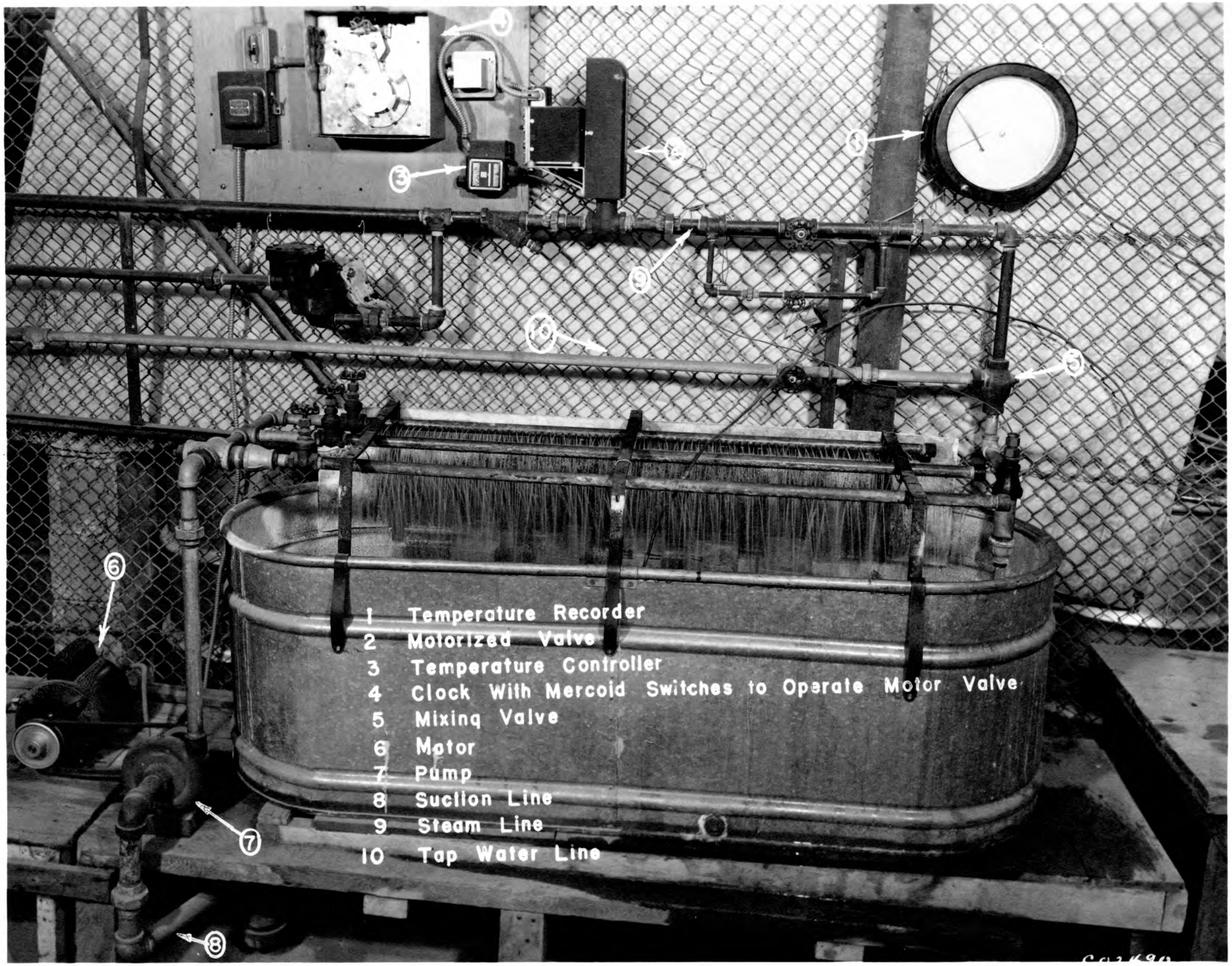
Oven used in heating and cooling and in wetting and drying exposures. The temperature of the oven was maintained at 130° F.

PLATE III

EXPLANATION OF PLATE IV

Spray tank installation used in Exposure 10. The specimens were exposed to a continuous spray of water of changing temperature. During one complete cycle, the temperature of water changed from 68° F. to 130° F. and back to 68° F. During each 24 hours, 32 complete cycles were obtained.

PLATE IV


1 Temperature Recorder
2 Motorized Valve
3 Temperature Controller
4 Clock With Mercoid Switches to Operate Motor Valve
5 Mixinq Valve
6 Motor
7 Pump
8 Suction Line
9 Steam Line
10 Tap Water Line

Heating and Cooling Dry. The specimens were placed alternately in the drying oven at 130° F. for four (or eight) hours and then cooled in indoor air for four (or eight) hours. The cycle was repeated eight times a week. Readings were taken at room temperature.

Flexure. A flexure machine was built to determine the effect of repeated bending load on creep of concrete. This is illustrated by Plate V. A load of about 1710 lbs. was applied at the center of the beam and caused the bending stress at the bottom to become zero and that at the top to become 2000 psi compression.

Specimens under flexure test were loaded axially as usual at 28-day age and stayed in the indoor air for nine days. Then they were placed into the flexure machine and left there until 1,000,000 cycles were reached. Readings were taken at the same time intervals as were the other specimens.

Table 4 gives the schedule of various storage treatments for specimens designated for each exposure.

METHOD OF READING AND DISCUSSION OF ACCURACY

Method of Measurement

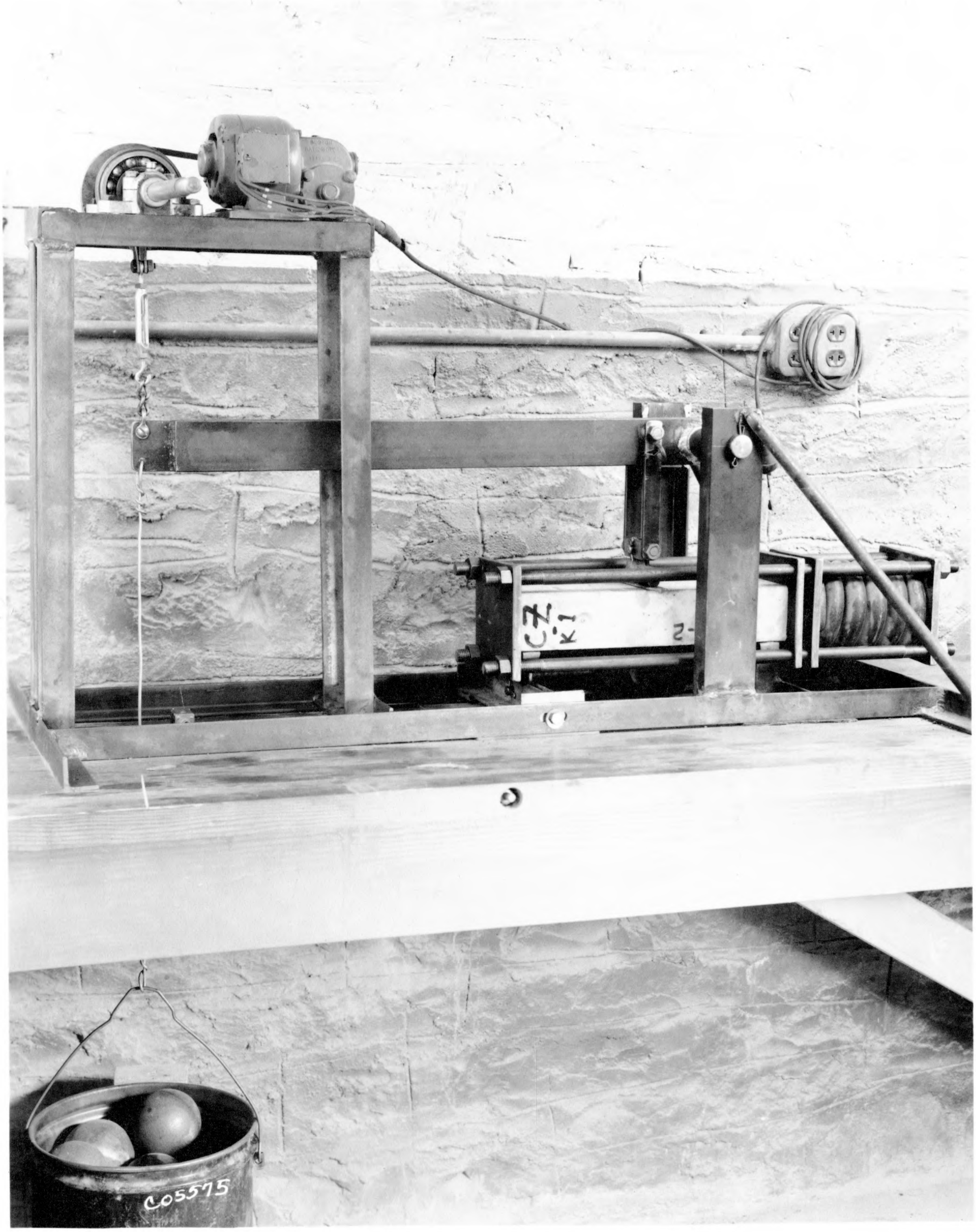
Readings of change of length were obtained by a Berry strain gage with an 8-inch gage length. The dial of the gage read to .0001 inch, and the mechanical linkage of the Berry gage was 5.517:1, thus giving an accuracy of approximately .00002 inches in 8-inch or .0000025 inches per inch.

When a reading was taken, the gage was first checked against a calibrated invar bar, and the dial adjusted to zero reading. During reading, the two conical points of the gage rested in the gage holes in the pins cast in the

EXPLANATION OF PLATE V

Flexure machine. A load of about 1710 lbs. was alternately applied and removed at the center of the specimen by a dead load and linkage.

PLATE V



specimen. The gage was then rocked to and fro until a maximum reading was indicated. An electric shaver was used to help overcome the internal friction of the gage so that a reliable reading was obtained.

Discussion of Accuracy

It is believed that other errors were far greater than the error of the instrument. These other errors were the following:

Personal Error. Sometimes different persons obtained different readings. This resulted from the different ways of using the instrument, such as speed of rocking the gage, the force applied, and the time allowed for the indicator to settle down to a certain reading. Repeated trials showed that this error was likely not to exceed .010 on the dial, or, in other words, .000025 in/in after being converted to strain.

Bad Gage Holes. Sometime no definite reading could be ascertained. On such occasions, either the indicator continued to increase when one tried to get a maximum, or the gage had to be tilted very far to one side in order to get a maximum. It was found that the cause of this was poorly drilled holes. The holes were usually redrilled in such cases and the error of unreliable readings was eliminated.

Temperature Effect. Since no temperature control was provided, the temperature variation made a very pronounced effect upon the readings. This is shown by the curves of Figs. 1 and 2. For instance, observing the curve CC-loaded in Fig. 1, it may be seen that the strain reading at 100° F. is 150×10^{-6} in/in less than that obtained at 70° F. This sort of error is entirely caused by temperature changes.

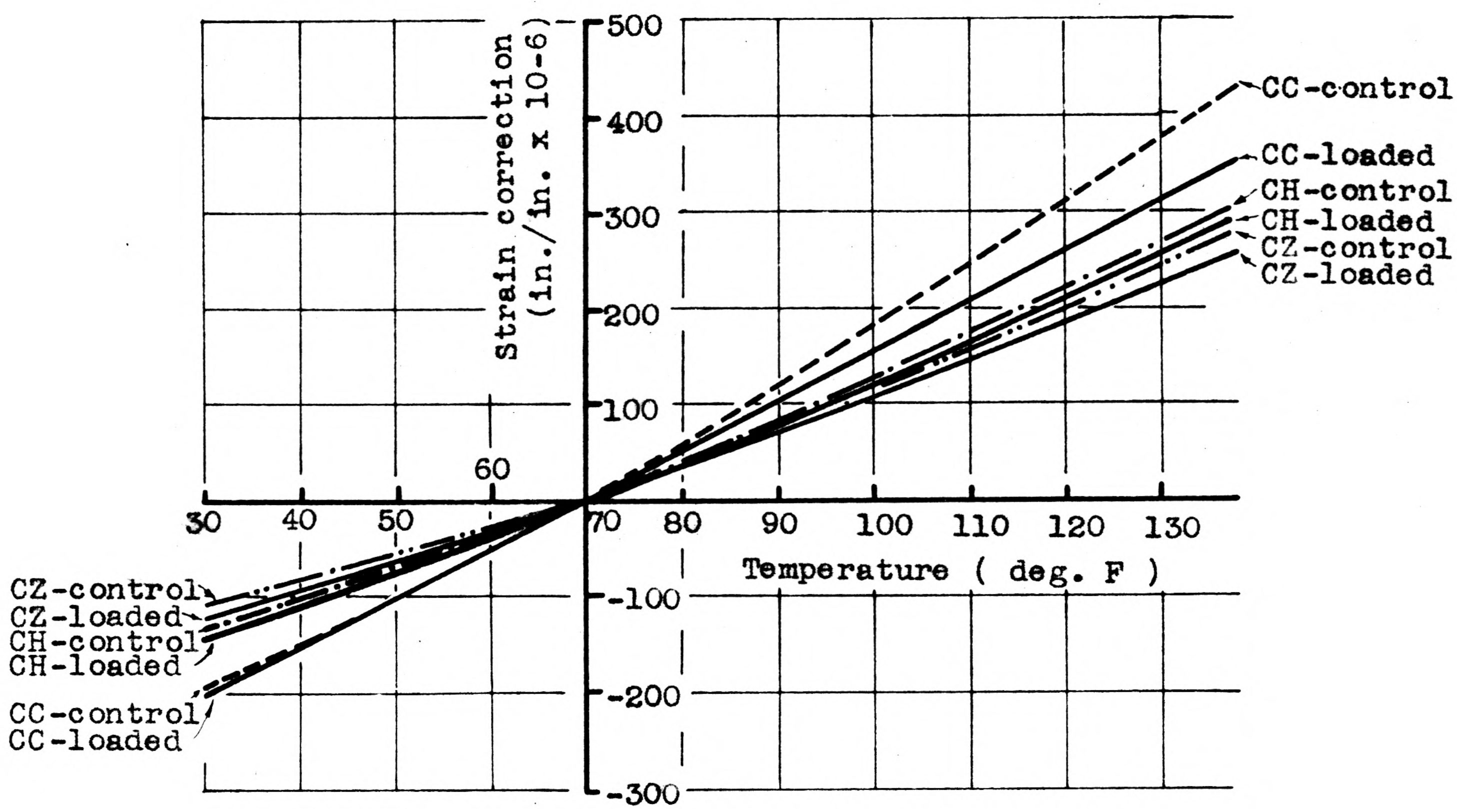


Fig. 1. Temperature correction curves for dry specimens.

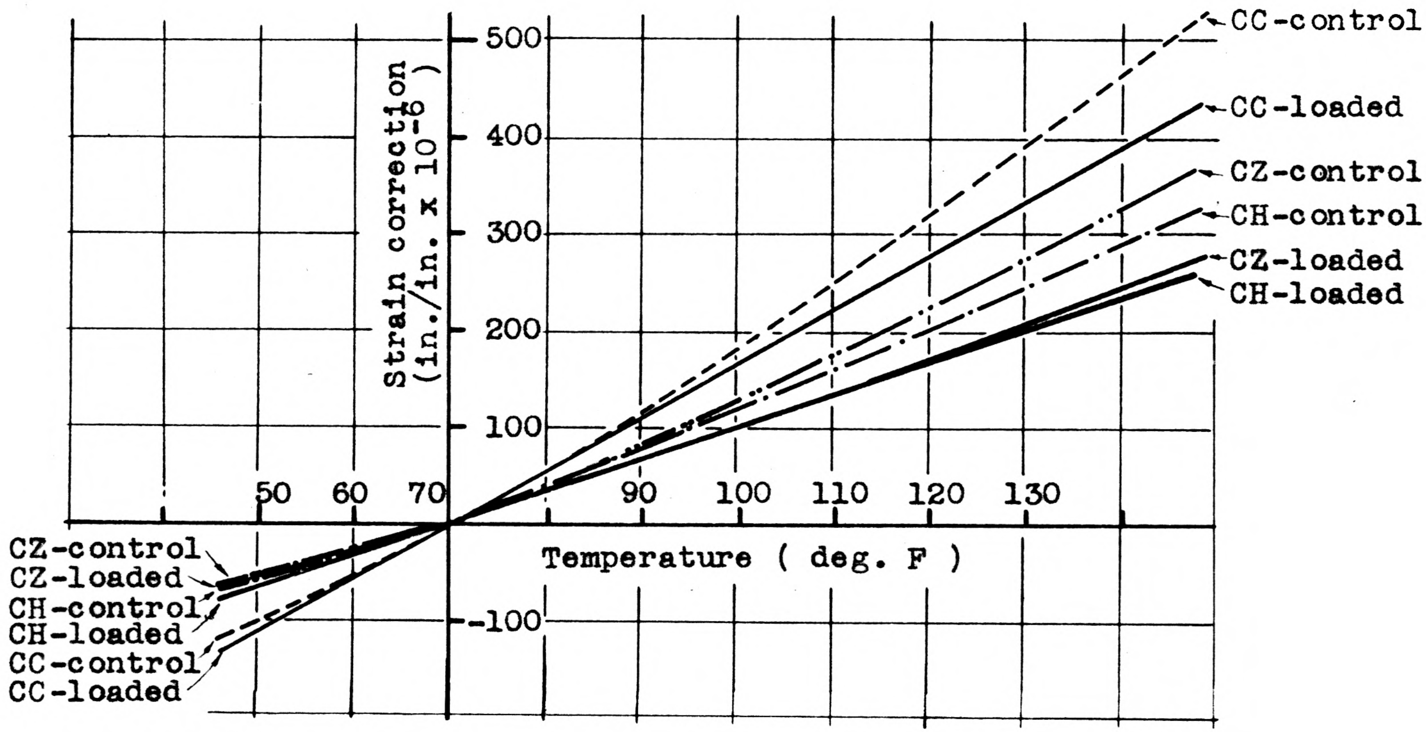


Fig. 2. Temperature correction curves for saturated specimens.

In order to eliminate this error, a thermal expansion determination was made for each mix for both loaded specimens and controls. These correction values, as shown in Figs. 1 and 2, were the total effects of temperature variation upon our readings. Therefore, correction was made by adding or subtracting these corrections at any temperature.

To justify this correction, an example is shown in Fig. 3. The dotted line represents the gross strain curve plotted before temperature correction, and the solid line the same curve plotted with corrected data. It is at once evident that the corrections result in a much smoother curve.

Humidity Effect. There was no humidity record during the test; therefore, no correction could be made to allow for the effect of change in humidity. At any rate, the value of creep was computed on a comparison basis. Since the loaded and control specimens were always subjected to the same conditions, effects common to them would be cancelled out during subtraction to get the creep strain. The effect of humidity was not a variable under study.

Miscellaneous Effects. During the time while creep continued, not only did water move in and out of the gel, but the gel itself underwent chemical change. Both physical and chemical changes were involved, and neither was uniform. The concrete was a heterogeneous material to begin with. The variation in properties of different specimens, such as composition, water content, and shape could not be avoided. The variation in modulus of elasticity of the specimens of the same set was an indication that our results were reliable only in a statistic sense.

One question which naturally arose was that of the confidence that might be given to the results. In other words, when sets of specimens under different storage conditions were compared, what portion of the difference of results

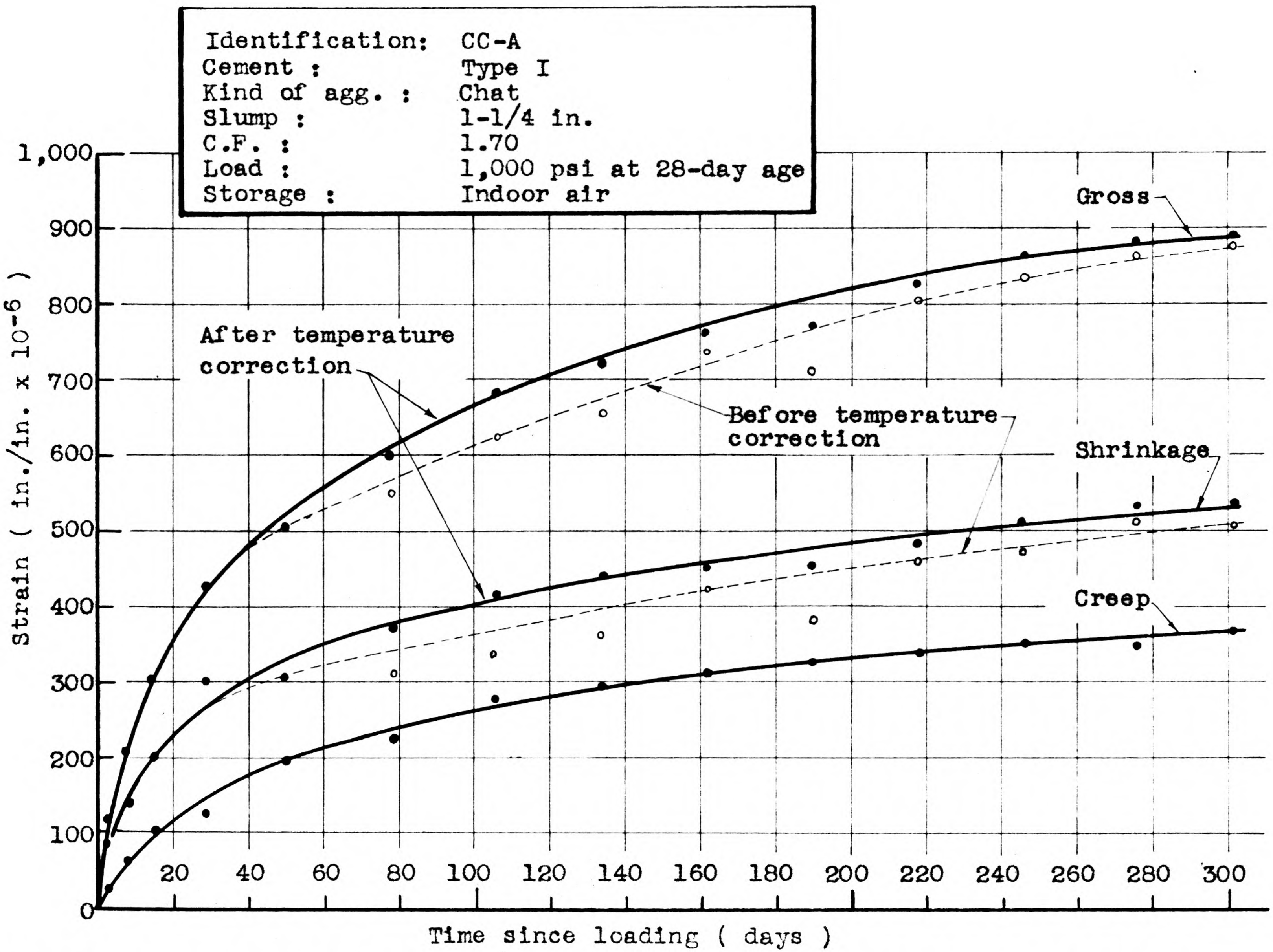


Fig. 3. A comparison of strain curves with and without temperature correction.

could be regarded as caused by the influence of treatment and what portion of this difference should be thought of as a sampling variation?

In order to examine this problem, a study was made comparing the difference of creep strain of specimens in the same set. Since they were under the same conditions all the time, any differences between them were due to the effects of uncontrolled factors, and might be regarded as a kind of measure of the variance due to sampling.

It was found that this variation among identical specimens varied from 10×10^{-6} to about 80×10^{-6} in/in. The average deviation was around 40×10^{-6} in/in, or about seven percent when the ultimate creep was 600×10^{-6} in/in. Using this as a standard, we might say that any differences less than 40×10^{-6} in/in probably had no significance and was possibly due to the variation in sampling. Only differences greater than 40×10^{-6} in/in were considered caused by different storage conditions.

RESULTS

Results are here presented by (a) strain curves as shown by Figs. 4 through 22 which includes all curves for mix CZ and four representative curves for each mix CC and CH, and (b) Table 5 which gives the final strains.

ANALYSIS OF RESULTS

Emperical Formulae

Previous investigators have suggested the following formulae for correlating creep data:

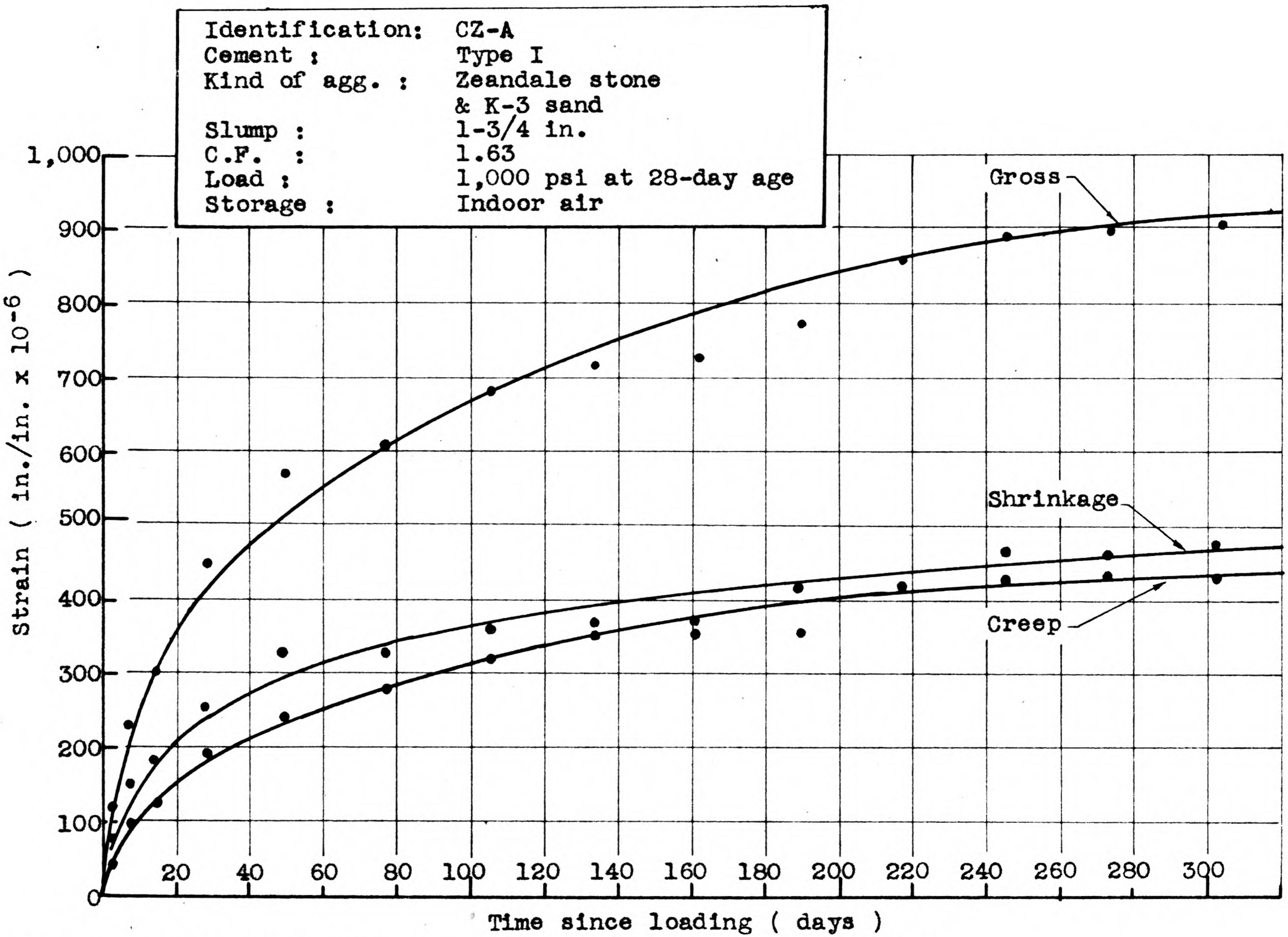


Fig. 4. Strain-time curve for mix CZ under indoor air exposure.

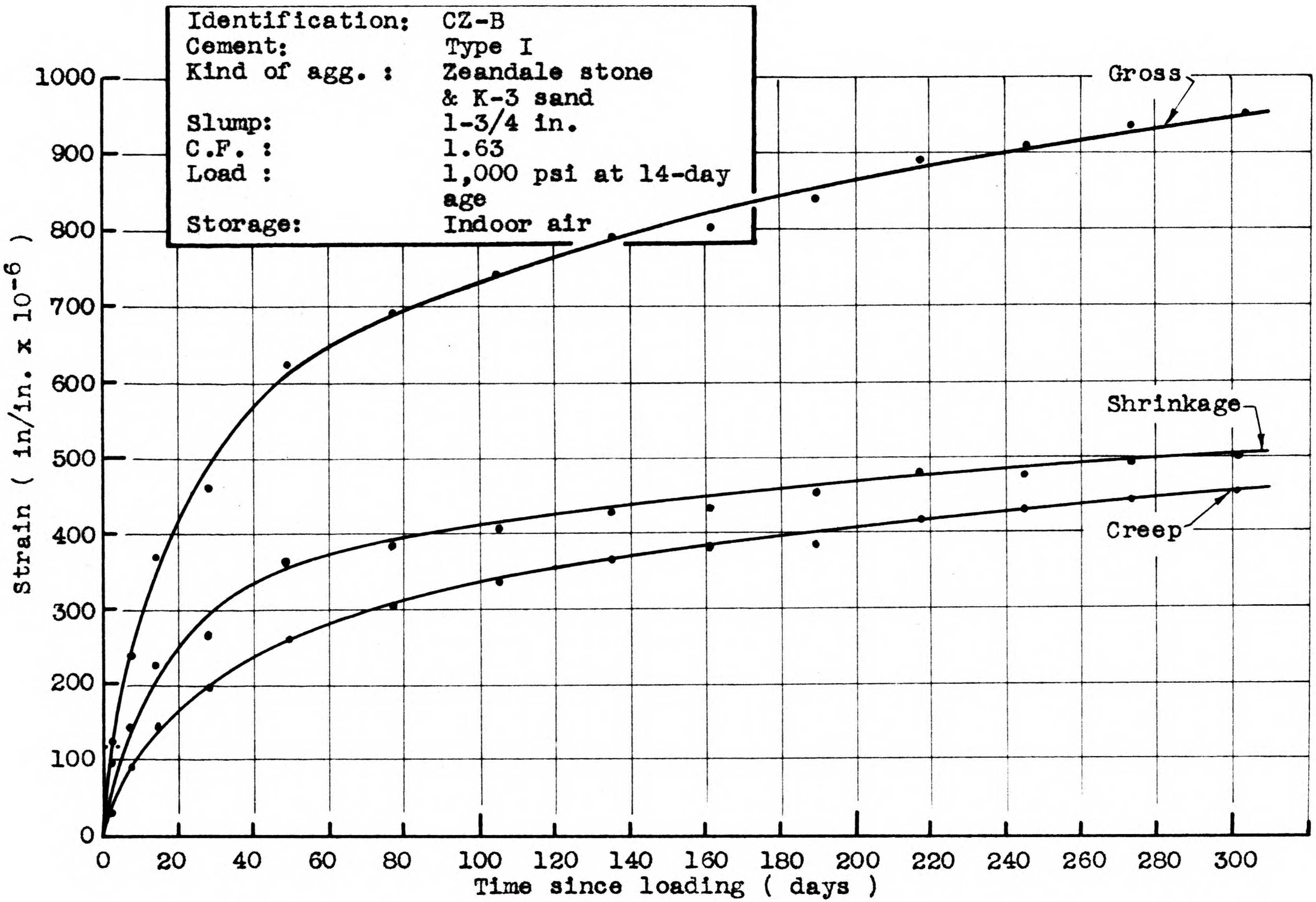


Fig. 5. Strain-time curve for mix CZ under indoor air exposure.

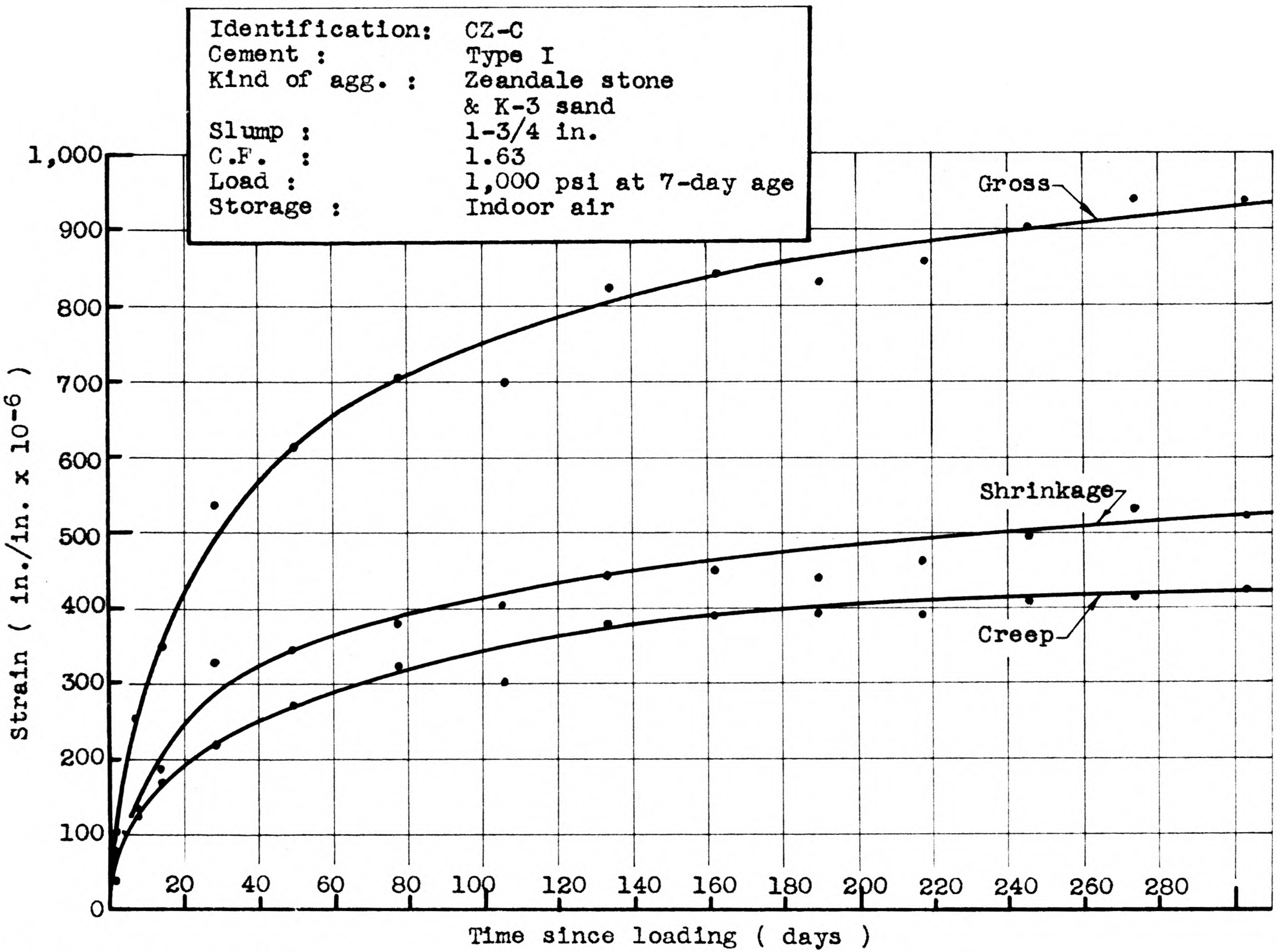


Fig. 6. Strain-time curve for mix CZ under indoor air exposure.

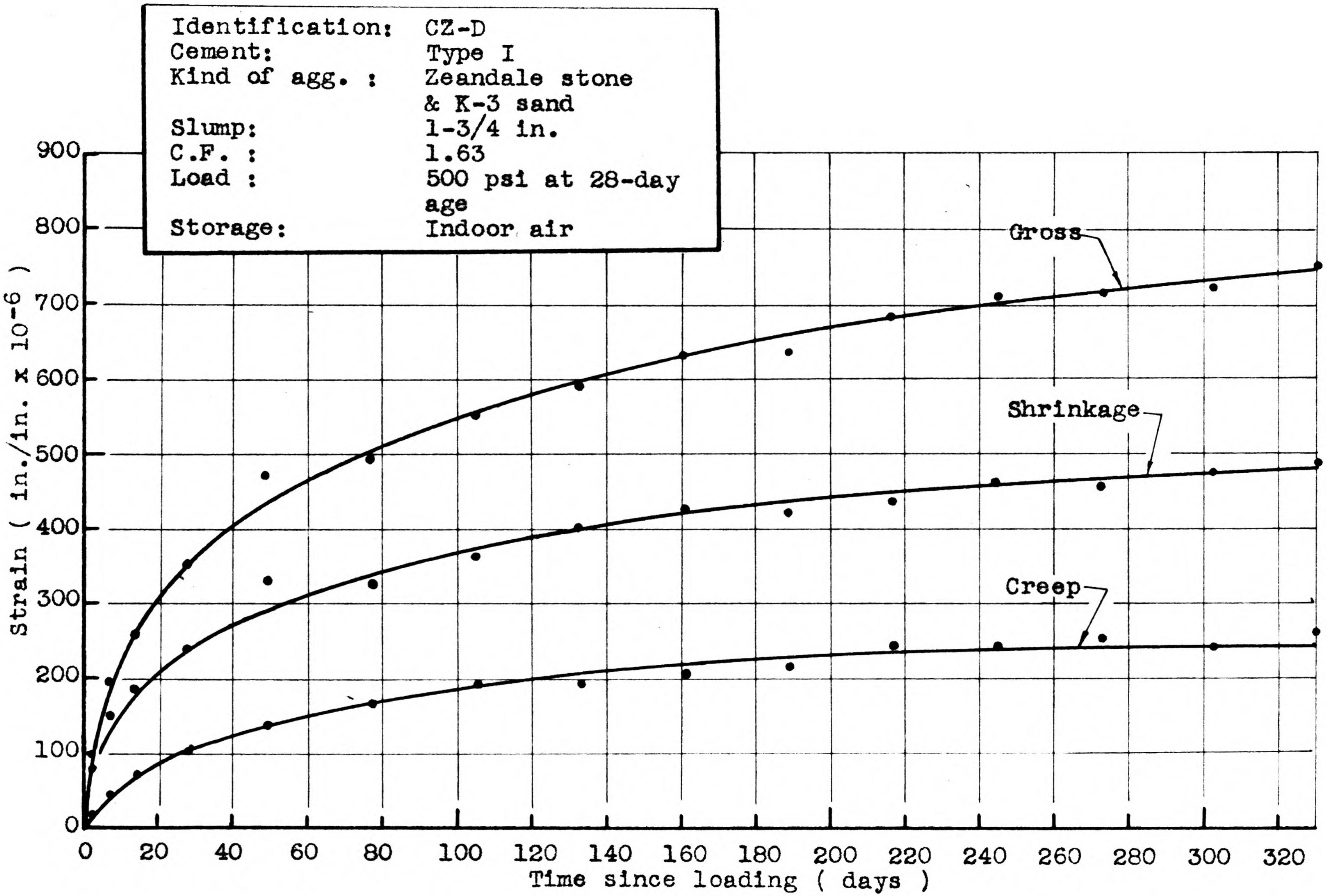


Fig. 7. Strain-time curve for mix CZ under indoor air exposure.

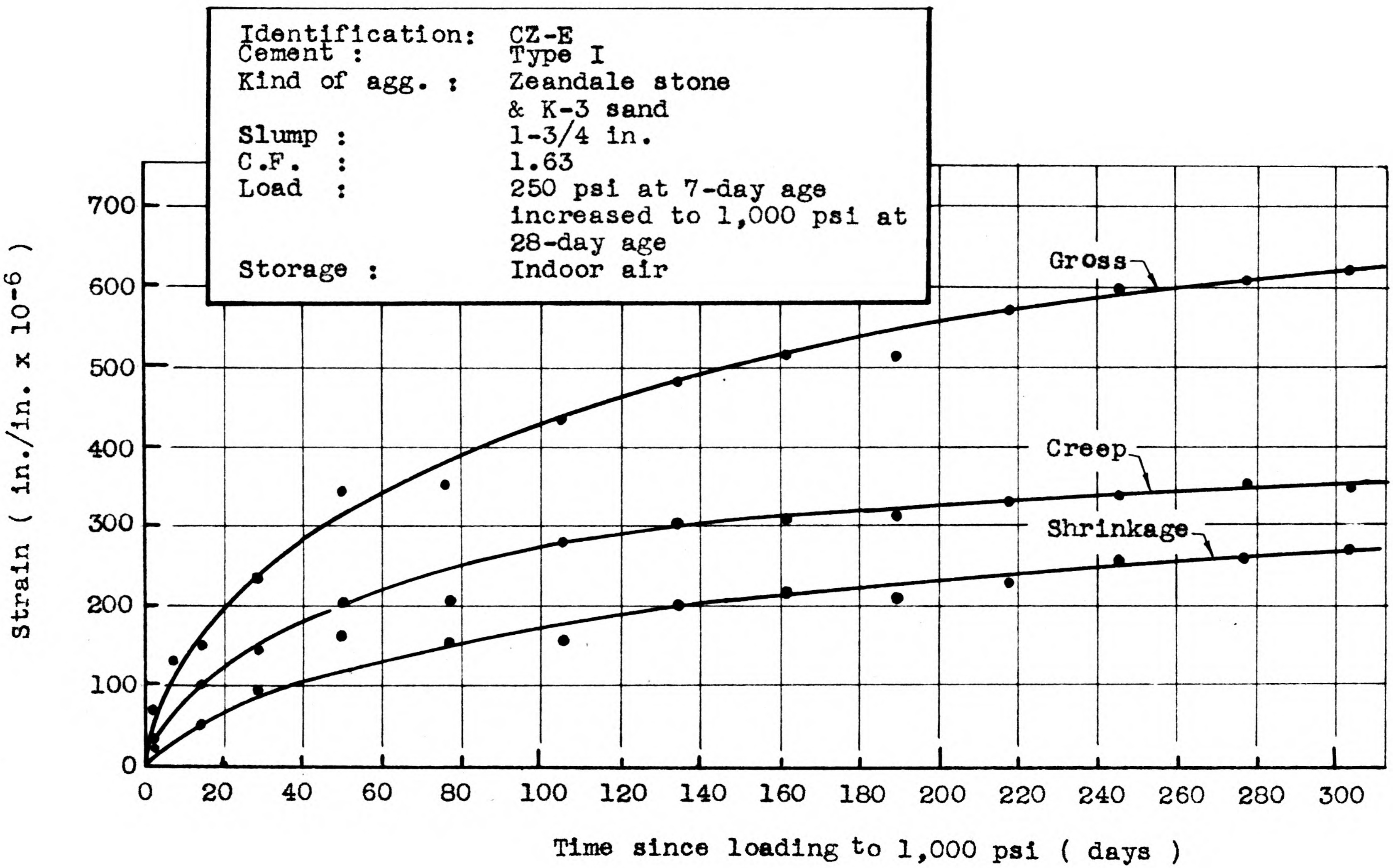


Fig. 8. Strain-time curve for mix CZ specimens prestressed at 7-day age to 250 psi and under indoor air exposure.

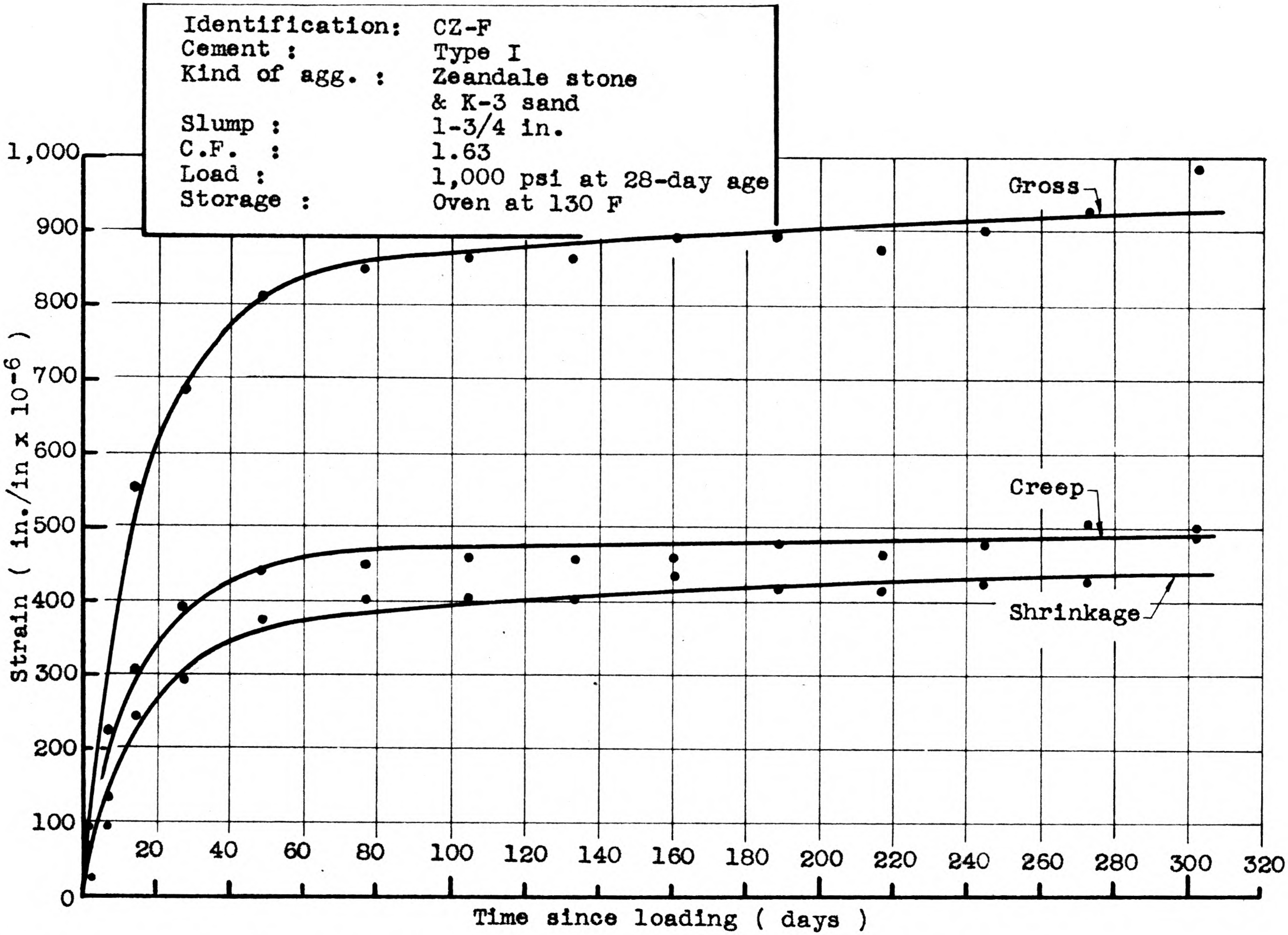


Fig. 9. Strain-time curve for mix CZ specimens stored in oven at 130 F.

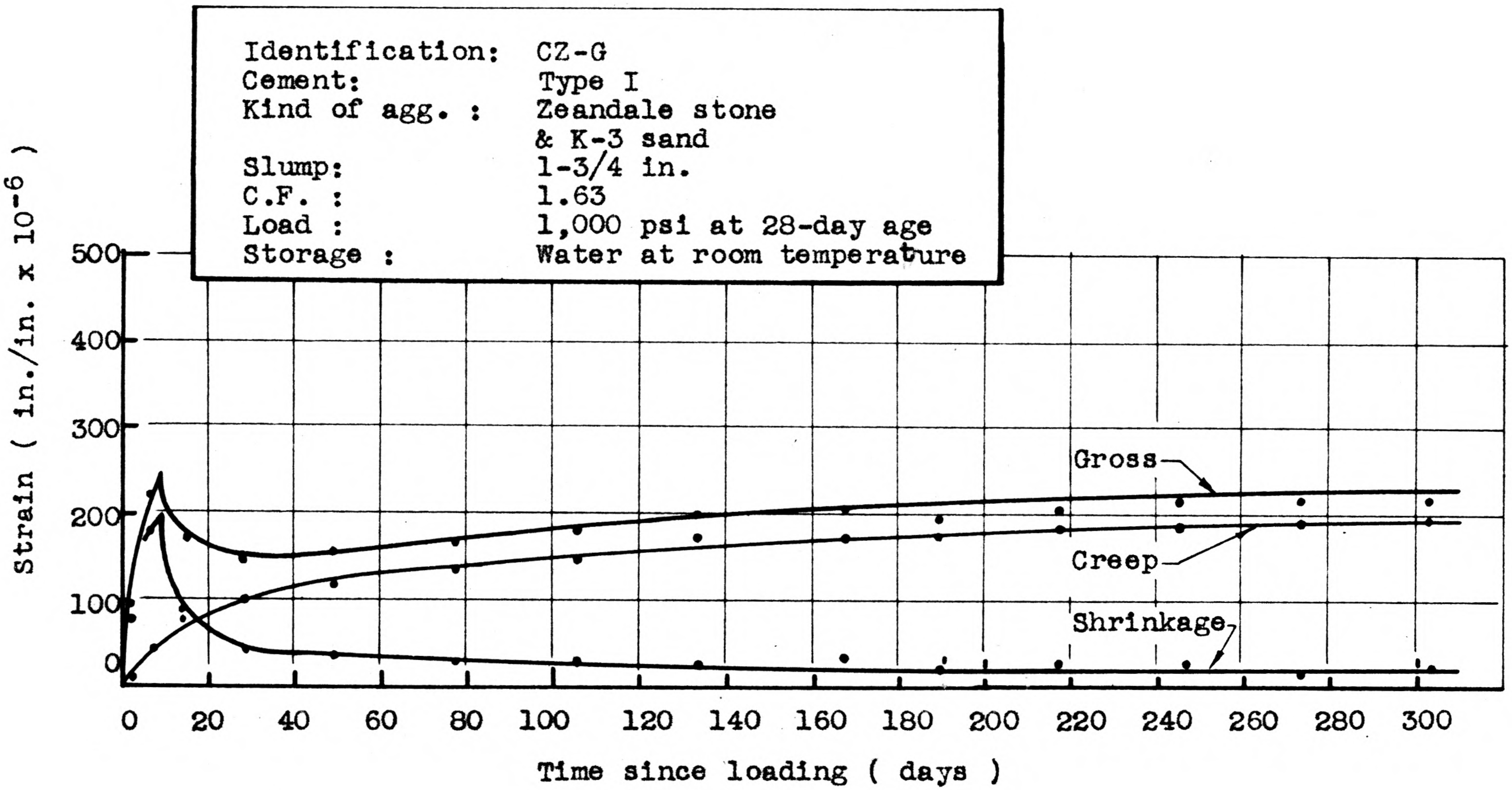


Fig. 10. Strain-time curve for mix CZ specimens stored in water at room temperature.

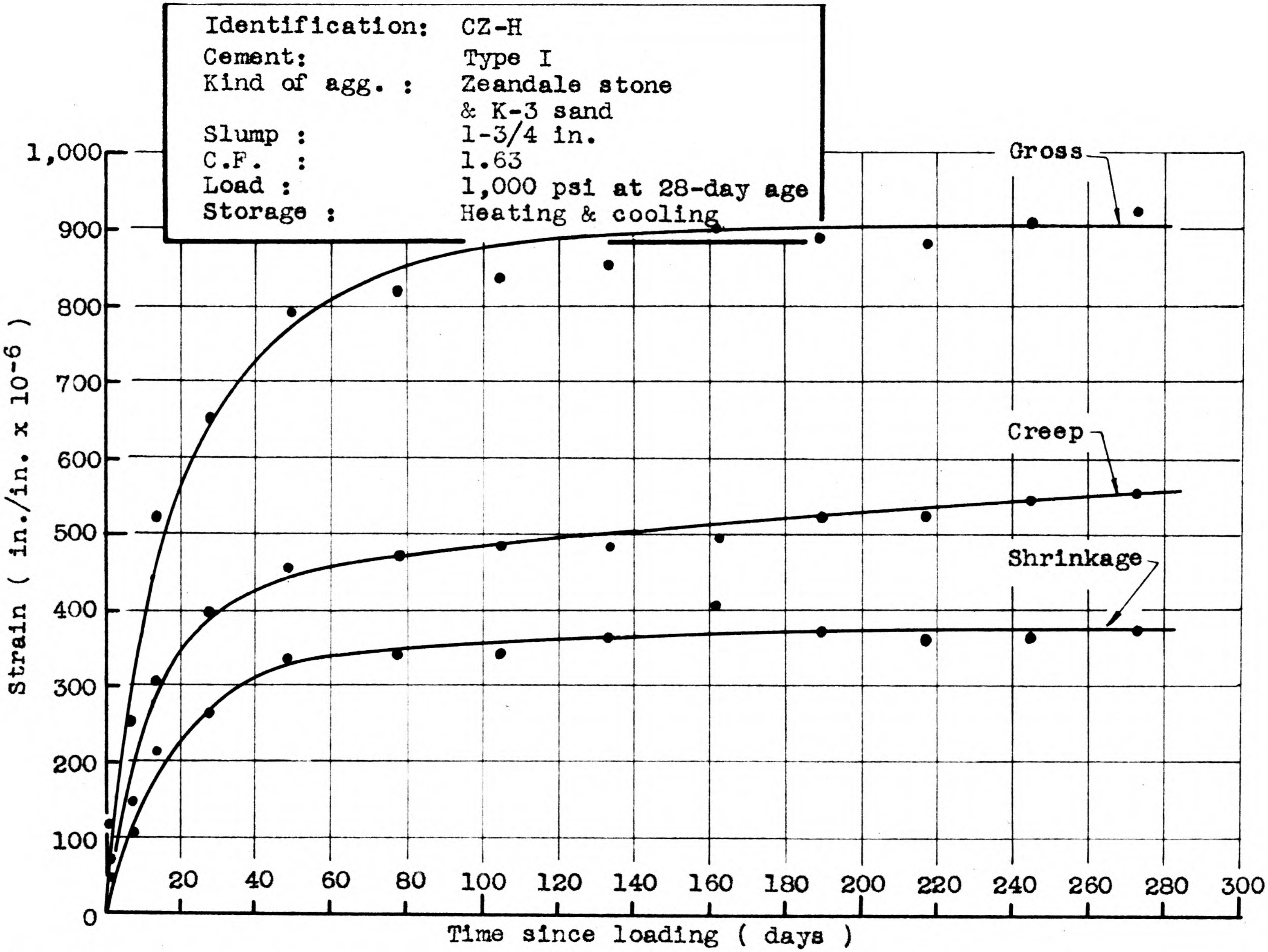


Fig. 11. Strain-time curve for mix CZ under heating and cooling exposure.

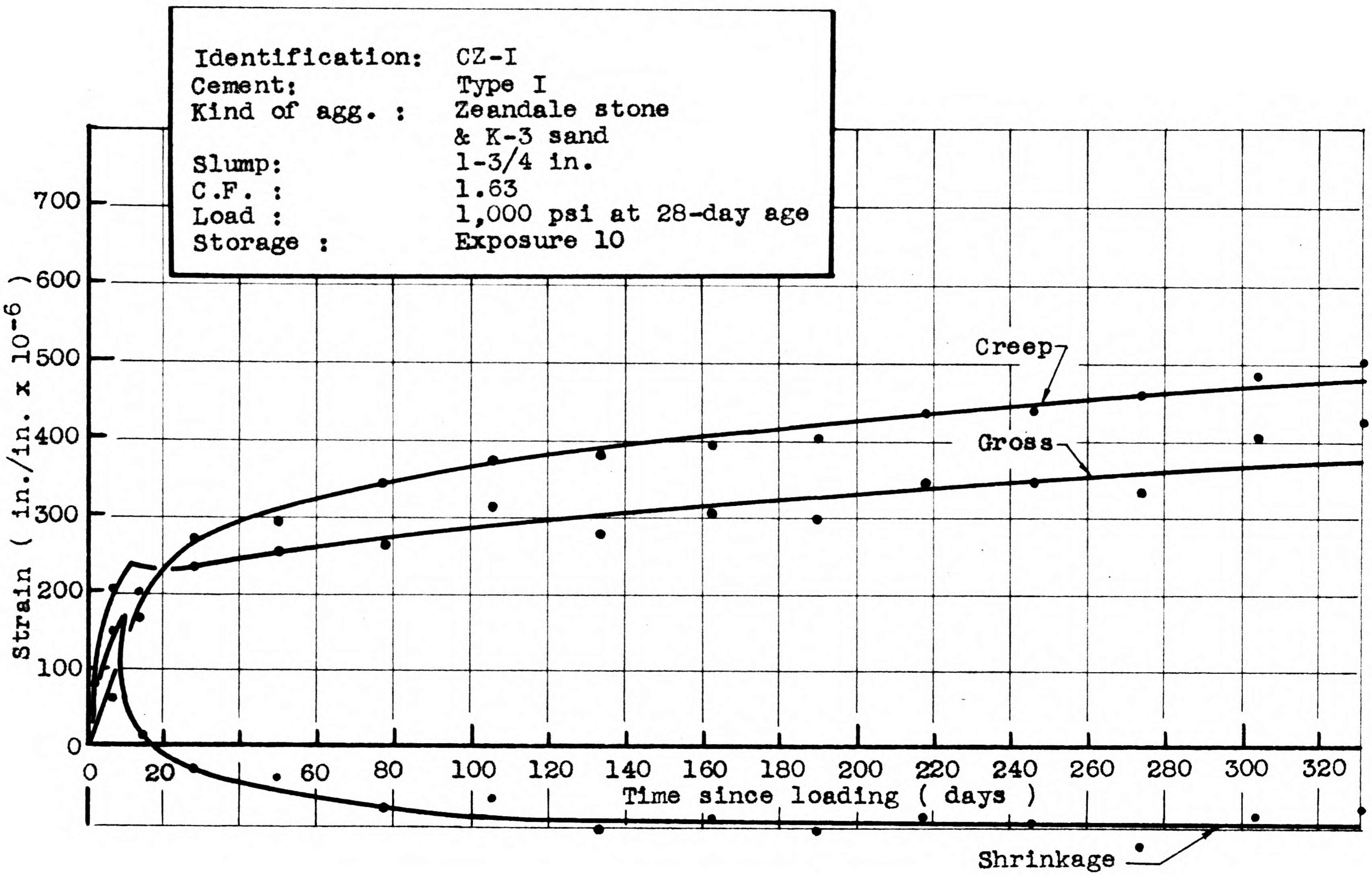


Fig. 12. Strain-time curve for mix CZ under Exposure 10.

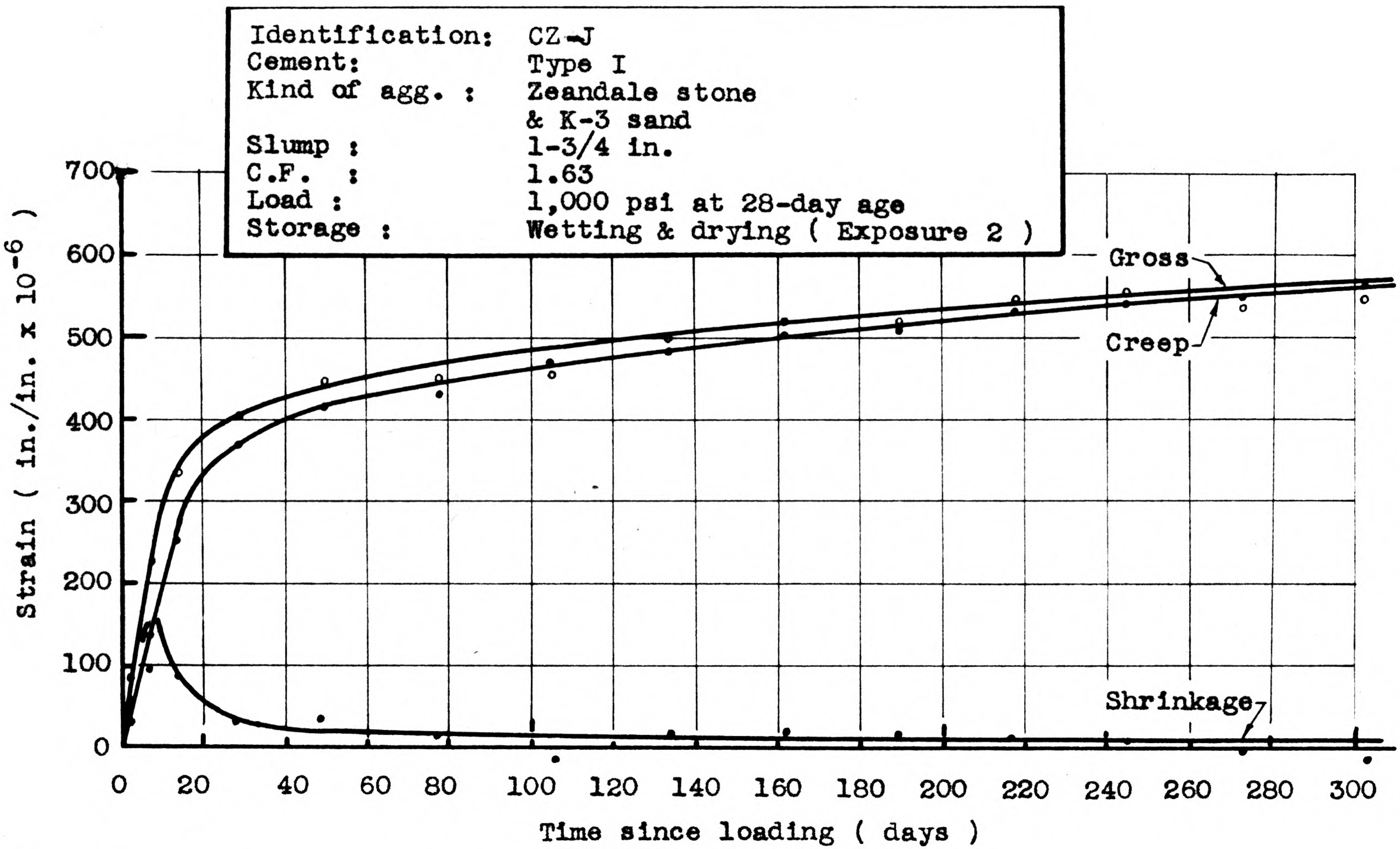


Fig. 13. Strain-time curve for mix CZ under Exposure 2.

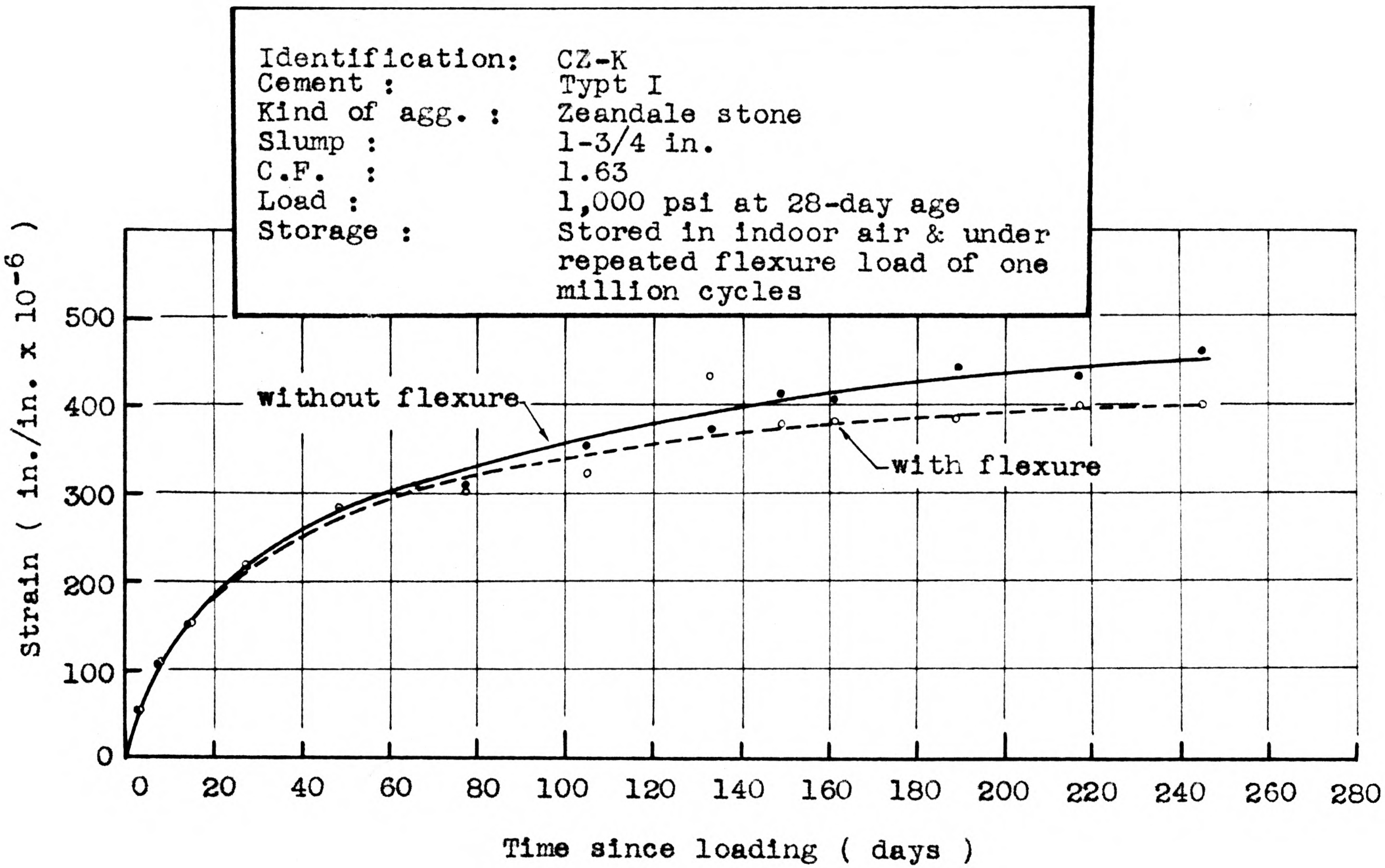


Fig. 14. Creep strain curves for mix CZ specimens with and without flexure load.

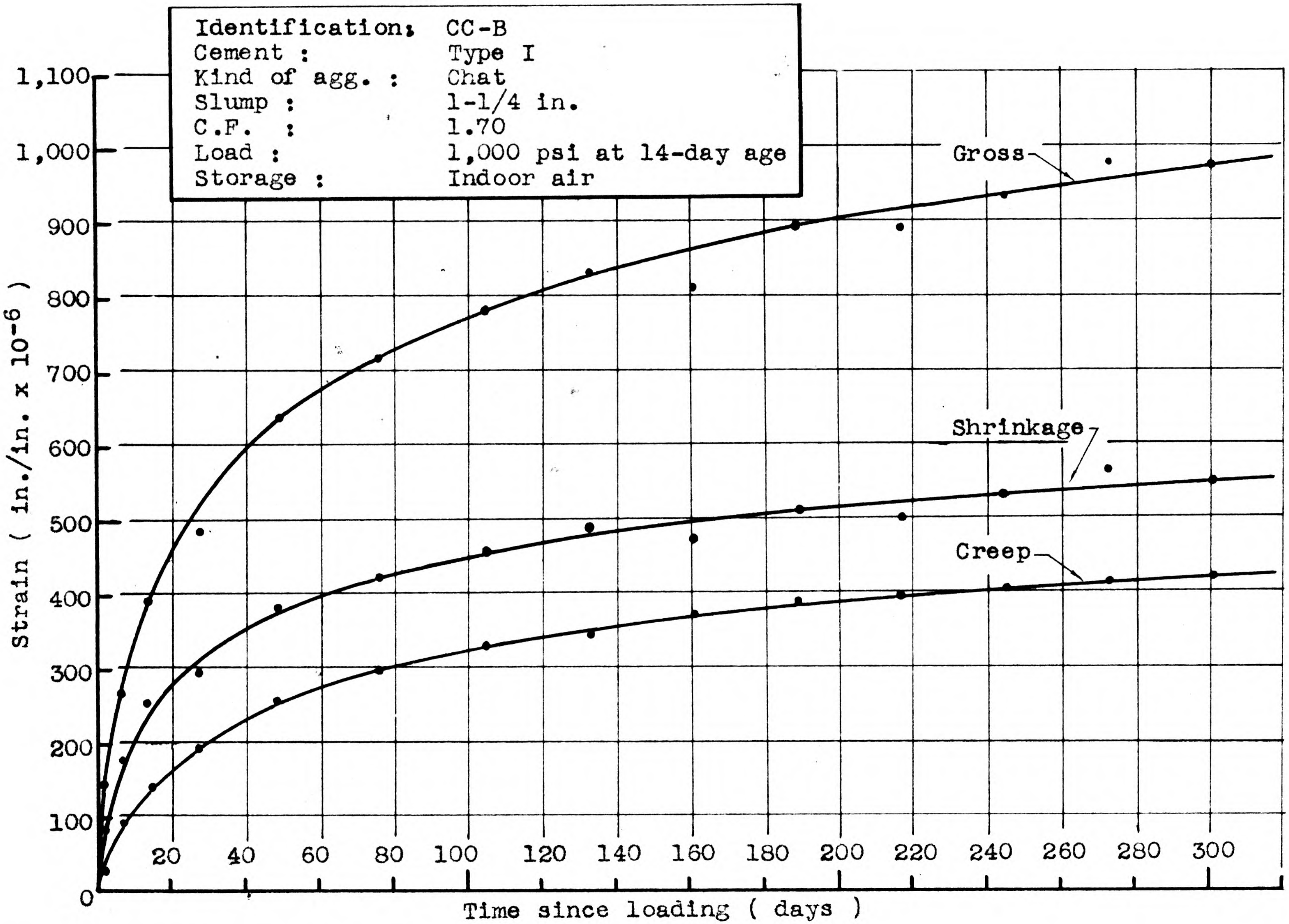


Fig. 15. Strain-time curve for mix CC under indoor air exposure.

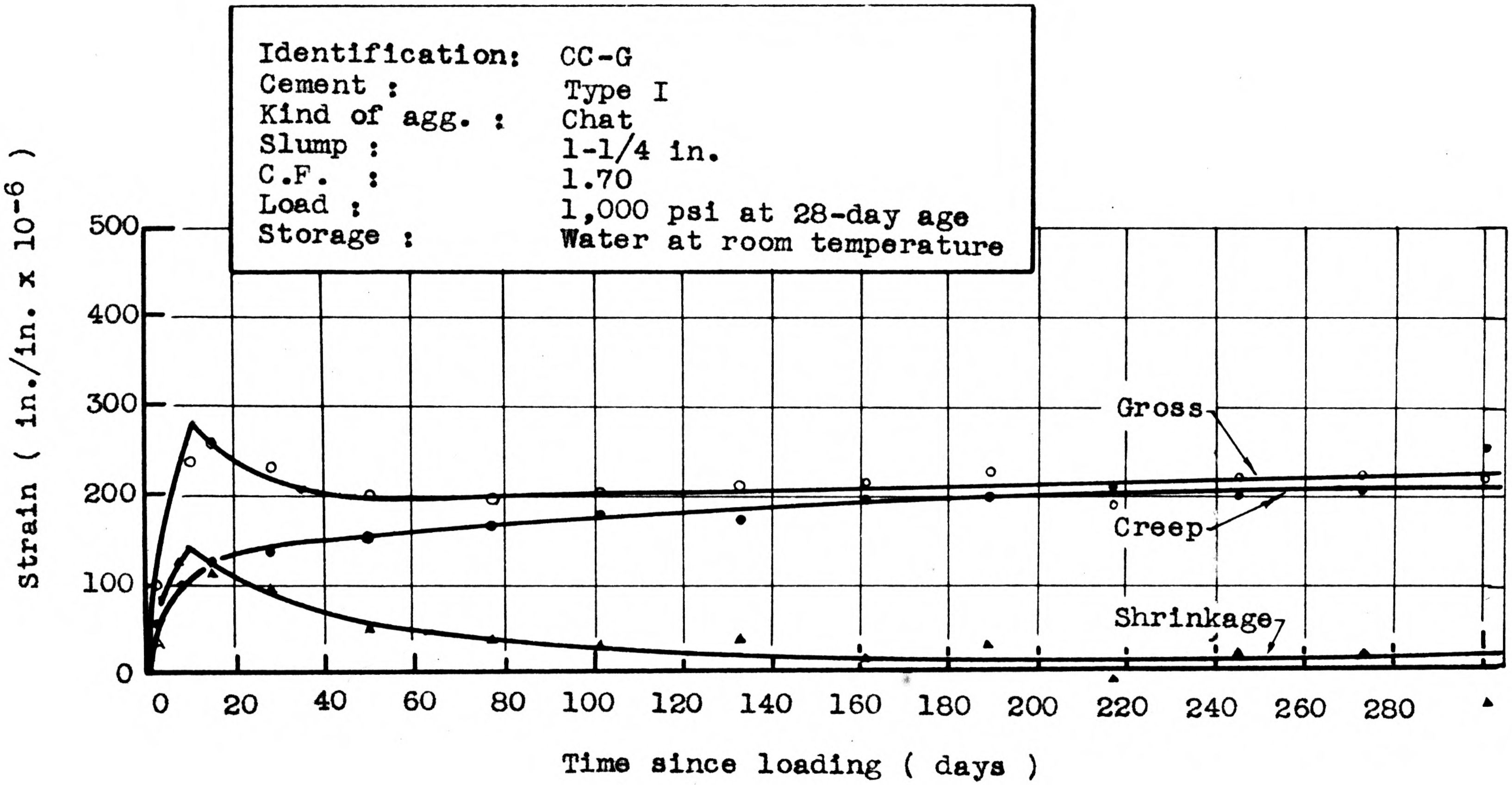


Fig. 16. Strain-time curve for mix CC specimens stored in water at room temperature.

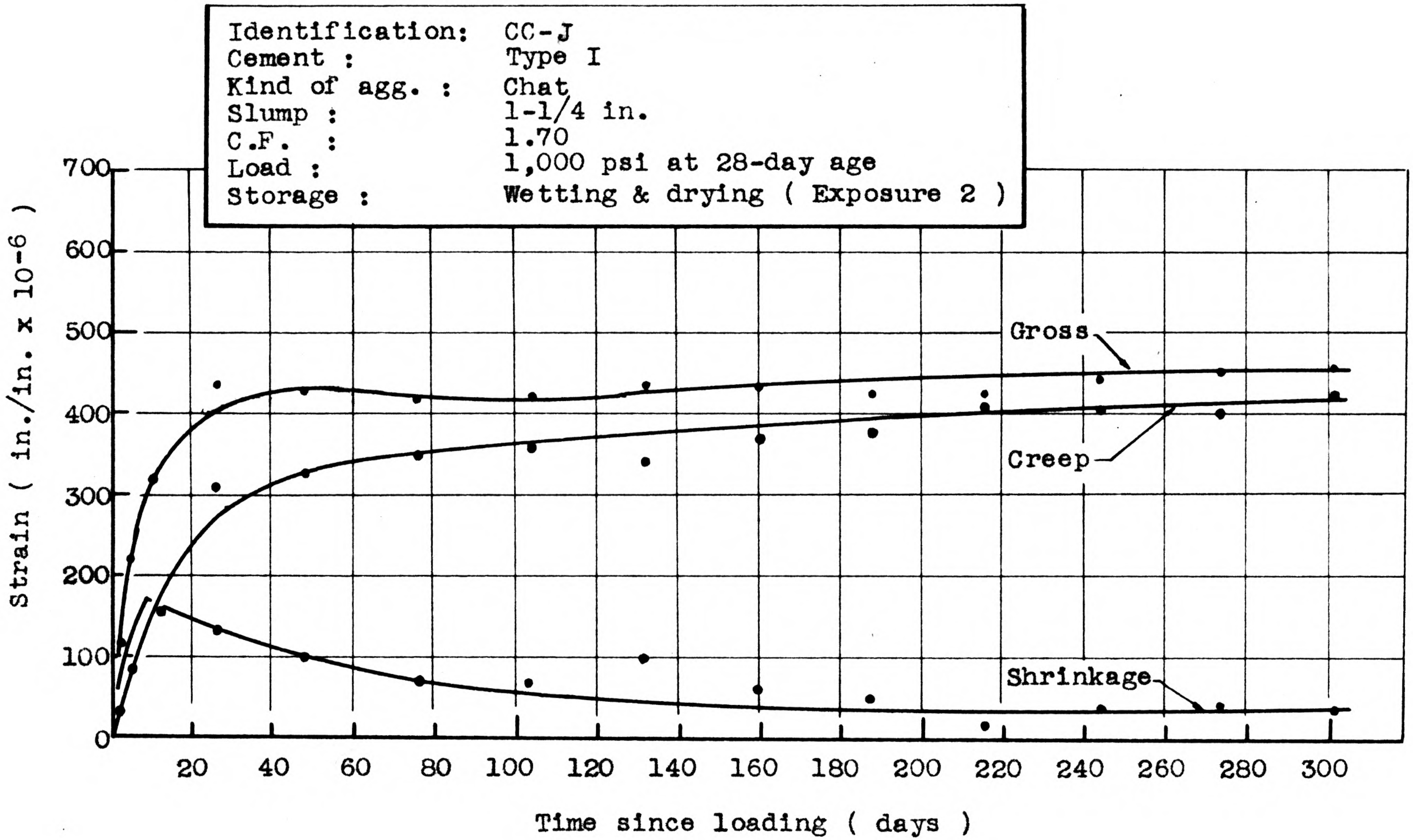


Fig. 17. Strain-time curve for mix CC under Exposure 2.

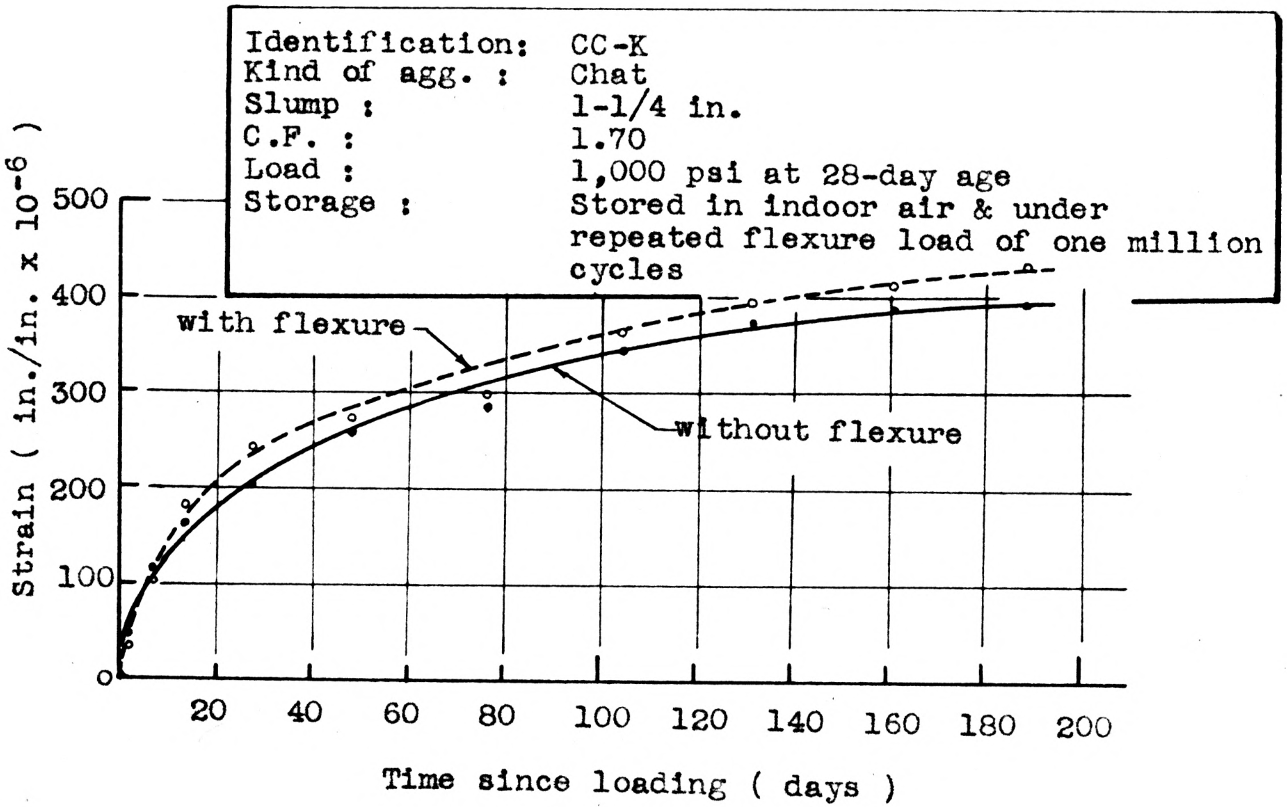


Fig. 18. Strain-time curves for mix CC specimens with and without flexure load.

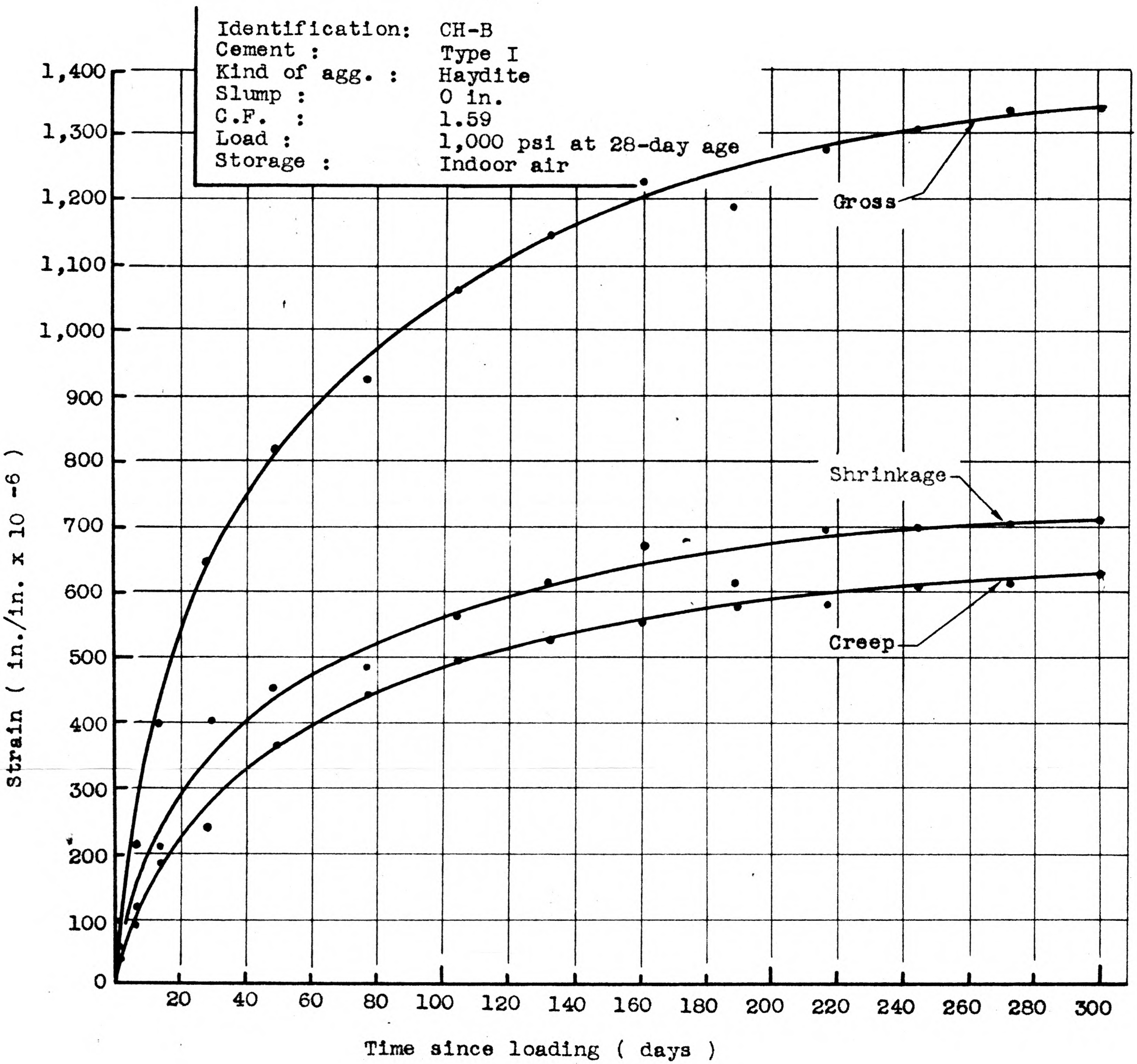


Fig. 19. Strain-time curve for mix CH under indoor air exposure.

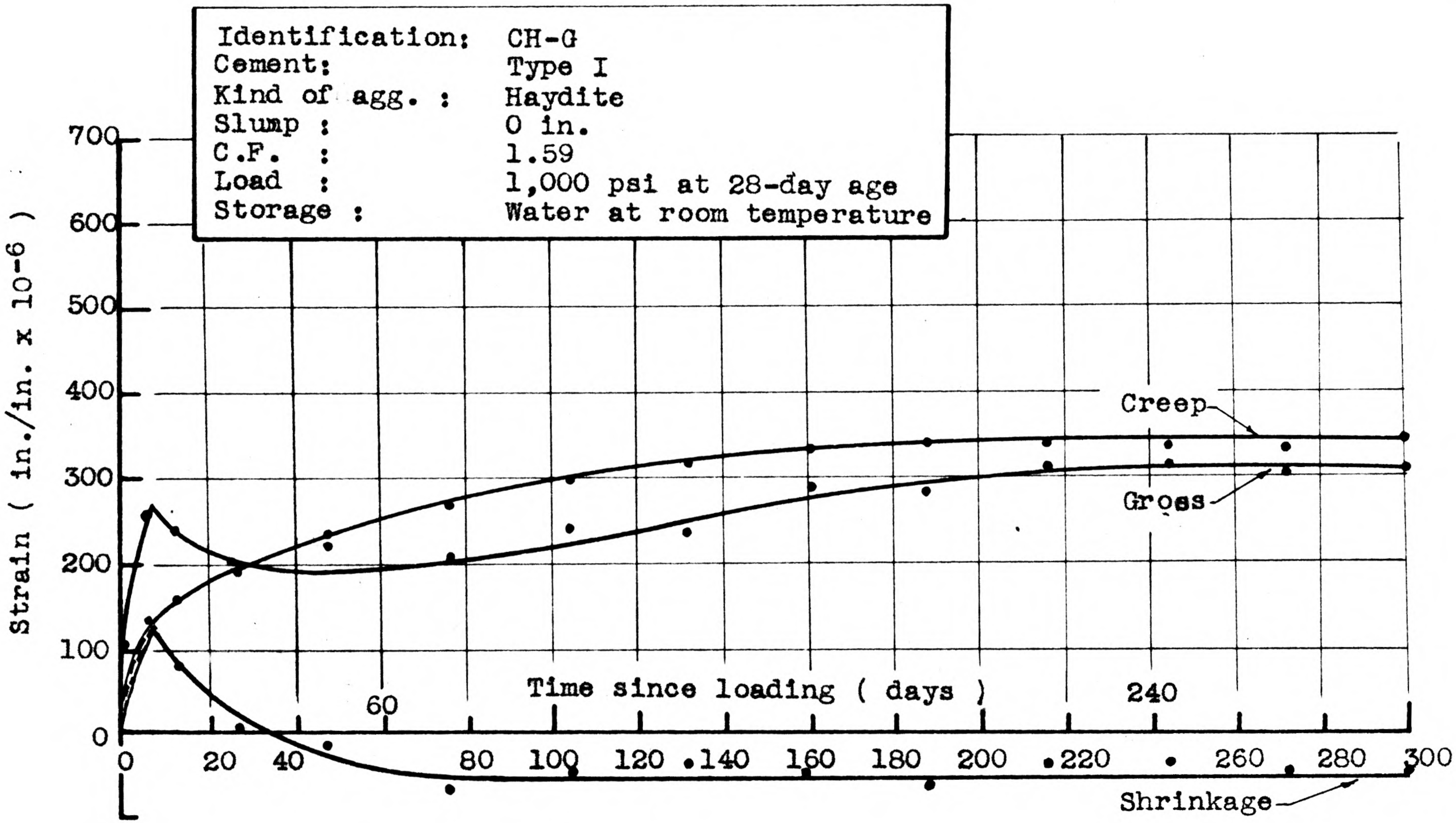


Fig. 20. Strain-time curve for mix CH specimens stored in water at room temperature.

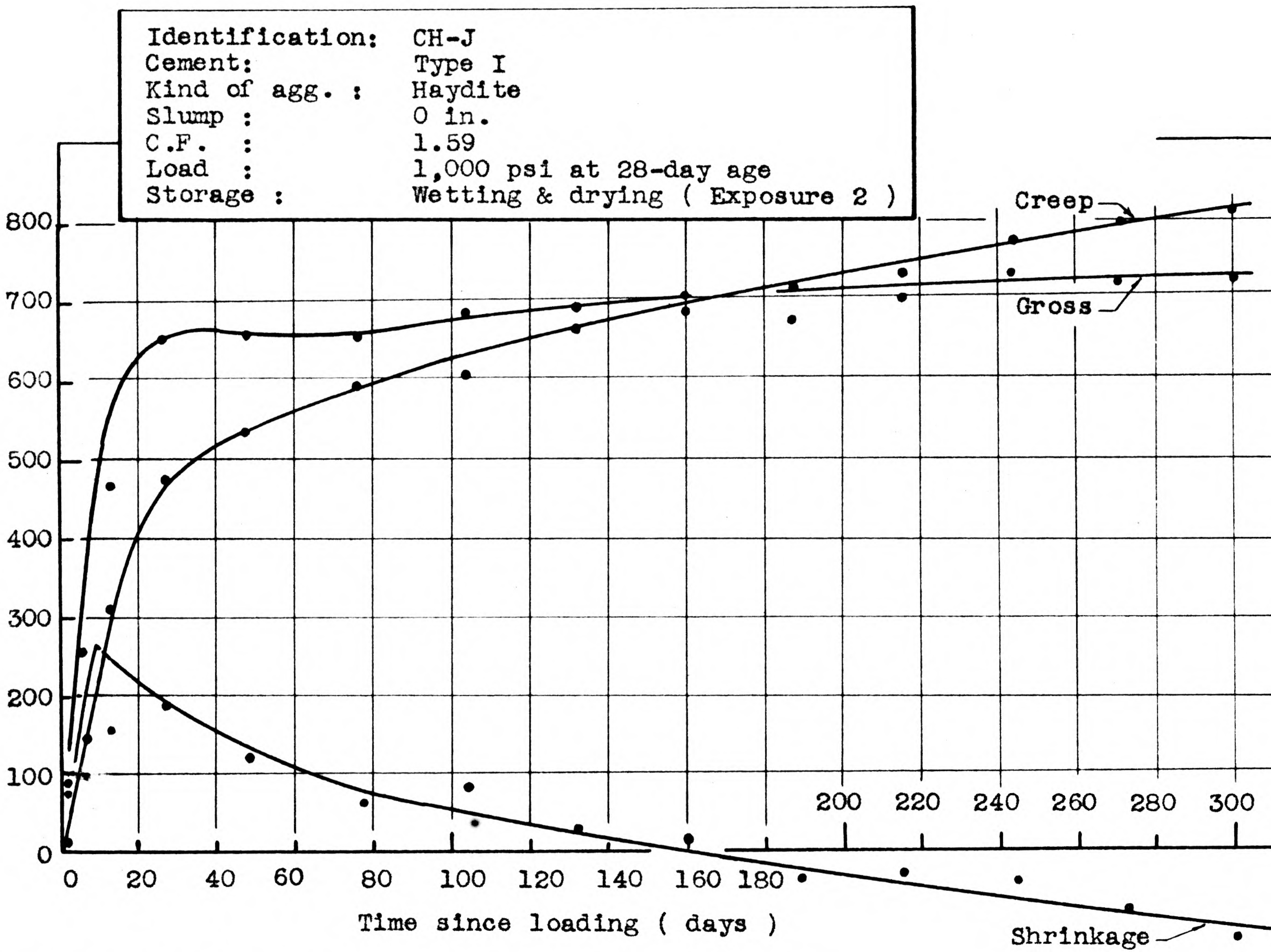


Fig. 21. Strain-time curve for mix CH under Exposure 2.

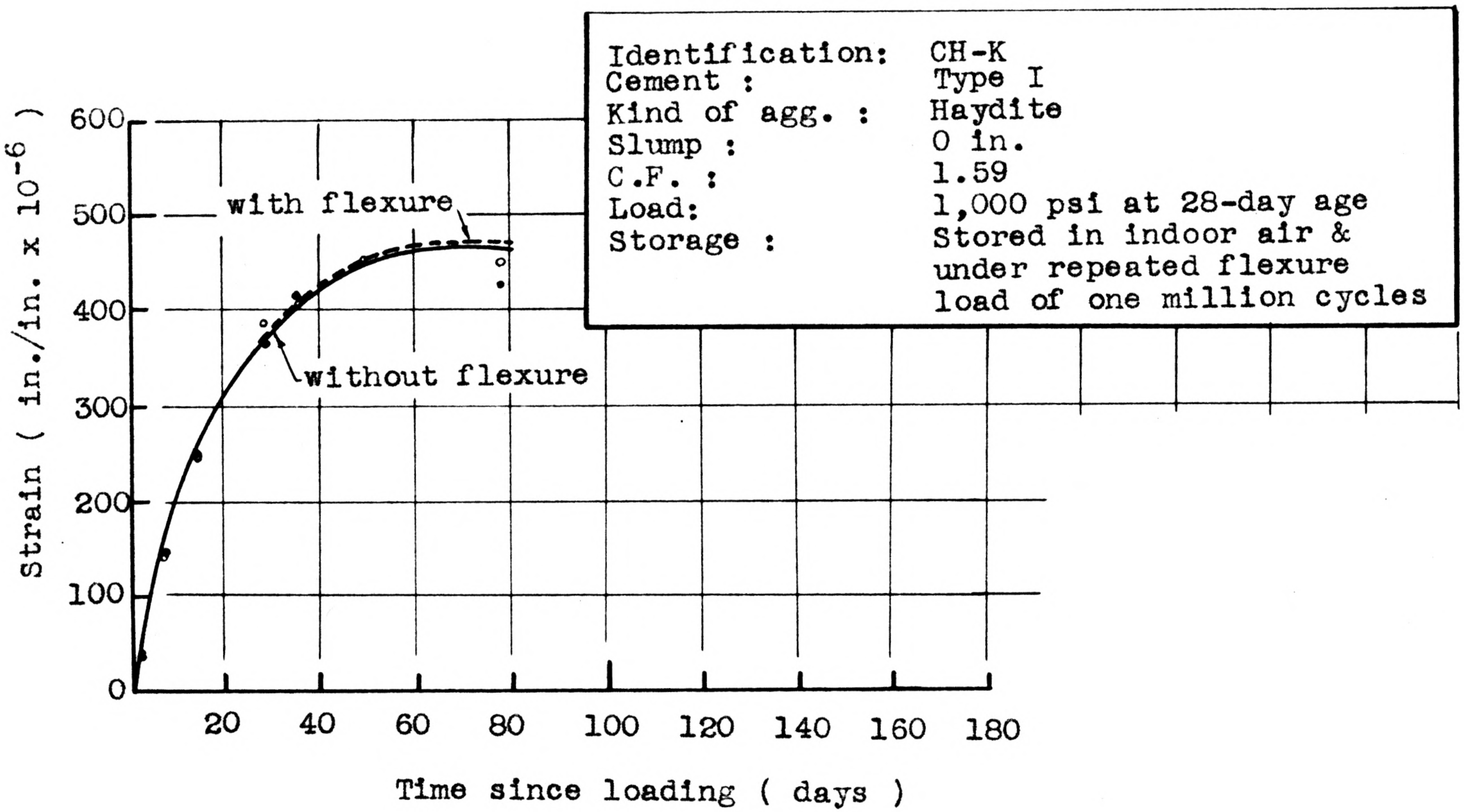


Fig. 22. Creep strain curves for mix CH specimens with and without flexure load.

Table 5. Strains and Lorman coefficients obtained for each series of each mix.

Mix	Series	Strains after loading (in/in x 10^{-6}): Age (days)	Gross	Creep	Shrinkage	Lorman's coefficients: m	n
	A	329	901	380	521	445	70
	B	329	1011	430	581	475	40
	C	329	1019	467	552	506	41
	D	329	718	248	470	250	40
	E	329	607	338	269	402	72
CC	F	329	892	374	518	380	10
	G	329	252	271	-19	280	10
	H	329	888	423	465	430	12
	I	329	387	396	-9	450	35
	J	329	464	425	39	485	22
	K-1	189	944	434	510	—	—
	K-2	189	904	394	510	—	—
	A	301	1371	627	744	700	65
	B	301	1339	629	710	712	47
	C	301	1375	650	725	759	38
	CE	301	1520	761	759	874	40
	D	301	1186	442	744	490	56
	E	301	1106	707	399	850	38
CH	F	301	1516	737	779	796	12
	G	301	343	386	-43	400	23
	H	301	1527	792	735	870	18
	I	301	389	403	14	520	30
	J	301	692	812	-120	985	32
	K-1	105	1207	648	559	—	—
	K-2	105	1231	672	559	—	—
	A	303	916	437	479	525	66
	B	303	958	455	503	564	65
	C	303	948	426	522	492	40
	D	303	721	242	479	292	54
	E	303	628	351	277	412	52
CZ	F	303	1011	521	490	575	13
	G	303	213	193	20	270	35
	H	303	1022	573	449	686	20
	I	303	403	488	-83	586	40
	J	303	546	564	-18	670	22
	K-1	273	858	427	431	—	—
	K-2	273	903	472	431	—	—

L. G. Straub's formula (50):

$$e_c = ks^p t^q \quad (1$$

Thomas's formula (19):

$$e_c = ks(1-e^{-A(t+a)^x} - a^x) \quad (2$$

Shank's formula (44):

$$e_c = k\, t^{1/a} \quad (3$$

D. McHenry's formula (33):

$$e_c = s\left[a(1-e^{-pt}) + be^{-qy}(1-e^{-rt})\right] \quad (4$$

Ross-Lorman formula (25):

$$e_c = \frac{mst}{n + t} \quad (5$$

Symbols in the above formulae have the following meanings:

e_c = the unit strain occurring in t days (in/in)

x = unit stress (psi)

t = time since loading (days)

a = the cross sectional area of the specimen (sq. in)

e = the Naperian base

y = age at time of loading (days)

p,q,r,m,n,a,x,k = constants obtained from test.

Since all the above formulae are emperical or semi-emperical, the Ross-Lorman method was chosen.

Ross-Lorman Method

This method has the advantages of being simple and self explanatory because the two constants m and n in the formula

$$e_c = \frac{mst}{n + t}$$

have the following physical meanings:

m = ultimate strain (in/in) per unit stress

n = time in days at which half of the ultimate strain is attained.

This can be easily verified as follows:

$$e_c = \frac{mst}{n + t} \quad \text{-------------------} \quad (5$$

$$\lim_{t \to \infty} e_c = \lim_{t \to \infty} \frac{mst}{n + t} = ms \quad \text{or } m = e_{c_\infty}/s = \text{Ultimate strain per unit stress}$$

Also, equation (5 may be written as:

$$t = ne_c / (ms - e_c)$$

when $e_c = e_{c_\infty}/2 = ms/2$

$$t_{\frac{1}{2}} = n$$

Therefore, n = time in days at which half of the ultimate strain is attained.

To determine the constants from the given experimental data, the formula was rewritten as follows:

$$t = m(st/e_c) - n \quad \text{-------------------} \quad (6$$

Let $v = st/e_c$, (6) becomes

$$t = mv - n \quad \text{-------------------} \quad (7$$

This is a straight line formula, m being the slope of the line and n the intercept of this line on the vertical axis.

To determine m and n, v was calculated from known data, and then plotted in a t-v plane. An example is shown in Fig. 23. The close correlation between experimental and calculated curve is shown in Fig. 24. For other specimens, the values of m and n were obtained in a similar manner. Table 5 gives these values in comparison with the final strain readings.

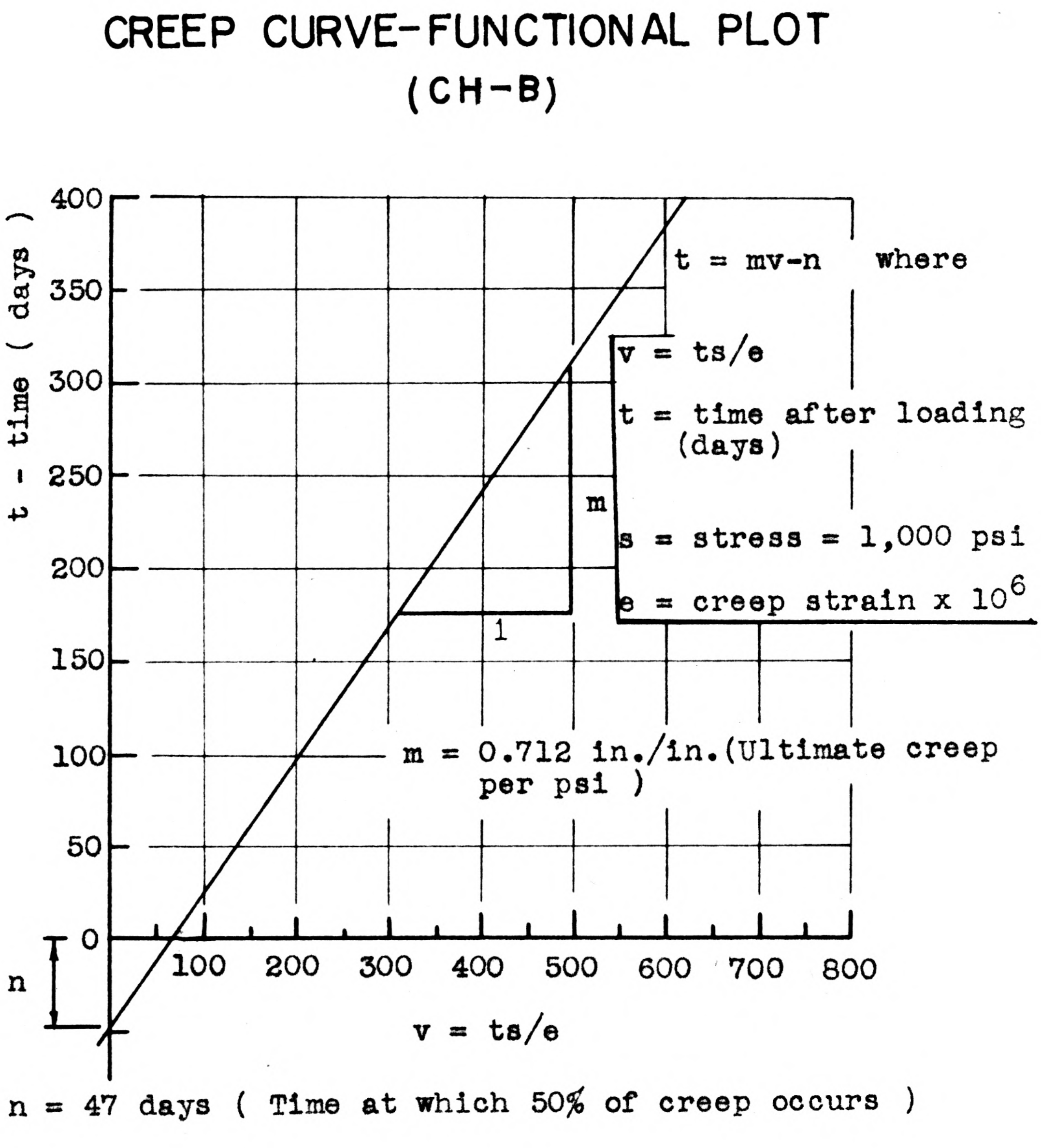


Fig. 23. Creep curve illustrating Lorman's method of determining ultimate creep and age at 50% creep.

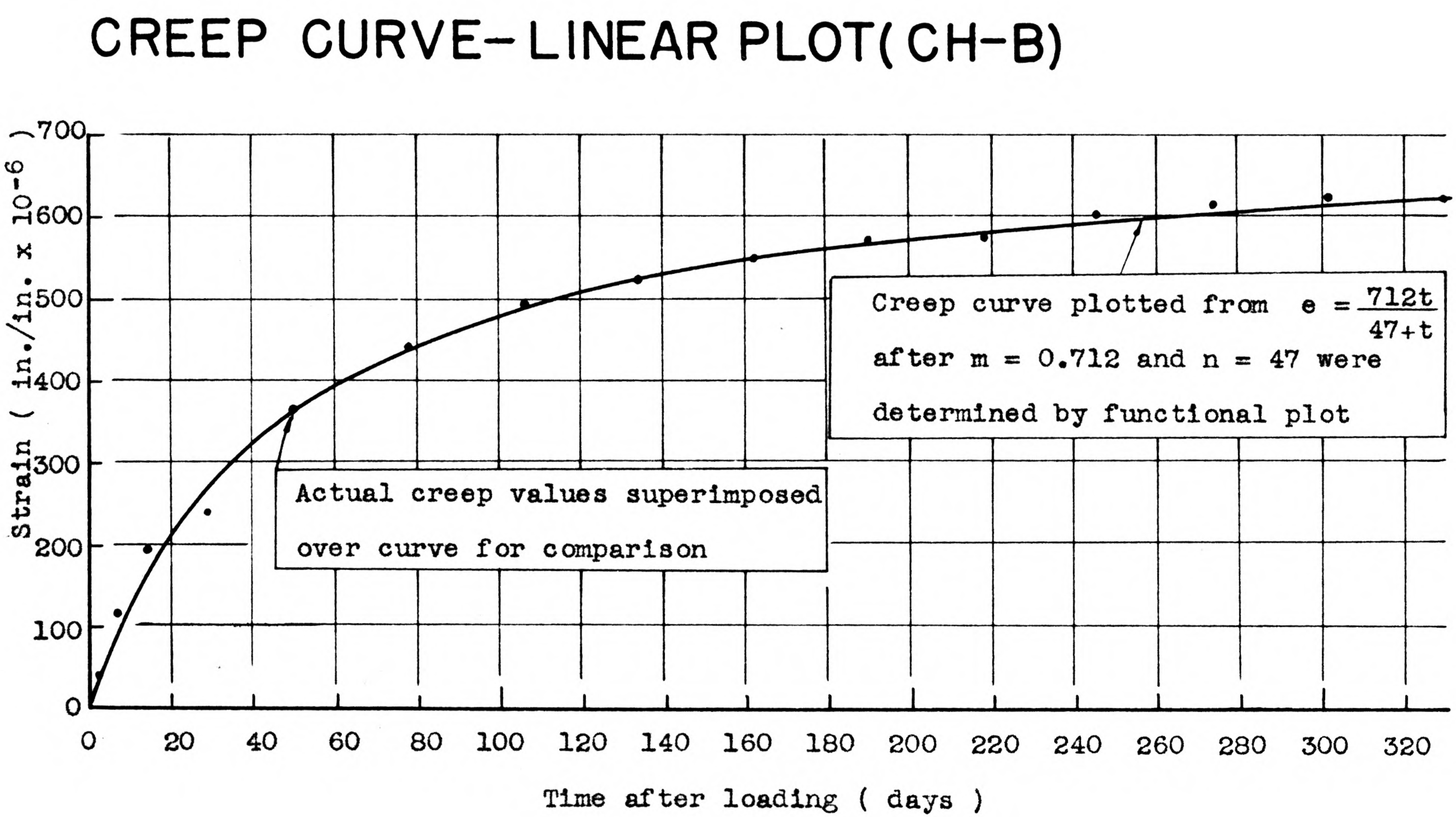


Fig. 24. Calculated curve by Lorman's method and actual plotted points.

DISCUSSION OF RESULTS

Effect of Age at Time of Loading

In Fig. 25 ultimate creep is plotted against the age at which the specimens were loaded. It is evident that the earlier the specimens were loaded the greater the ultimate creep. For example, specimens loaded at 7-day age would have about 10 percent more creep than specimens loaded at 28-day age.

The reason for this is that the cement hydration progresses with the increase of age of the concrete. Following is tabulated the modulus of elasticity at 7, 14, and 28-day age for each concrete:

	CC	CH	CZ
7-day	4.10×10^6	1.72×10^6	4.41×10^6
14-day	4.53×10^6	1.84×10^6	4.59×10^6
28-day	4.57×10^6	2.11×10^6	4.85×10^6

It is seen that with increasing age at loading, the concrete paste becomes more hardened, and, therefore, resulted in less creep.

Effect of Storage Conditions on Magnitude of Ultimate Creep

The ultimate creep is given for each exposure as a percentage of the creep occurring in indoor air. The ultimate creep of the indoor exposure is taken as 100 percent. The figures given for each exposure are the averages of the three mixes.

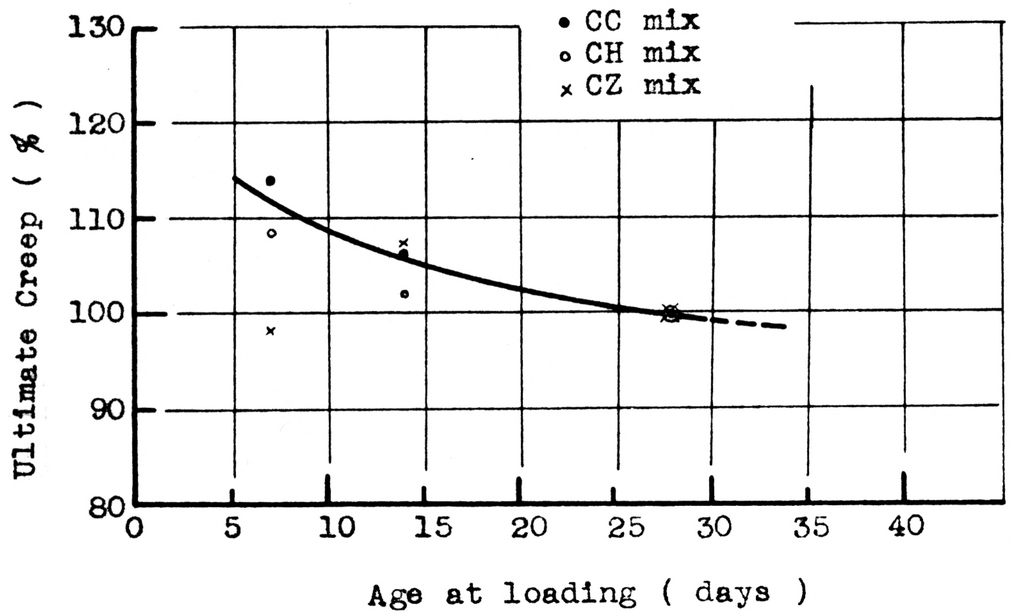


Fig. 25. The ultimate creep coefficient m as affected by age of concrete at loading.

Exposure	Ultimate Creep (%)
Soaking	56.9
Exposure 10	95.7
Indoor air	100.0
Oven	102.9
Heating and Cooling	117.1
Exposure 2	125.8

Soaking. In this case, the ultimate creep was only about half of the ultimate creep obtained for air-stored specimens. Actually, the effect of soaking was even greater than indicated above since the specimens stayed in the indoor air for nine days before they were soaked. From the creep curve, it can be seen that during the nine days stored in air, the creep which occurred was about 50 percent of the ultimate creep. In other words, the creep that occurred during soaking was only half of the creep which occurred in the air-stored specimens from time of loading on. Thus, the creep in the soaked specimens was about one-third that of the air-stored specimens during the period from nine days after loading to the end of observation. These results are in agreement with conclusions obtained by Davis et al (9).

Oven Storage. Another extreme exposure was storage in the oven at 130° F. As indicated in the above tabulation the ultimate creep was not affected by oven storage. Davis et al (9) states:

> If the moisture conditions are constant, temperature appears to have little effect upon flow. Observed difference in flow, for air-stored concretes at various temperatures, may be attributed to differences in the moisture content of the air at the given temperature.

Results of this study are in agreement with Davis' conclusions.

A study of the results from oven exposure indicates that the controlling factor may be the original moisture content. This conclusion is invalid, however, as shown by the creep resulting from the exposures listed below.

Heating and Cooling (dry). In this exposure the ultimate creep was increased by about 17 percent over that for air storage. The discussion is included below under Exposure 2.

Exposure 2 (wetting and drying). Following is shown the ultimate creep percent for three cases:

Exposure	Creep Percent
Oven	102.9
Heating and Cooling	117.1
Exposure 2 (wetting and drying)	125.8

It is seen here that temperature alone did not increase creep, but when there was moisture, creep was definitely increased. This observation is supported by Davis and Troxell (13) who found that:

> Saturated or completely dry concrete will creep much less under sustained load than will a corresponding concrete which is partially dry; and the more rapid the drying occurs, the greater will be the rate of creep.

One possible explanation may be that when a moist concrete specimen is exposed to dry air, water evaporates from the open ends of the channels and produces surface tension. The greater the moisture gradient, the greater is the surface tension. Accompanying this loss of water with resulting surface tension is a greater amount of shrinkage and a greater internal stress.

Carlson (3) believes three phenomena may take place:

1. Local stresses within the concrete, largely due to the fact that aggregate particles tend not to shrink, result in abnormally large creep in

zones of high stress and thus an increase in the average creep.

2. Possible internal cracking due to the drying.

3. An increased creep due to a non-linear stress-strain relationship as suggested by Pickett (37).

For specimens which stayed in the oven, the effect was not at first evident. When they were exposed to the air repeatedly, they absorbed moisture from the surrounding air, and underwent a drying process each time they were put back into the oven. During each drying, all the above effects possibly existed, and caused additional creep. When the specimens were soaked repeatedly as in Exposure 2, the effect of drying was more severe, and this resulted in greater creep.

Exposure 10 (heating and cooling saturated). Specimens kept in Exposure 10 had an average creep of 95.7 percent. This may be explained by the fact that these specimens were exposed to a continuous spray of water and the rate of loss of moisture was less than that without a water spray.

Effect of Storage Conditions on Rate of Creep

The rate of creep is indicated by the value n, which is the age in which one-half of the ultimate creep takes place. Following are values of n for the various exposures:

Exposure	n (days)	Rate of drying	Rate of changing conditions
Indoor air	65-70	Medium	Low
Exposure 10	30-40	None	High
Exposure 2	22-32	Low	High
Soaking	10-35	None	Low
Heating and cooling (dry)	12-20	High	Fairly high
Oven	10-13	High	Low

It is apparent in general that a high rate of creep (low n) is fostered by rapid drying and by rapidly changing conditions. The creep for soaked specimen appears to be an exception. However, here the total creep was low.

Effect of Magnitude of Unit Stress Applied

Following is a comparison of ultimate creep and of rate of creep for specimens in indoor air:

Unit stress (psi)	m, Ultimate creep (%)	n, Rate of creep coefficient (days)
1,000	100.0	65-70
500	57.8	38-54

The first two columns show the generally accepted conclusion that the ultimate creep is approximately proportional to the stress applied.

From the second column it can be concluded that the rate of creep (strain per day) was approximately equal for both cases during the first 40-50 days. The 500 psi specimens exhibited smaller ultimate creep; therefore, it took less time to attain half of that ultimate value.

Effect of Aggregate

The aggregates used in the three mixes, CC, CH, and CZ were respectively chat, haydite, and limestone. A detailed description is given in Table 2.

The effect of aggregate was compared upon the assumption that, cement being the same, the modulus of elasticity of the concrete may serve as an indication of the effect of the aggregate. This is shown below; the values for mix CC are taken as unity for purpose of comparison.

	Ratio of moduli of elasticity	Ratio of ultimate creep	Product
Chat (CC)	1.00	1.00	1.00
Haydite (CH)	0.37	1.75	0.65
Limestone (CZ)	0.84	1.04	1.04

With a decrease of modulus of elasticity, the ultimate creep strain was increased. The last column is the product of the first two columns, and indicates that the value of creep is roughly inversely proportional to the modulus of elasticity. The product for CH was extremely low; this means that the creep for CH concrete was less than it would be if inversely proportional to modulus of elasticity. In general, however, the creep is less in a material with a high modulus of elasticity.

Effect of Repeated Flexure Load

Repeated flexure load had no effect on creep. As shown by Figs. 14, 18, and 22, the difference between the two specimens with and without flexure load was within 40×10^{-6} in/in and probably was caused by sampling variation. Therefore, it may be concluded that repeated flexure has no effect on creep.

Effect of Partial Prestressing

One series of specimens of each mix, namely the E series, was loaded to 250 psi at 7-day age, stored in the indoor air, and then loaded to 1,000 psi at 28-day age. The 250 psi load was applied for the purpose of studying the effect of prestressing.

The comparison here is for slightly different curing conditions. The prestressed specimens were cured seven days in the moistroom, loaded to 250 psi, stored in indoor air until 28 days of age, and then loaded to 1000 psi. The creep of these specimens is then compared to that of specimens which were cured in moistroom 28 days and then loaded to 1,000 psi. Both groups were then stored in indoor air thereafter. The respective creep constants are shown below:

Mix	Ultimate creep, m		Creep rate coefficient, n	
	No partial prestress (Series A)	With partial prestress (Series E)	No partial prestress (Series A)	With partial prestress (Series E)
CC	445	402	70	72
CH	700	894	65	40
CZ	525	412	66	52

The two solid aggregate concretes indicate from prestressing to 250 psi a decrease in creep after full stressing whereas the light weight concrete exhibits an increase. The decrease seems reasonable because the specimens were dryer at the time of full stressing and because some of the easily-slipped bonds had already moved. The increase in creep of Haydite concrete seems to be an exception when compared to results in another study dealing with lightweight aggregates.

Rate of creep seems to be decreased somewhat by prestressing. This reduction may be a manifestation of the fact that the ultimate creep was less and the easily-slipped bonds were moved early in both cases.

CONCLUSIONS

Based on this study the following conclusions may be drawn regarding the creep of concrete:

1. The ultimate creep strains varied from 350×10^{-6} in/in to 985×10^{-6} in/in for specimens loaded to 1,000 psi, and from 240×10^{-6} in/in to 500×10^{-6} in/in for specimens loaded to 500 psi. Storage conditions and type of concrete had a great influence on the magnitude of creep.

2. A major portion of the creep strain was apparently due to seepage. This was indicated by the fact that water stored specimens had only 1/2 to 1/3 as much creep as those stored in air.

3. Humidity had a pronounced effect upon the creep inasmuch as low humidity speeded the seepage process. Therefore, wetting and drying gave an extremely large ultimate creep, while Exposure 10, with similar heating and cooling cycles, produced considerably less creep, as the loss of moisture was less in the latter case.

4. Temperature alone appeared to have little or no effect upon ultimate creep. The rate of creep, however, was greatly increased with higher temperature.

5. The drying process involved in Exposure 2 appeared to increase the ultimate creep by about 25 percent, indicating the greater creep might be caused by internal stress and a non-linear stress-strain relationship of the concrete.

6. The age at time of loading affected the ultimate creep appreciably. Because of progressive hydration, ultimate creep was decreased when specimens were loaded at a later date.

7. Ultimate creep was affected by aggregates used in the concrete, and was approximately in inverse proportion to the modulus of elasticity of concrete.

8. Ultimate creep strain was approximately proportional to the unit stress applied on the specimen.

9. Repeated flexure load did not have an effect upon creep.

10. The effect of prestressing seemed to decrease the ultimate creep in the sense that part of the creep had progressed during the prestressing period; the effect, however, was not definite in that all mixes did not react alike.

11. The rate of creep was greatly influenced by the rate of change of conditions; in general, a high rate of creep is fostered by rapid drying or by rapidly changing conditions.

12. The age at which half of ultimate creep occurred depended on the magnitude of applied stress, being increased or decreased in the same way as that of applied stress.

13. Heating and cooling increased the ultimate creep by about 17 percent. This was possibly due to the repeated drying effect occurring each cycle.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Professor C. H. Scholer, Head of the Department of Applied Mechanics, for his advice and encouragement during the course of this study; to Professor E. R. Chubbuck for his guidance during carrying on the test, and for his advice and help in preparing this thesis; to Professors F. J. McCormick, P. G. Kirmser, and E. C. Lindly for counsel and assistance, and to Mr. S. W. Lin for suggestions and discussions.

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THE ANELASTIC BEHAVIOUR OF CONCRETE UNDER
SUSTAINED LOADS

by

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B. S., National Central University, Nanking, China, 1944

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Applied Mechanics

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1955

The objective of the work was to study the creep of concrete with special reference to the effect exposures.

The term creep is defined as the gradual yielding of concrete due to applied stress. It was obtained by subtracting from the total deformation of compressed specimens the amount of shrinkage measured from control specimens.

In the tests, a total of 136 specimens were made for observation. Factors studied were (a) unit stress applied (for most of the specimens the unit stress was 1,000 psi though a few were stressed to 500 psi), (b) type of coarse aggregate (chat, Haydite, or limestone), (c) age when loaded (7-day, 14-day, or 28-day), (d) storage conditions (indoor air, oven at 130° F., water at room temperature, heating and cooling dry, Exposure 2, and Exposure 10). In addition, the effects of (e) repeated flexure load of 1,000,000 cycles and (f) prestressing to 250 psi before normal loading were also examined. The investigation lasted for about one year.

Results were plotted into shrinkage, creep and gross strain curves. For correlating the data, the Ross-Lorman formula

$$e_c = \frac{mts}{n+t}$$

was employed, where e_c stands for creep; t, time in days; s, unit stress in psi; m and n, two constants determined by test and representing respectively ultimate creep and age after loading at which one-half of the creep occurs. Effect of various exposures was studied by comparing the value of these constants.

It was found that m varied from 350×10^{-6} to 985×10^{-6} in/in for 1,000 psi load and from 240×10^{-6} to 500×10^{-6} in/in for the 500 psi load. Water-stored specimens had the lowest ultimate creep, being 1/2 to 1/3 that of air-stored specimens, a result indicating that a major portion of creep is due to seepage. Specimens in Exposure 2 (alternate wetting and drying) had about 25 percent more creep than air-stored specimens, showing the effect of drying. Heating cooling dry as well as Exposure 10 (heating and cooling saturated) appeared to have little effect on the ultimate creep.

Value of n varied from 12 to 70 days. The more rapid the loss of moisture, and the more rapid the change of conditions, the more rapid the creep.

Creep was related to the mechanical properties of concrete in a manner similar to deformation under loads. It was approximately proportional to applied unit stress and inversely proportional to modulus of elasticity of the concrete. Also, the creep was less when the specimens were loaded at a later age. This was probably caused by the progress in hydration.

The effect of prestressing was not apparent. It may be that creep would be reduced if that which occurred prior to normal loading were disregarded. Flexure load, so far as the test results indicated, had very little or no effect upon creep.