TECHNICAL REPORT C-69-8

EFFECTS OF AXIAL RESTRAINT ON LENGTH CHANGE OF EXPANDING MORTAR BARS

by

B. J. Houston

July 1969

Sponsored by

Office, Chief of Engineers
U. S. Army

Conducted by

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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Foreword

The investigation reported herein was authorized by Office, Chief of Engineers (OCE) by first indorsement, dated 13 July 1959, to a letter dated 16 June 1959, from the U. S. Army Engineer Waterways Experiment Station (WES), subject, "Project Plan for Limited Study of the Effects of Restraint on Alkali-Aggregate Reaction Expansion, CW 603, Alkali-Aggregate Reaction"; by Comment No. 2, dated 13 February 1962, on DF from WES dated 6 February 1962 to OCE, subject same as above; by first indorsement dated 11 August 1964 to a WES letter dated 17 July 1964, subject, "Project Plan for Investigation of the Effect of Restraining Rods Embedded Axially in Mortar Bars upon Expansion Caused by Alkali-Aggregate Reaction (ES-603)"; and by first indorsement dated 7 April 1967 from OCE to a WES letter dated 26 January 1967, subject, "Project Plan for Effect of Axial Restraint on Expansion of Mortar Prisms Caused by Alkali-Aggregate Reaction - Creep and Compressive Strength Tests (ES Item 603)."

The work was conducted during the period 1959-1968 by members of the staff of the Concrete Division of WES under the supervision of Messrs. Thomas B. Kennedy, Bryant Mather, James M. Polatty, E. E. McCoy, R. L. Curry, E. C. Roshore, and B. J. Houston, and Mrs. K. Mather. Mr. Houston was project leader and prepared this report. Dr. H. G. Geymayer and Mr. E. E. McCoy provided valuable assistance in analysis of the data.

Directors of WES during this investigation and the preparation and publication of this report were COL Edmund H. Lang, CE; COL Alex G. Sutton, Jr., CE; COL John R. Oswalt, Jr., CE; and COL Levi A. Brown, CE. Technical Directors were Messrs. J. B. Tiffany and F. R. Brown.

Contents

Conversion Factors, British to Metric Units of Measurement

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
square inches	6.4516	square centimeters
gallons (U. S.)	3.785412	cubic decimeters
pounds	0.45359237	kilograms
pounds per square inch	0.070307	kilograms per square centimeter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

Summary

This report presents the results of an investigation conducted to determine the effects of axial restraint on observed length change of mortar prisms tending to expand due to alkali-silica reaction.

During the investigation, three approaches were taken to accomplish the objective. The first approach involved the use of external restraint on expansive mortar prisms. Restraining rigs consisted of aluminum rods held in place by steel header plates and load cells for determining stress caused by expansion. The results of the tests using this approach were questionable for a number of reasons. The next approach involved the use of polyester laminated strain gages embedded axially in 2- by 2- by 10-in. expansive prisms for determining stress. Restraint was provided by external frames giving restraining loads of 0, 1, 5, 10, 25, 50, and 100 psi on three prisms per load. Prisms were stored at 100 F and 100 percent relative humidity. The results indicated that restraint does act to reduce expansion; however, the accuracy of these results was also doubtful because it was discovered that the polyester cover of the strain gages would expand when exposed to 100 F and 100 percent relative humidity even with no external stress transferred to it. The third approach involved the use of axially embedded calibrated steel restraining rods with end plates screwed on the ends of each rod. Control prisms containing no rods and test prisms containing 1/4-, 3/8-, and 1/2-in.-diam rods were tested. The stress developed on the end plates at 1-yr age was greater with the larger diameter rods because the smaller rods elongated more under tensile stress and relieved some of the end-plate pressure. Linear expansion was reduced 80, 90, and 94 percent by the three restraints. Tests of cubes sawed from the prism after 1-yr exposure indicated that restraint had little or no effect on compressive strength.

An estimate of strains and stresses that might be expected in the restrained specimens was obtained by an approximative analysis involving linear superposition of measured unrestrained expansion values and elastic and creep behavior of nonexpanding reference prisms. The measured strains ranged only between 16 and 52 percent of the calculated or theoretical values, indicating that such calculations are at best only useful in giving a very conservative estimate. Further research will be required to make such calculations more meaningful.

EFFECTS OF AXIAL RESTRAINT ON LENGTH CHANGE OF EXPANDING MORTAR BARS

Background and Objective

1. Earlier studies have shown that expansion or shrinkage of mortar or concrete[1-4] can be reduced by applying restraining forces to the mass opposing the dimensional change. Data are needed to explain why a small restraining force is apparently sufficient to restrain a volume change that would take a much larger force to restore. The objective of this investigation was to obtain information concerning the effects of axial restraint on the development of expansion in mortar prisms due to alkali-silica reaction.

Scope

2. During the investigation, three approaches were taken to accomplish the objective. The first approach (Phase I) involved the use of external restraint on mortar bars containing high-alkali cement and crushed Pyrex aggregate. The restraining rigs consisted of aluminum rods spaced 120 deg apart and held in place by steel header plates, as shown in plate 1. Rods of different diameters were used in order to apply different amounts of restraint. The second approach (Phase II) involved the use of internal polyester laminated strain gages embedded axially in 2- by 2- by 10-in.* mortar bars, which were placed in external restraining rigs as shown in plate 2 and photograph 1. Restraint varied from 0 to 100 psi on the bars. Bars were also cast containing internal strain gages but with special molds constructed so that stress could be placed on the molds prior to casting of the bars, but no stress would be on the bars until they expanded (Phase III). The combined molds and restraining rigs are shown in photograph 2. The third approach (Phase IV) involved the use of axially embedded restraining rods, as shown in plate 3, of varying diameters with steel plates screwed on each end to restrain the bars.

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* A table of factors for converting British units of measurement to metric units is presented on page ix.

Tests and Results

Phase I: external restraint and measurements*

3. Test specimens and conditions. Eighteen 2- by 2- by 11-in. mortar bars, each containing nickel-plated reference points, were fabricated. All prisms contained high-alkali cement and crushed Pyrex glass aggregate, proportioned according to requirements of CRD-C 123-58.[5]** The bars were cured in a fog room to an age of 24 ± 4 hr, then removed from the molds. After removal from the molds, 14 of the bars were placed in restraining rigs, and the other three (one was broken during stripping from the mold) were left unrestrained.

4. Restraining rigs. Restraining rigs were constructed as shown in plate 1. Each rig consisted of three aluminum rods spaced 120 deg apart and held in place by steel header plates. Rods of different diameters (1/16, 1/8, 1/4, 3/16, and 1/2 in.) were used to determine the effects of different amounts of restraint on expansion of the bars. Triplicate tests were run, but because of the bar that was broken, only two bars were tested in the rig with the 1/8-in.-diam rods. Aluminum load cells with attached resistance wire strain gages were used on each restraining rod.

5. Length-change measurements. Initial length-change measurements, using a horizontal comparator, were made on the restrained bars at 2 days age and on the unrestrained bars at 1 days age. Bars were stored at 100 F but were allowed to reach equilibrium at 73.5 ± 2 F before measurements were made. Subsequent to the initial measurement, length-change determinations were made at 7, 14, 21, 28, 49, 70, and 91 days. The results, given in table 1, show that unrestrained prisms exhibited more length change than did the restrained bars. The length changes of the restrained bars were not inversely proportional to the size of the rods, as would be expected, in two of the three rounds. It was noted that the inserts were rather badly corroded, which probably caused the above-mentioned deviation and also lends

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* The results of Phase I tests are taken from Mr. E. C. Roshore's unpublished report, "Effects of Axial Restraint on Length Change of Mortar Bars--Studies Using External Strain Gages," which is on file at WES.

** This method has been superseded by CRD-C 123-68, which requires a different grading of the aggregate in the mortar.

doubt as to the accuracy of the data. Another reason for suspecting that the data are inaccurate is the fact that the bars lost weight during the period of the investigation, indicating loss of water by the bars.

6. Load cell readings. Readings were taken on all load cells each time the bars were measured. The readings were used to compute the load changes in pounds during the periods of storage. The changes are given in table 2. The changes were not as large as expected, the maximum being +780 lb on bar No. 6 in round 1, which was restrained by 1/2-in.-diam rods. It appears that a number of factors combined to make the load cell readings, and therefore the indicated load changes, questionable. Some of these factors may have been (a) variation in room temperature, (b) relaxation of restraining rods, and (c) creep of the mortar.

Phase II: external restraint and embedded polyester-covered strain gages

7. Strain measured using a polyester-covered strain gage as a compensating gage. Twenty-one 2- by 2- by 10-in. bars were cast from mortar containing high-alkali cement and Pyrex glass aggregate, with each bar containing an axially embedded strain gage. The gages, shown in photograph 3, have an effective gage length of 60 mm, resistance of 120 ohms, and overall dimensions of 3/16 in. thick by 1/2 in. wide by 5 in. long. Basically, these gages involve strain-sensitive wires cemented between two polyester strips for protection, with the outside surfaces of the strips having a coarse sandpaper texture for bonding purposes. Three bars, one per round, were made for each condition of restraint as follows: no restraint (control), 1, 5, 10, 25, 50, and 100 psi. Bars were stripped at 24 hr, inundated in water at 100 F for an additional 24 hr, and then all bars except the control were stressed in rigs as shown in photograph 1. Immediately after stressing, all bars were sealed over water in 15-gal metal drums. Three drums, one for each round, were used. One unstressed (control) bar and a compensating gage suspended in an open glass bottle were also placed in each drum. Electrical leads from the gages were brought out through a small hole in the center of the lids of the drums so that the strain could be determined without disturbing the bars. The hole around the bundle of electrical leads was then sealed to prevent moisture loss. Initial gage

readings from which all subsequent expansions were calculated were made 1 hr after stressing.

8. The strain gage readings of the embedded gages indicated that the bars began to shrink early in the test. Since these results were obviously in error, a number of theories were advanced in an attempt to explain the phenomenon. It was eventually discovered that the apparent shrinkage of the bars was caused by drift of the reference or compensating gage, apparently due to expansion of the polyester cover in the 100 F and 100 percent humidity environment. This was verified by placing one of the gages, suspended freely, at 100 F and 100 percent humidity. The gage was monitored over a period of two months using a standard resistance box set at 120 ohms as a compensating gage. The results are shown in plate 4.

9. Strain measured using a resistance box as a compensating gage. The tests described in the preceding section were repeated. In these replicate tests, a resistance box was used as a reference gage. Results are shown below and in plate 5.

Age Weeks	Percent Expansion of Bars Subjected to Indicated Amounts of Restraint						
	Unrestrained	1 psi	5 psi	10 psi	25 psi	50 psi	100 psi
1	0.074	0.095	0.089	0.097	0.062	0.060	0.052
2	0.121	0.157	0.126	0.121	0.143	0.077	0.077
3	0.147	0.197	0.155	0.155	0.177	0.098	0.103
4	0.173	0.229	0.177	0.184	0.206	0.115	0.120
8	0.312	0.353	0.301	0.323	0.355	0.225	0.226
12	0.482	0.483	0.410	0.445	0.476	0.341	0.299
16	0.588	0.587	0.478	0.510	0.524	0.406	0.318
20	0.693	0.708	0.556	0.557	0.545	0.449	0.331
24	0.899	0.816	0.611	0.596	0.568	0.517	0.353
28	1.003	0.856	0.695	0.637	0.581	0.535	0.352
32	1.037	0.892	0.755	0.708	0.603	0.560	0.366
36	1.068	0.924	0.760	0.766	0.649	0.613	0.386
40	1.077	0.949	0.769	0.661	0.720	Gages failed	0.406
44	1.077	0.964	0.821	0.661	0.730	Gages failed	0.449
48	1.083	0.994	0.861	0.646	0.726	Gages failed	0.471
52	1.070	1.002	0.878	0.648	0.723	Gages failed	0.506

Phase III: effect of restraint on prisms cast in prestressed molds

10. Three 2- by 2- by 10-in. bars containing Pyrex aggregate and high-alkali cement, proportioned according to CRD-C 123-58, were cast in molds of the type shown in plate 6. The molds were constructed so that there would be no pressure on the bars until they expanded. The molds

were restrained to 100 psi prior to casting of the bars. Three unrestrained bars, containing the same materials as the restrained bars, were cast. All six bars contained axially embedded 30-mm strain gages obtained from the same company that made the 60-mm gages used in the Phase II tests. The overall dimensions of the 30-mm gages were 3-3/8 in. long by 1/2 in. wide by 3/16 in. thick. Immediately after the bars were cast, they were stored at 100 F and 100 percent humidity for 24 hr, at which time the screws shown in plate 6 were removed from the prestressed molds and the sides of the molds were tapped away from the bars a fraction of an inch so there would be no bond between the bars and the sides of the mold to inhibit expansion. In this position, the sides of the molds would still prevent pressure on the bars until they elongated. The bottoms of the molds, which were sealed to the molds by a mixture of paraffin and rosin, were removed completely. The three unrestrained bars were stripped from the molds and all six were then sealed airtight over water in a metal drum. Strain gage electrical leads were brought out through a small hole in the center of the lid of the drum, and the hole was resealed around the bundle of the leads and storage continued at 100 F. The initial gage readings were made when the bars were 24 ± 2 hr of age, and subsequent readings were made at 2, 4, 7, 14, 21, and 28 days age and each 28 days thereafter until the bars were 1 yr old.

11. The results shown below and in plate 7 show that restraint will reduce expansion caused by alkali-silica reaction.

Age Weeks	Percent Expansion (Avg of 3 Bars) No Restraint	Percent Expansion (Avg of 3 Bars) 100-psi Restraint	Age Weeks	Percent Expansion (Avg of 3 Bars) No Restraint	Percent Expansion (Avg of 3 Bars) 100-psi Restraint
1	0.024	0.010	24	0.155	0.101
2	0.030	0.016	28	0.149	0.093
3	0.036	0.017	32	0.145	0.098
4	0.038	0.016	36	0.151	0.097
8	0.103	0.070	40	0.157	0.092
12	0.135	0.093	44	0.161	0.099
16	0.154	0.105	48	0.161	0.099
20	0.150	0.098	52	0.158	0.099

Phase IV: effect of restraint on prisms by use of axially embedded restraining rods

12. Test specimens. Since serious doubt existed as to the accuracy

of the strain measurements made using the embedded strain gages, this final phase was conducted. Twelve 2- by 2- by 10-in. bars were proportioned according to CRD-C 123-58, containing high-alkali cement and Pyrex aggregate. Three of the bars contained a 1/4-in.-diam stainless steel rod centered axially, three contained a 3/8-in. rod, three contained 1/2-in. rods, and three were unrestrained. Molds of the type used for casting the bars are shown in plate 8 and photograph 2. Overall dimensions are shown in plate 3. The end plates remained in place after the sides and bottoms of the molds were removed. The restraining rods were threaded at each end only enough that the separation of the end plates could be adjusted to the correct distance. It was necessary to machine the ends of the rods to suitable size and shape to fit into the comparator. Each rod was fitted into a length of plastic tubing of an inside diameter equal to that of the rod and an outside diameter of 5/8 in. prior to embedment as shown in photograph 4. This was done to minimize bonding of the mortar to the rod and also so that all bars would contain the same amount of mortar. Stress-strain characteristics of each restraining rod were determined prior to casting of the bars as discussed in the following paragraph. All bars were stripped at 24-hr age, and initial length measurements were made. They were then stored in plastic containers of the type shown in CRD-C 123[5] but with absorbent cardboard sleeves placed inside the container (photograph 5) to ensure that the desired relative humidity was present. Subsequent measurements were made at 7, 14, and 28 days and each 28 days thereafter until the bars were 1 year old.

13. Calibration of restraining rods. The first approach made to develop a true stress-strain curve for the restraining rods was to employ a resistance-wire strain gage glued to the rod at the approximate center, and take stress-strain measurements at intervals up to 60 percent of the ultimate strength of the rod. This technique, however, would only supply data on what happened to the center of the rod under various loads, and would not take into account the strain developed in the threaded areas of the rods where they screwed into the end plates. Since the stress developed in the rod is a result of the mortar expanding against the end plates, it was felt that a calibration arrangement should be utilized that would simulate the action of the mortar as it placed stress on the rod. Such an

arrangement is shown in photograph 6. In this arrangement, the rod is extended through a small hole in the center of a steel plate resting on the top of the upper crossarm of the testing machine, and the end plate is screwed in place. In like manner, the lower end plate is screwed in place within the cage arrangement shown in photograph 6. A universal joint was utilized below the cage so that the direction of stress applied on the rods would be aligned with the rod.

14. Test results. Results are shown in plate 9 and table 3 and are summarized as follows:

	1/4-in. Rods		3/8-in. Rods		1/2-in. Rods	
Age days	Average Stress on Embedded Rods, psi	Average Total Load on End Plates, lb	Average Stress on Embedded Rods, psi	Average Total Load on End Plates, lb	Average Stress on Embedded Rods, psi	Average Total Load on End Plates, lb
7	6,630	325	3,130	345	2800	550
14	11,830	580	6,330	700	4170	815
28	18,730	920	9,330	1030	6930	1360
56	22,430	1100	11,000	1215	7730	1520
84	24,370	1200	12,230	1350	8230	1615
112	25,430	1250	13,100	1445	9400	1850
140	25,830	1270	12,800	1415	8570	1685
168	25,600	1260	12,800	1415	8470	1665
196	26,230	1290	13,030	1440	8370	1715
224	26,300	1290	13,030	1440	8630	1695
252	26,370	1295	13,030	1440	8730	1715
280	26,370	1295	13,100	1445	8800	1730
308	25,670	1260	13,100	1445	8300	1630
336	26,400	1295	13,030	1440	8000	1570
364	25,900	1270	12,870	1420	8230	1615

The stress developed at the end of 1 year on the end plates was somewhat lower for the prisms containing the smaller rods and higher for those containing larger rods (1270, 1420, and 1615 lb). This was because the smaller rods elongated more as the expanding mortar applied pressure and relieved some of the stress. Expansion and prism stress data are as follows:

Age days	Unrestrained Prisms Expansion %	1/4-in. Rods Average Expansion %	1/4-in. Rods Average Load on Prisms psi	3/8-in. Rods Average Expansion %	3/8-in. Rods Average Load on Prisms psi	1/2-in. Rods Average Expansion %	1/2-in. Rods Average Load on Prisms psi
7	0.069	0.029	88	0.016	93	0.012	149
14	0.163	0.051	157	0.027	190	0.018	221
28	0.310	0.080	249	0.040	279	0.030	369
56	0.481	0.096	255	0.047	329	0.033	412
84	0.546	0.104	325	0.052	366	0.036	438
112	0.572	0.109	339	0.056	392	0.041	447
140	0.573	0.110	344	0.054	383	0.037	457
168	0.575	0.109	341	0.054	383	0.037	457
196	0.574	0.112	350	0.055	390	0.038	465
224	0.574	0.112	350	0.055	390	0.037	459
252	0.575	0.113	351	0.055	390	0.038	465
280	0.570	0.113	351	0.056	392	0.038	469
308	0.570	0.113	341	0.056	392	0.036	442
336	0.567	0.113	351	0.055	390	0.035	425
364	0.568	0.111	344	0.055	385	0.035	438

15. Compressive strength of restrained mortar prisms. After the 1-yr expansion measurements had been completed, the three prisms that contained no restraint, the three that contained 1/4-in.-diam rods, the three that contained 3/8-in.-diam rods, and the three that contained 1/2-in.-diam rods were sawed into three 2- by 2- by 2-in. cubes and the cubes were broken in compression. It should be recalled that the diameter of the hole in all nine restrained prisms was 5/8 in. There was no hole in the three unrestrained prisms. The hole in the sawed cubes, where present, was aligned vertically in the direction of the load while being broken in compression. Since it was not known what effect the hole would have on the compressive strength of the cubes, a pilot study was made. In this study, two 2- by 2- by 10-in. prisms were made from the same mixture and material as in the restrained bars. One of the bars contained a 5/8-in.-diam hole axially down the center the same as the restrained bars, and the other did not. Both bars were stripped from the molds at 1 days age, the bar was removed from the one prism, and both were inundated in water at 73.4 ± 2 F until 28 days of age. The results were used to correct the compressive strength of the cubes sawed from the test prisms. Results were as follows:

Restraining Rod Diameter, in.	Corrected According to Pilot Study, Average of 3 Bars, psi	Corrected Using 3.7-sq-in. Surface Area Except for Control, psi
1/4	3635	3465
3/8	3715	3540
1/2	3960	3775
Control	3775	3775

The results indicated that the restraint did not have any appreciable effect on 1-yr compressive strengths.

16. Creep tests of Pyrex-cement mortar prisms. In order to compute an estimate of strains and stresses in the restrained specimens caused by expansion of the mortar in the tests described in paragraphs 12, 13, and 14, creep data were needed and tests were performed. Twelve 2- by 2- by 10-in. mortar prisms were fabricated using type II, low-alkali cement and Pyrex aggregate graded the same as in the expansion prisms tested. Low-alkali cement was used so there would be no alkali-silica expansion of the prisms. The prisms, proportioned the same as the test prisms, were demolded at 1-day age, and Whittemore gage points were attached 10 in. apart to two sides of the prisms. The prisms were then coated with an impermeable clear plastic coating to prevent loss of water. Initial loadings to develop creep data were made as follows:

a. Three prisms with no load.

b. Three prisms with a 400-psi load at 3 days age.

c. Three prisms with a 400-psi load at 7 days age.

d. Three prisms with a 400-psi load at 28 days age.

17. The 400-psi load was selected because it was the approximate ultimate stress developed by expansion of the mortar in the earlier tests. The loads were maintained on the prisms until they were 100 days old. Loading frames containing the loaded prisms were replaced in the compression machine (photograph 7) weekly, and the applied load was checked to ensure that creep in the steel frame was not reducing the stress applied to the prisms. The prisms were stored at 73.4 ± 3 F, and creep measurements were made daily for 14 days and weekly thereafter until 100 days age with a Whittemore gage as shown in photograph 8. The results are given in table 4 and plate 10.

Analysis of Results and Conclusions

Phase I: external restraint and measurements

18. Since there is doubt as to the validity of the test results, no analysis of these results was made.

Phase II: external
restraint and embedded
polyester-covered strain gages

19. The results of tests to determine the expansion of prisms containing embedded strain gages and using a resistance box as a compensating gage are shown in paragraph 9 and plate 5. The data indicate that restraint does act to prevent expansion; however, the overall expansions appear to be too high by a factor of approximately 2. Since it has been shown (plate 4) that the gages used would expand when exposed unconfined at the elevated temperature and humidity, it is possible that the embedded gages expanded more than would have been caused by expansion of the mortar prisms alone. Because of this, no detailed analysis of these data or those from Phase III tests was made.

Phase III: effect of restraint
on prisms cast in prestressed molds

20. The results are shown in paragraph 11 and plate 7. For the reason stated in paragraph 19, no detailed analysis of the data was made.

Phase IV: effect of restraint
on mortar bars by use of axially embedded restraining rods

21. An estimate of strains and stresses in the restrained specimens at 7, 28, and 84 days was obtained by an approximative analysis based on the results of unrestrained expansion tests, on deformation measurements of nonexpanding specimens under load, and on the following assumptions. This is somewhat the same type of calculation that is used to estimate loss of prestress in beams that have attained considerable maturity.[6]

- a. Validity of simple superposition.
- b. Fully elastic behavior of restraining rig (effective elastic modulus, 23×10^6 psi).
- c. Linear relation between concrete stresses and concrete deformations (elastic and time-dependent).
- d. Total time-dependent concrete deformations at the end of a chosen time interval due to a gradually increasing load are 75 percent of the time-dependent deformations that would

have occurred had the full load been applied throughout the time interval.

e. Elastic and creep properties determined on nonexpanding reference specimens are representative for the expanding specimens.

22. Using the assumptions above, a crude theoretical value of concrete stresses (and subsequently of strains and total end-plate loads) at various ages can be derived by fulfilling the equilibrium of forces equation; i.e., for 7 days age:

$$A_R E_R \left[\epsilon_{ur7} - \sigma_{c7} \cdot \left(\alpha_{ce}^{3} + \frac{3}{4} \alpha_{cc7}^{3} \right) \right] = A_c \sigma_{c7}$$

Subsequently, for 28 days age:

$$A_R E_R \left[\Delta\epsilon_{ur7-28} - \sigma_{c7} \alpha_{cc7-28}^{3} - \Delta\sigma_{c7-28} \cdot \left(\alpha_{ce}^{7} + \frac{3}{4} \alpha_{cc28}^{7} \right) \right] = A_c \Delta\sigma_{c7-28}$$

and for 84 days age:

$$A_R E_R \left[\Delta\epsilon_{ur28-84} - \sigma_{c7} \alpha_{cc28-84}^{3} - \Delta\sigma_{c7-28} \cdot \alpha_{cc28-84}^{7} - \Delta\sigma_{c28-84} \left(\alpha_{ce}^{28} + \frac{3}{4} \alpha_{cc84}^{28} \right) \right] = A_c \Delta\sigma_{c28-84}$$

where

A_c = area of concrete (3.7 in.^{2})

A_R = area of restraining rod $\begin{cases} \text{1/4-in. rods: } 0.049 \text{ in.}^2 \\ \text{3/8-in. rods: } 0.110 \text{ in.}^2 \\ \text{1/2-in. rods: } 0.196 \text{ in.}^2 \end{cases}$

E_R = effective elastic modulus of restraining rig ($23 \cdot 10^6$ psi)

σ_{c7} = concrete stress at 7 days age

σ_{c28} = concrete stress at 28 days age

σ_{c84} = concrete stress at 84 days age

$\Delta\sigma_{c7-28} = \sigma_{c28} - \sigma_{c7}$

$\Delta\sigma_{c28-84} = \sigma_{c84} - \sigma_{c28}$

α^{3}_{ce} = elastic deformation of concrete per unit stress at 3 days age ($0.52 \cdot 10^{-6}$ in. per psi)

α^{7}_{ce} = elastic deformation of concrete per unit stress at 7 days age ($0.45 \cdot 10^{-6}$ in. per psi)

α^{28}_{ce} = elastic deformation of concrete per unit stress at 28 days age ($0.28 \cdot 10^{-6}$ in. per psi)

α^{3}_{cc7} = creep deformation of concrete per unit stress at 7 days age when load was applied on third day ($0.28 \cdot 10^{-6}$ in. per psi)

α^{3}_{cc7-28} = creep deformation of concrete per unit stress between 7 and 28 days age when load was applied on third day ($0.40 \cdot 10^{-6}$ in. per psi)

$\alpha^{3}_{cc28-84}$ = creep deformation of concrete per unit stress between 28 and 84 days age when load was applied on third day ($0.55 \cdot 10^{-6}$ in. per psi)

α^{7}_{cc28} = creep deformation of concrete per unit stress at 28 days when load was applied on seventh day ($0.46 \cdot 10^{-6}$ in. per psi)

$\alpha^{7}_{cc28-84}$ = creep deformation of concrete per unit stress between 28 and 84 days age when load was applied at 7 days ($0.57 \cdot 10^{-6}$ in. per psi)

α^{28}_{cc84} = creep deformation of concrete per unit stress at 84 days age when load was applied at 28 days ($0.80 \cdot 10^{-6}$ in. per psi)

ϵ_{ur7} = unrestrained expansion at 7 days age (0.069 percent)

ϵ_{ur28} = unrestrained expansion at 28 days age (0.310 percent)

ϵ_{ur84} = unrestrained expansion at 84 days age (0.546 percent)

$\Delta\epsilon_{ur7-28} = \epsilon_{ur28} - \epsilon_{ur7}$

$\Delta\epsilon_{ur28-84} = \epsilon_{ur84} - \epsilon_{ur28}$

23. Table 5 shows that all measured strains (and end-plate loads) ranged between about 16 and 52 percent of the theoretical values obtained by linear superposition of unrestrained expansion values and elastic plus creep behavior of nonexpanding reference specimens. Obviously, this

indicates that such superposition is at best useful only in giving a very conservative estimate, but does not predict the actual behavior of the restrained expanding specimen, since in reality the elastic and time-dependent characteristics of an expanding mortar are certainly a function of the degree of expansion and will therefore deviate from the properties of a nonexpanding reference specimen. It is reasonable to assume that with progressive expansion, the elastic modulus will rapidly decrease and creep will probably increase. Thus a considerably lower actual concrete stress than that computed using the assumptions above would be expected. However, it is somewhat surprising that measured stresses and expansions were only a small fraction of the computed values.

24. It should be recalled that the creep tests were conducted at 73.4 ± 3 F, whereas the restrained expansion tests in Phase IV were conducted at 100 F. Creep at 100 F should be considerably greater, perhaps as much as 50 percent, than creep at 70 F.[7] Had the creep tests been conducted at 100 F, the calculated and measured strains would have been in somewhat closer agreement. However, this difference in creep would not have been nearly enough for close agreement as it would take a total (creep and elastic) deformation four to five times as great as that measured.

25. In the creep test results, the order of magnitude of creep measured and the smooth curves obtained, as well as smooth load curves obtainable if load at the three ages is plotted, tend to rule out any possibility of gross error in length-change measurements. Therefore, another explanation should be sought to reconcile the unexplained gap. Also, the compressive strength data of 1-year-old restrained and unrestrained prisms, as shown in paragraph 15, would indicate that it was permissible to apply creep data from unrestrained bars in making the calculation of estimated strains and stresses. However, to check this it is recommended that creep tests be conducted on expansive prisms at various ages starting with low constant loads at early ages with all loads checked periodically because of tendency of the prisms to expand. The loads should be adjusted if necessary. Tests should be run at 100 F, and the lateral expansion, if any, should be monitored.

26. A comparison of test results developed in this phase of the

program with results obtained by McGowan and Vivian,[8] reported from Australia in 1955, provides some interesting results. In McGowan and Vivian's experiments, reactive and nonreactive 1- by 1- by 10-in. bars were restrained with deadweights of 0, 1, 5, 10, 20, and 50 psi in such a manner as to restrict linear expansion. Some were loaded immediately after demolding, and a few of these were continuously restrained until 1 year of age while companion bars were restrained until 112 days of age at which time weights were removed and exposure continued. Other bars were unrestrained until 112 days age, then restrained, and exposure was continued until 1 year age. All bars were exposed over water in sealed containers at room temperature. Results indicated that magnitude of load affected (a) aggregate reaction and expansion, (b) crack initiation and propagation, and (c) crack patterns. Reactive bars restrained so that essentially no expansion occurred until 112 days age expanded significantly when restraint was removed and exposure continued. Only 20 psi of continuously applied load was required to reduce to 0.040 percent at 1 year age a mortar that unrestrained expanded 1.16 percent at 1 year age. In comparison, WES results showed that approximately 400 psi of a gradually increasing load would be required to reduce 1-year unrestrained expansion of 0.568 percent to 0.040 percent.

27. Perhaps the reason restraint works is that water is unable to get into the fine cracks containing an alkali-silica complex (gel). It is necessary for this gel to imbibe water in order to swell.

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Table 1

Length Changes (Restrained and Unrestrained Prisms), Phase I

Round No.	Prism No.	Diameter of Restraining Rods in.	Length Change, Percent × 100, at Age Shown* 2 Days	7 Days	14 Days	21 Days	28 Days	49 Days	70 Days	91 Days
1	1	None**	0	3.8	7.6	8.8	9.9	12.4	14.6	13.9
	2	1/16	0	1.3	3.4	5.8	Test discontinued due to rod breakage			
	3	1/8	0	1.0	2.9	3.6	3.3	4.1	4.7	4.7
	4	3/16	0	1.5	3.0	4.4	2.6	4.6	5.1	5.4
	5	1/4	0	0.8	3.4	4.7	4.2	6.1	7.0	7.7
	6	1/2	0	1.3	3.9	3.4	5.4	5.0	6.3	6.2
2	7	None**	0	5.0	9.1	12.1	13.0	15.7	17.7	--
	8	1/16	0	Test discontinued--prism was broken in compression machine						
	9	1/8	0	2.8	6.0	8.4	9.1	10.1	14.4	--
	10	3/16	0	2.6	6.2	6.1	6.5	7.9	7.7	--
	11	1/4	0	3.4	6.2	7.1	8.2	9.6	10.0	--
	12	1/2	0	3.5	5.6	6.1	6.9	7.2	8.4	--
3	13	None**	0	7.0	12.3	14.0	15.8	21.1	22.8	--
	14	1/16	0	5.2	8.7	9.8	11.7	12.2	12.9	--
	15	1/8	Prism was broken during removal from mold							
	16	3/16	0	1.7	5.8	7.3	7.7	9.0	9.3	--
	17	1/4	0	3.0	4.9	7.1	7.0	8.5	8.8	--
	18	1/2	0	3.3	4.6	5.1	5.1	5.8	5.9	--

Note: All percent length changes in this table are positive, indicating expansion or increase in length.

* Days of storage at 100 F are in all cases equal to age in days minus 2.

** Prisms 1, 7, and 13 were unrestrained.

Table 2

Load Changes, Phase I

Round No.	Prism No.	Diameter of Restraining Rods in.	Load Change,* lb, Between Periods Shown** 2-7 Days	7-14 Days	14-21 Days	21-28 Days	28-49 Days	49-70 Days	70-91 Days
1	2	1/16	+102	+81	+81	Test discontinued			
2	8	1/16	Prism was broken in compression machine						
3	14	1/16	+66	-81	-135	+117	-135	-48	--
1	3	1/8	+153	+153	+108	-129	-87	-153	-42
2	9	1/8	-42	+21	+87	-129	+153	-63	--
3	15	1/8	Prism was broken during removal from mold						
1	4	3/16	+273	+243	+153	-183	-30	±00	+153
2	10	3/16	-60	±00	+30	-243	+153	-243	--
3	16	3/16	+60	-60	-306	+183	-153	+30	--
1	5	1/4	+381	+303	+228	-264	±00	+39	+189
2	11	1/4	-153	-39	+78	-228	+153	-264	--
3	17	1/4	+39	-114	-264	+381	-381	-39	--
1	6	1/2	+780	+477	+294	-537	±00	-294	+174
2	12	1/2	-114	-114	+174	-417	+294	-417	--
3	18	1/2	+174	±00	-417	-537	-357	+117	--

* A plus sign (+) indicates a load increase, and a minus sign (-) indicates a load loss.

** Prisms were stored at 100 F during the indicated periods.

Table 3

Expansion of Prisms and Stress on Restraining Rods, Phase IV

Age of Prism days	Bar No.	No-Restraint Expansion %	1/4-in. Rods Expansion %	1/4-in. Rods Stress on Rods psi	3/8-in. Rods Expansion %	3/8-in. Rods Stress on Rods psi	1/2-in. Rods Expansion %	1/2-in. Rods Stress on Rods psi
7	1	0.066	0.025	5,600	0.015	3,500	0.014	3,600
	2	0.070	0.030	7,200	0.015	1,600	0.011	2,300
	3	0.070	0.031	7,100	0.018	4,300	0.011	2,500
	Avg	0.069	0.029	6,630	0.016	3,130	0.012	2,800
14	1	0.146	0.047	10,600	0.025	11,200	0.021	5,300
	2	0.172	0.051	12,600	0.027	2,100	0.015	3,100
	3	0.170	0.054	12,300	0.029	5,700	0.018	4,100
	Avg	0.163	0.051	11,830	0.027	6,330	0.018	4,170
28	1	0.303	0.075	16,900	0.043	10,200	0.034	8,600
	2	0.331	0.082	20,300	0.031	6,900	0.026	5,400
	3	0.297	0.083	19,000	0.046	10,900	0.030	6,800
	Avg	0.310	0.080	18,730	0.040	9,330	0.030	6,930
56	1	0.566	0.085	19,200	0.049	11,600	0.036	9,100
	2	0.492	0.097	24,100	0.038	8,800	0.029	6,100
	3	0.385	0.105	24,000	0.053	12,600	0.035	8,000
	Avg	0.481	0.096	22,430	0.047	11,000	0.033	7,730
84	1	0.576	0.099	22,400	0.054	12,800	0.038	9,600
	2	0.577	0.103	25,600	0.045	10,400	0.031	6,500
	3	0.486	0.110	25,100	0.057	13,500	0.038	8,600
	Avg	0.546	0.104	24,370	0.052	12,230	0.036	8,230
112	1	0.619	0.102	23,100	0.056	13,300	0.043	10,900
	2	0.610	0.105	26,100	0.050	11,500	0.035	7,300
	3	0.488	0.119	27,100	0.061	14,500	0.044	10,000
	Avg	0.572	0.109	25,430	0.056	13,100	0.041	9,400
140	1	0.633	0.105	23,800	0.056	13,300	0.039	9,900
	2	0.597	0.106	26,300	0.048	11,100	0.033	6,900
	3	0.490	0.120	27,400	0.059	14,000	0.039	8,900
	Avg	0.573	0.110	25,830	0.054	12,800	0.037	8,570
168	1	0.635	0.106	24,000	0.056	13,300	0.039	9,900
	2	0.598	0.106	26,300	0.048	11,100	0.033	6,900
	3	0.491	0.116	26,500	0.059	14,000	0.038	8,600
	Avg	0.575	0.109	25,600	0.054	12,800	0.037	8,470
196	1	0.634	0.108	24,500	0.058	13,800	0.041	10,400
	2	0.598	0.109	27,000	0.048	11,100	0.033	6,900
	3	0.491	0.119	27,200	0.060	14,200	0.039	8,900
	Avg	0.574	0.112	26,230	0.055	13,030	0.038	8,730
224	1	0.634	0.108	24,500	0.058	13,800	0.040	10,100
	2	0.598	0.109	27,000	0.048	11,100	0.033	6,900
	3	0.491	0.120	27,400	0.060	14,200	0.039	8,900
	Avg	0.574	0.112	26,300	0.055	13,030	0.037	8,630
252	1	0.634	0.109	24,700	0.058	13,800	0.041	10,400
	2	0.598	0.109	27,000	0.048	11,100	0.033	6,900
	3	0.495	0.120	27,400	0.060	14,200	0.039	8,900
	Avg	0.575	0.113	26,370	0.055	13,030	0.038	8,730
280	1	0.616	0.109	24,700	0.058	13,800	0.041	10,400
	2	0.598	0.109	27,000	0.049	11,300	0.033	6,900
	3	0.497	0.120	27,400	0.060	14,200	0.040	9,100
	Avg	0.570	0.113	26,370	0.056	13,100	0.038	8,800
308	1	0.616	0.107	24,200	0.056	13,300	0.037	9,400
	2	0.598	0.116	26,300	0.049	11,300	0.034	7,100
	3	0.498	0.116	26,500	0.062	14,700	0.037	8,400
	Avg	0.570	0.113	25,670	0.056	13,100	0.036	8,300
336	1	0.612	0.107	24,200	0.055	13,100	0.037	9,400
	2	0.595	0.116	28,500	0.049	11,300	0.034	7,100
	3	0.495	0.116	26,500	0.062	14,700	0.033	7,500
	Avg	0.567	0.113	26,400	0.055	13,030	0.035	8,000
364	1	0.609	0.107	24,200	0.056	13,300	0.038	9,600
	2	0.598	0.107	26,500	0.048	11,100	0.031	6,900
	3	0.496	0.118	27,000	0.060	14,200	0.036	8,200
	Avg	0.568	0.111	25,900	0.055	12,870	0.035	8,230

Table 4

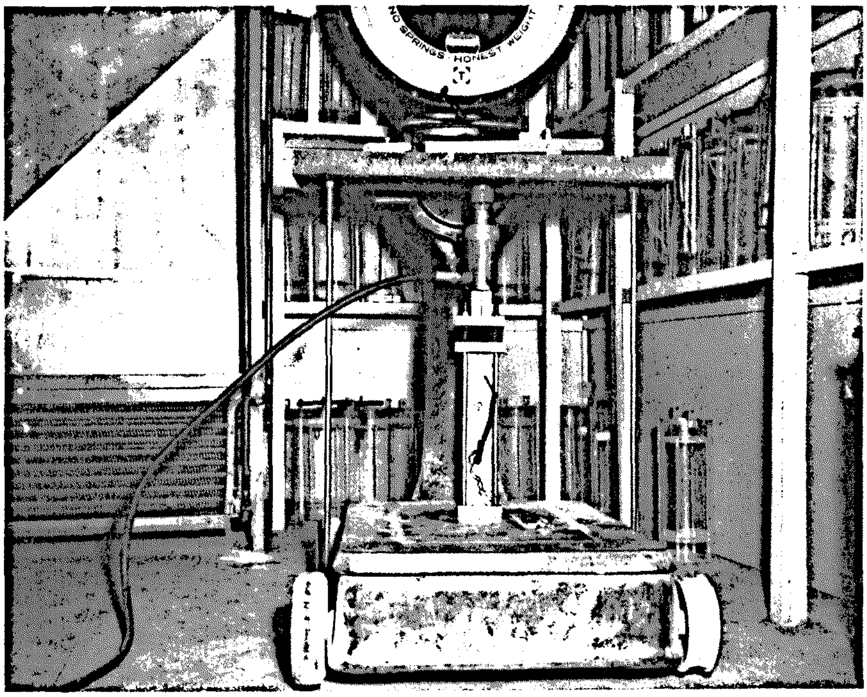
Elastic Plus Creep Strain in Cement-Pyrex Prisms, Phase IV

Prism Age days	Stressed at 3 Days Age Elastic + Creep Strain in.	Stressed at 3 Days Age Elastic + Creep Strain 10^{-6} in. per psi	Stressed at 7 Days Age Elastic + Creep Strain in.	Stressed at 7 Days Age Elastic + Creep Strain 10^{-6} in. per psi	Stressed at 28 Days Age Elastic + Creep Strain in.	Stressed at 28 Days Age Elastic + Creep Strain 10^{-6} in. per psi	Un-stressed Shrinkage in.
3	0.0021	0.52	--	--	--	--	--
6	0.0030	0.75	--	--	--	--	0.0001
7	0.0031	0.78	0.0018	0.45	--	--	0.0001
8	0.0034	0.85	0.0020	0.50	--	--	0.0001
9	0.0036	0.90	0.0023	0.58	--	--	0.0001
10	0.0037	0.92	0.0023	0.58	--	--	0.0001
13	0.0039	0.96	0.0027	0.68	--	--	0.0003
14	0.0042	1.05	0.0031	0.78	--	--	0.0003
21	0.0045	1.12	0.0033	0.82	--	--	0.0003
28	0.0048	1.20	0.0036	0.90	0.0014	0.35	0.0004
35	0.0052	1.30	0.0041	1.02	0.0023	0.58	0.0005
42	0.0055	1.38	0.0045	1.12	0.0026	0.70	0.0007
49	0.0060	1.50	0.0049	1.22	0.0032	0.80	0.0008
56	0.0063	1.58	0.0053	1.32	0.0036	0.90	0.0009
63	0.0065	1.62	0.0054	1.35	0.0037	0.92	0.0008
70	0.0068	1.70	0.0057	1.42	0.0040	1.00	0 0008
77	0.0070	1.75	0.0060	1.50	0.0043	1.08	0.0013
84	0.0069	1.72	0.0058	1.45	0.0043	1.08	0.0013
91	0.0070	1.75	0.0060	1.50	0.0043	1.08	0.0011
98	0.0071	1.78	0.0061	1.52	0.0046	1.15	--

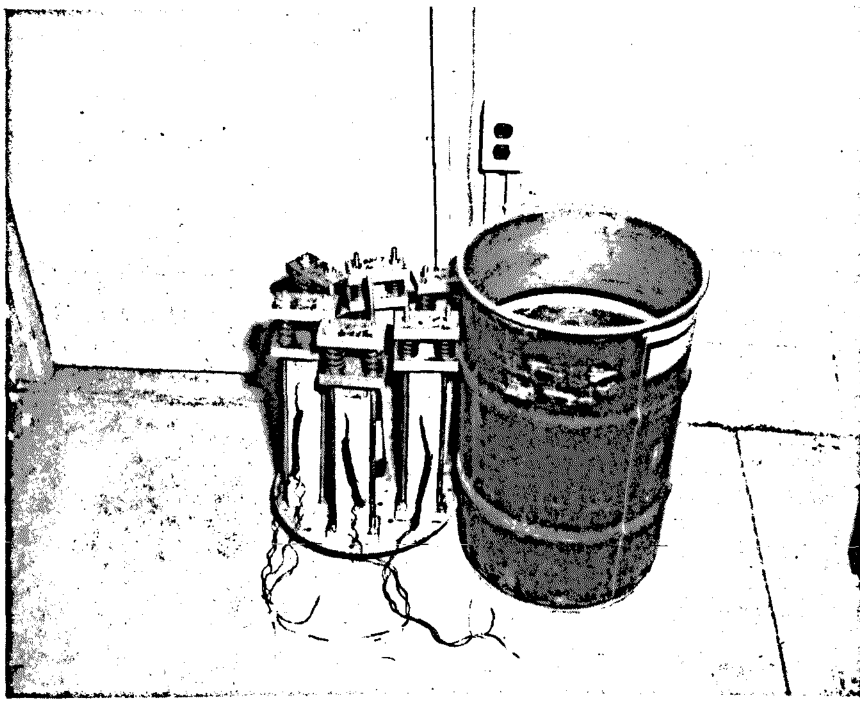
Table 5

Calculated and Measured Strains and Loads, Phase IV

Age and Type of Specimen	Unre-strained	1/4-in. Restraining Rod	3/8-in. Restraining Rod	1/2-in. Restraining Rod
7 days				
σ_{c7}, psi	--	171	315	446
Measured expansion, %	0.069	0.029	0.013	0.012
Calculated expansion, %	--	0.056	0.046	0.037
Ratio of measured to calculated expansion	--	0.51	0.29	0.33
Measured end-plate load, lb	--	325	345	550
Calculated end-plate load, lb	--	633	1166	1650
Ratio of measured to calculated load	--	0.51	0.30	0.33
28 days				
σ_{c7-28}, psi	--	575	1014	1383
σ_{c28}, psi	--	746	1327	1829
Measured expansion, %	0.310	0.080	0.040	0.030
Calculated expansion, %	--	0.244	0.194	0.150
Ratio of measured to calculated expansion	--	0.33	0.20	0.20
Measured end-plate load, lb	--	920	1030	1360
Calculated end-plate load, lb	--	2760	4914	6767
Ratio of measured to calculated load	--	0.33	0.21	0.20
84 days				
σ_{c28-84}, psi	--	467	686	793
σ_{c84}, psi	--	1213	2013	2622
Measured expansion, %	0.546	0.104	0.052	0.036
Calculated expansion, %	--	0.397	0.294	0.218
Ratio of measured to calculated expansion	--	0.26	0.18	0.16
Measured end-plate load, lb	--	1200	1350	1615
Calculated end-plate load, lb	--	4488	7448	9849
Ratio of measured to calculated load	--	0.27	0.14	0.16

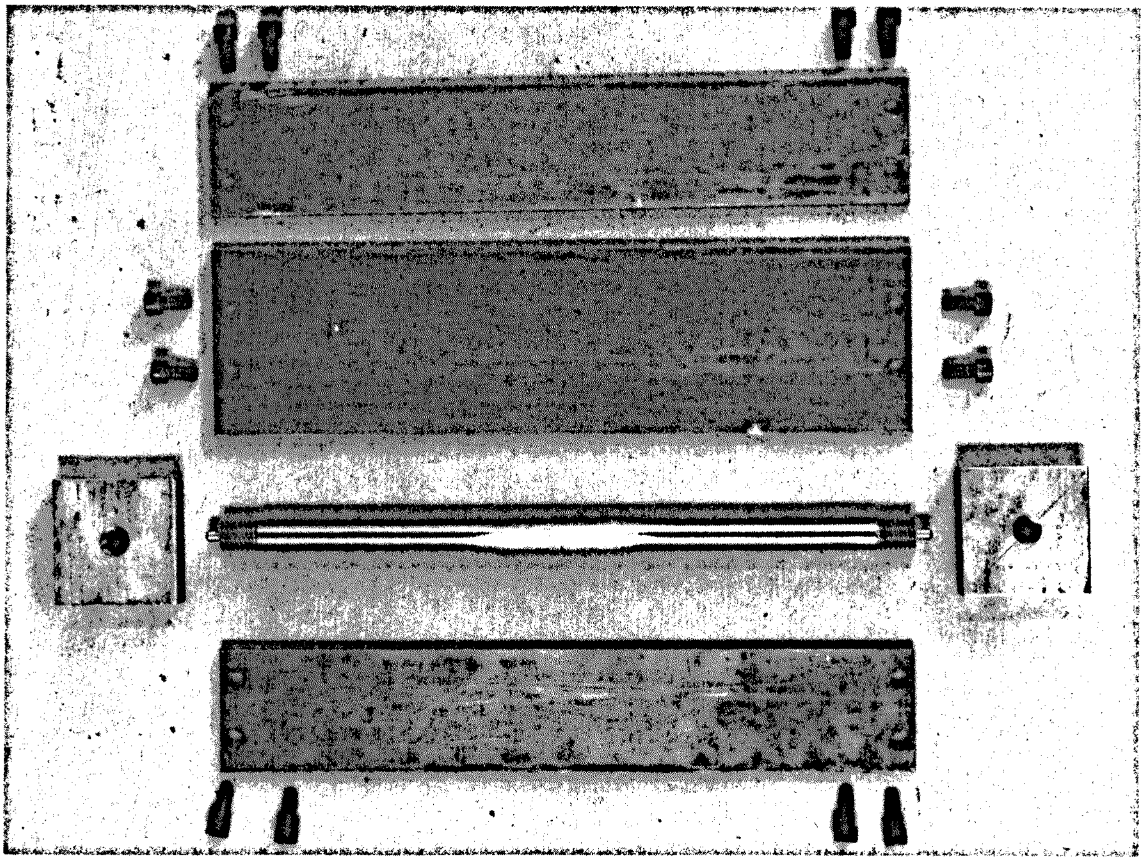


a. Method for applying restraint



b. Bars under restraint

Photograph 1. Method of restraining Phase II bars

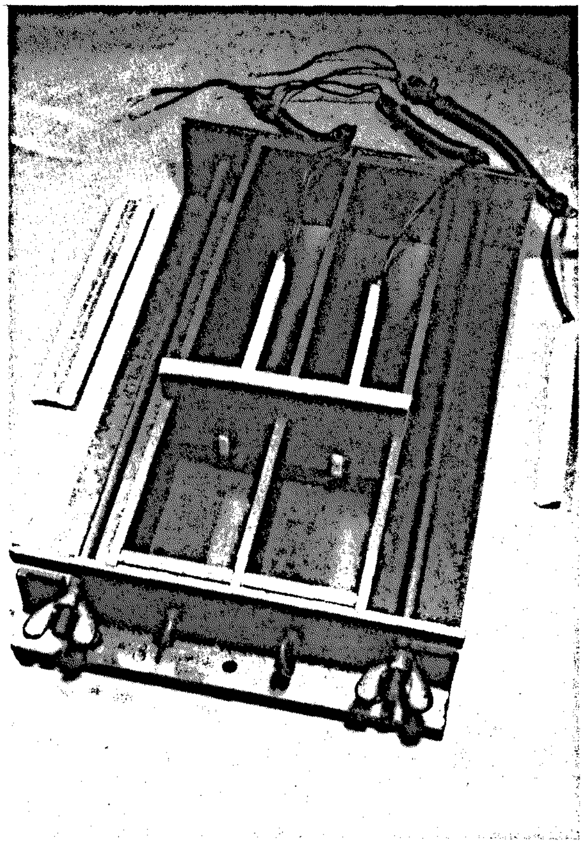


a. Disassembled

b. Assembled

Photograph 2. Molds for casting bars containing axially embedded restraining bars; Phase III

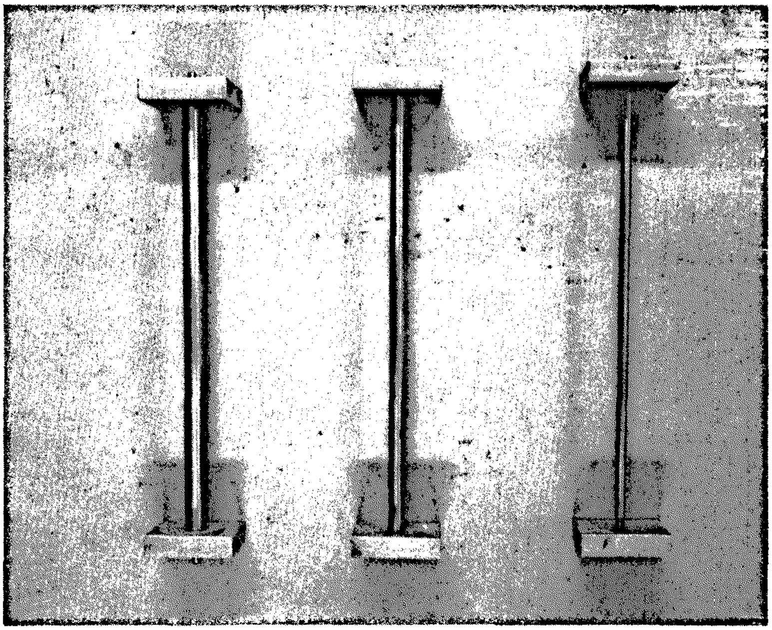
a. View showing gages



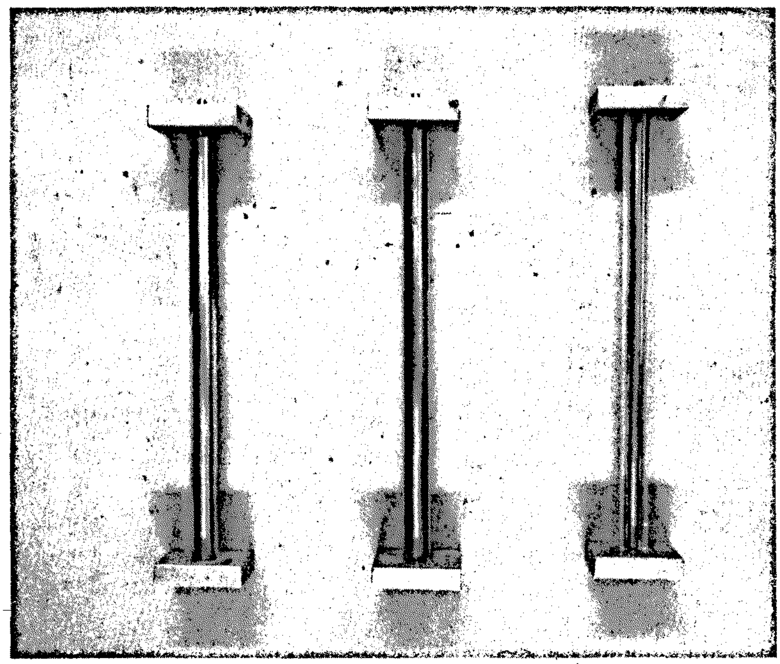
b. Gages in place

Photograph 3. Bar mold and arrangement for holding the strain gage in position during casting of the mortar bars; Phase II

62336

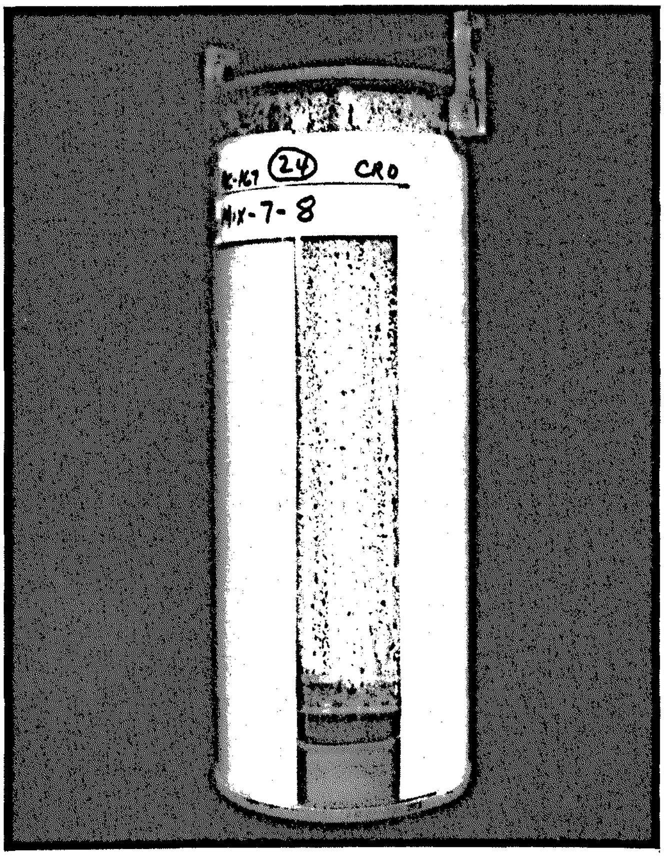


a. Without sleeves

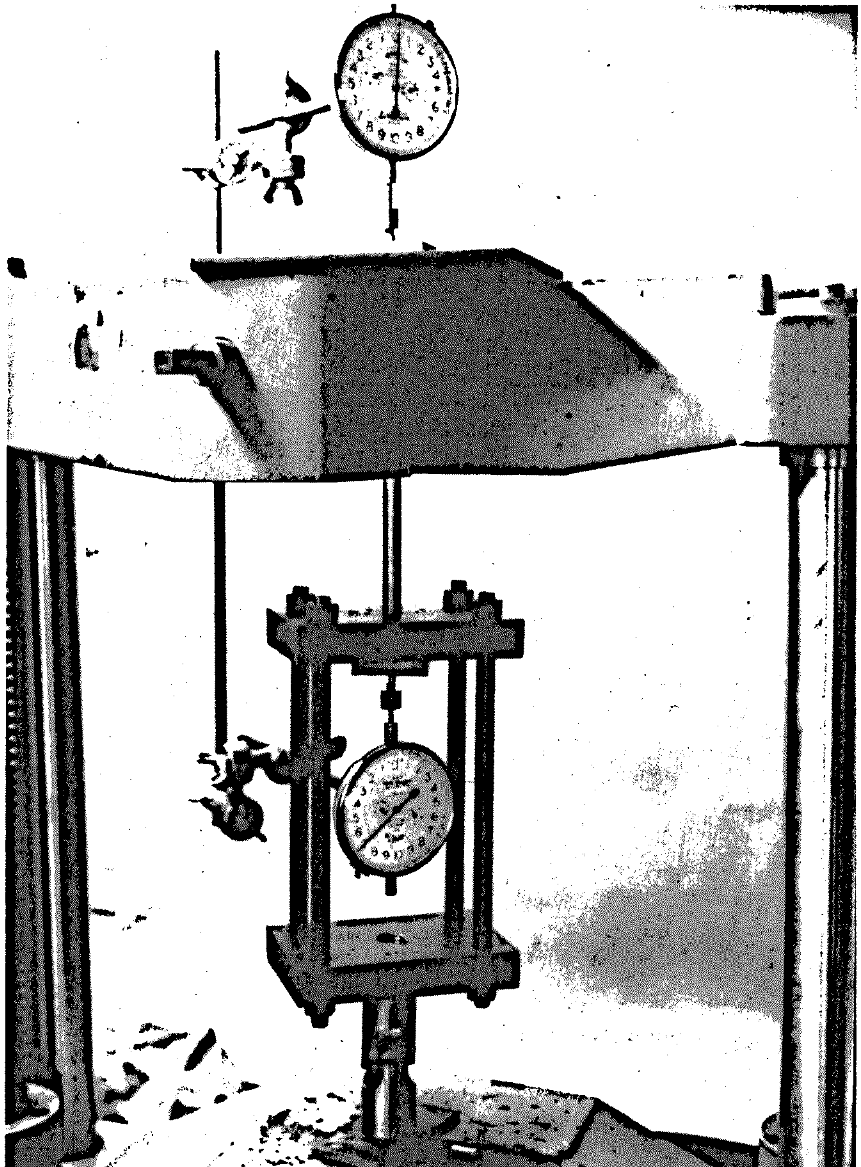


b. With sleeves

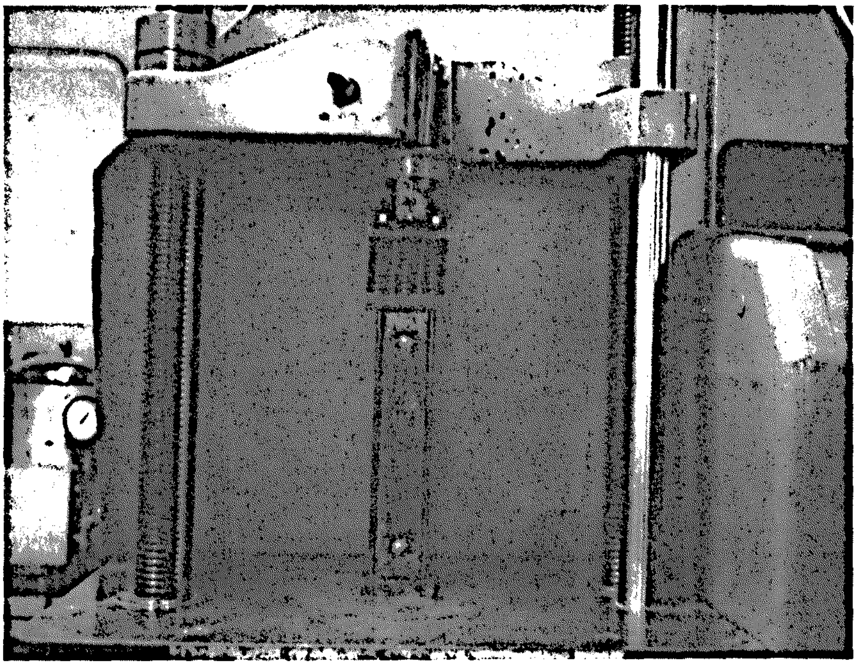
Photograph 4. Restraining rods showing end plates and plastic sleeves



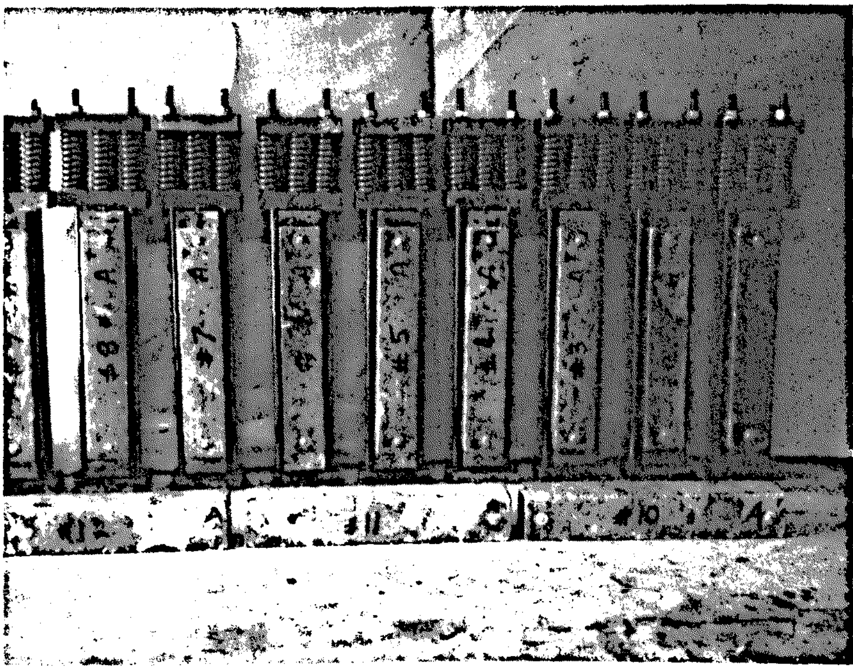
Photograph 5. Mortar bar container for exposing bars tested in Phase IV at 100 F and 100 percent humidity



Photograph 6. Assembly for determining stress-strain characteristics of restraining rods; Phase IV

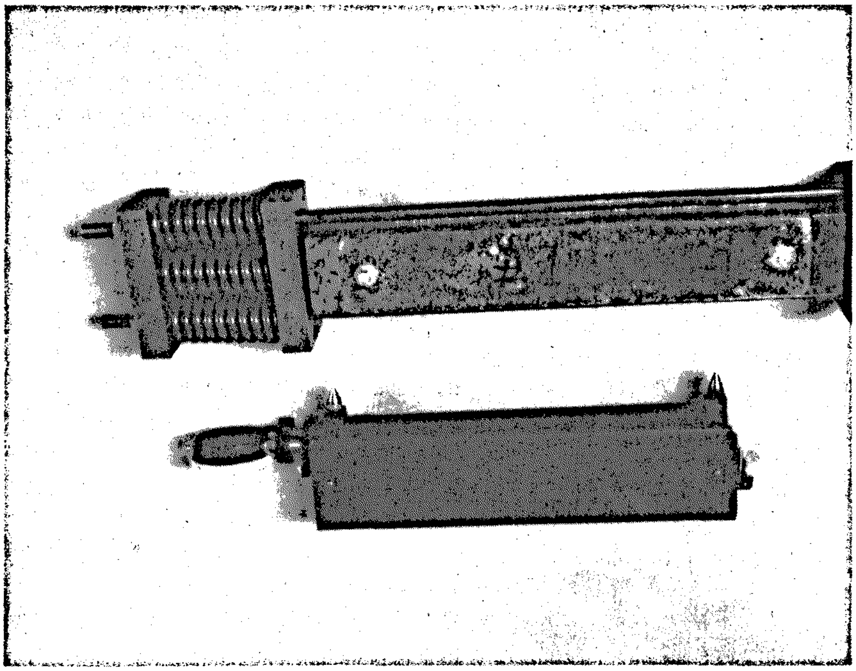


a. Applying stress to prism

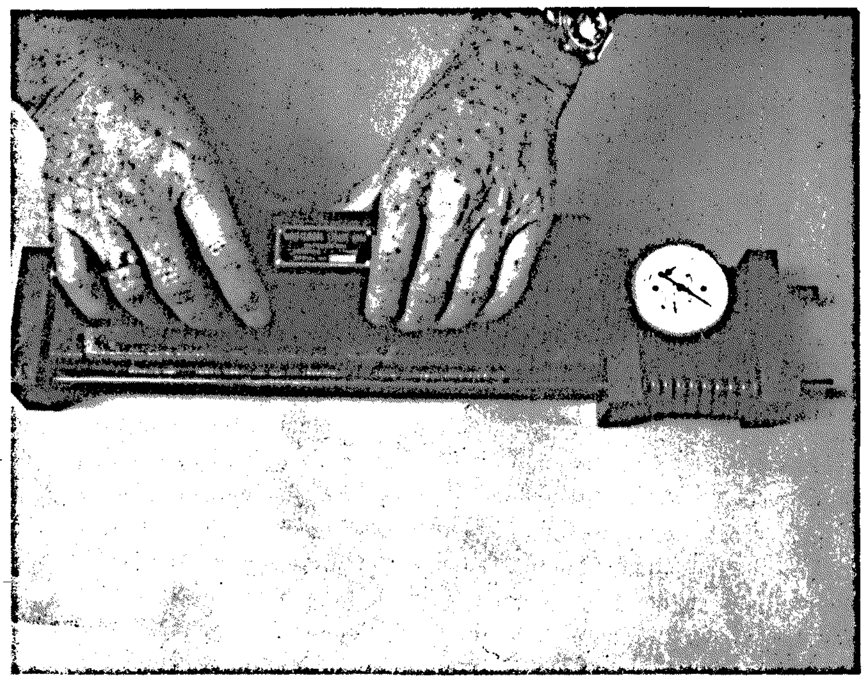


b. Twelve prisms under test

Photograph 7. Application of stress, and total number of prisms being tested for creep; Phase IV

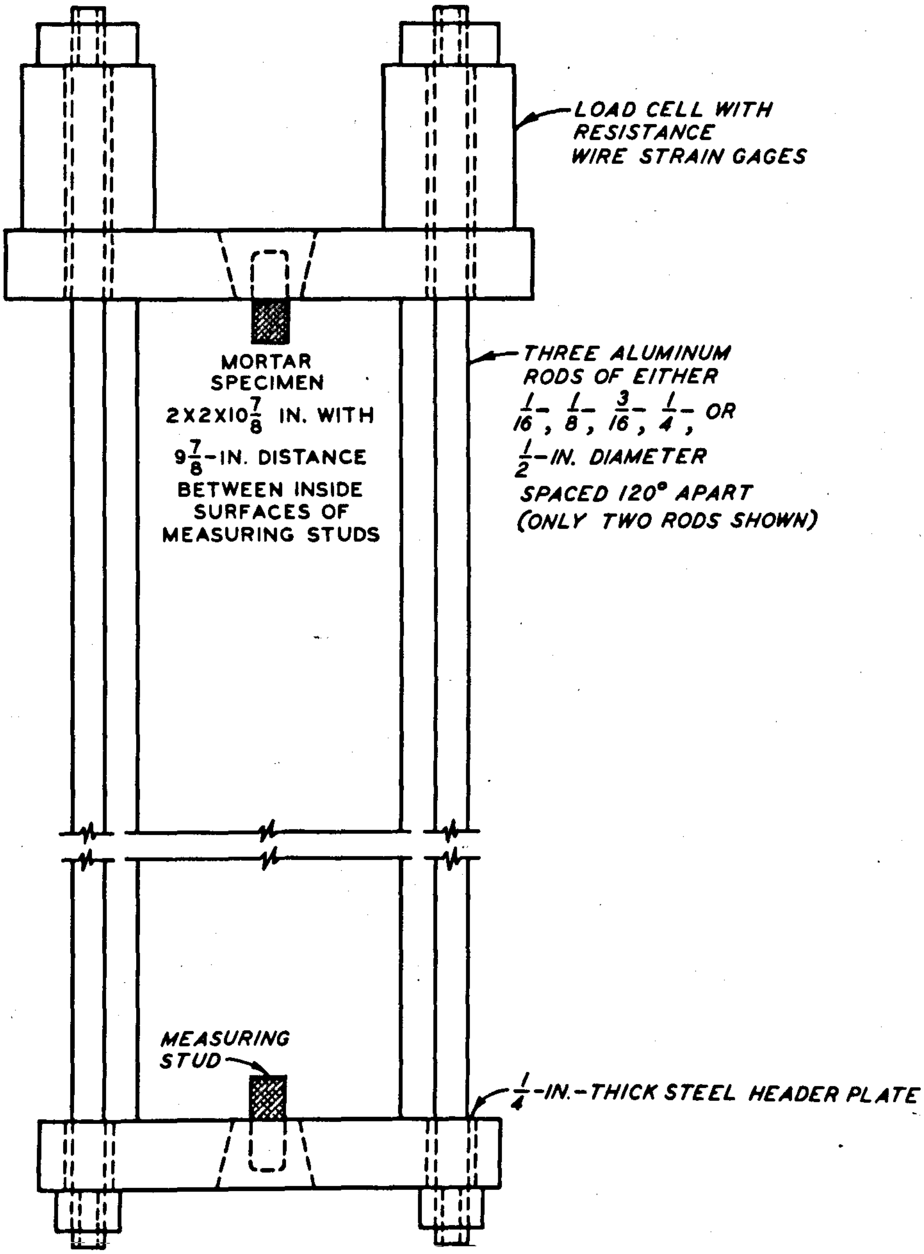


a. Equipment for measuring creep strain

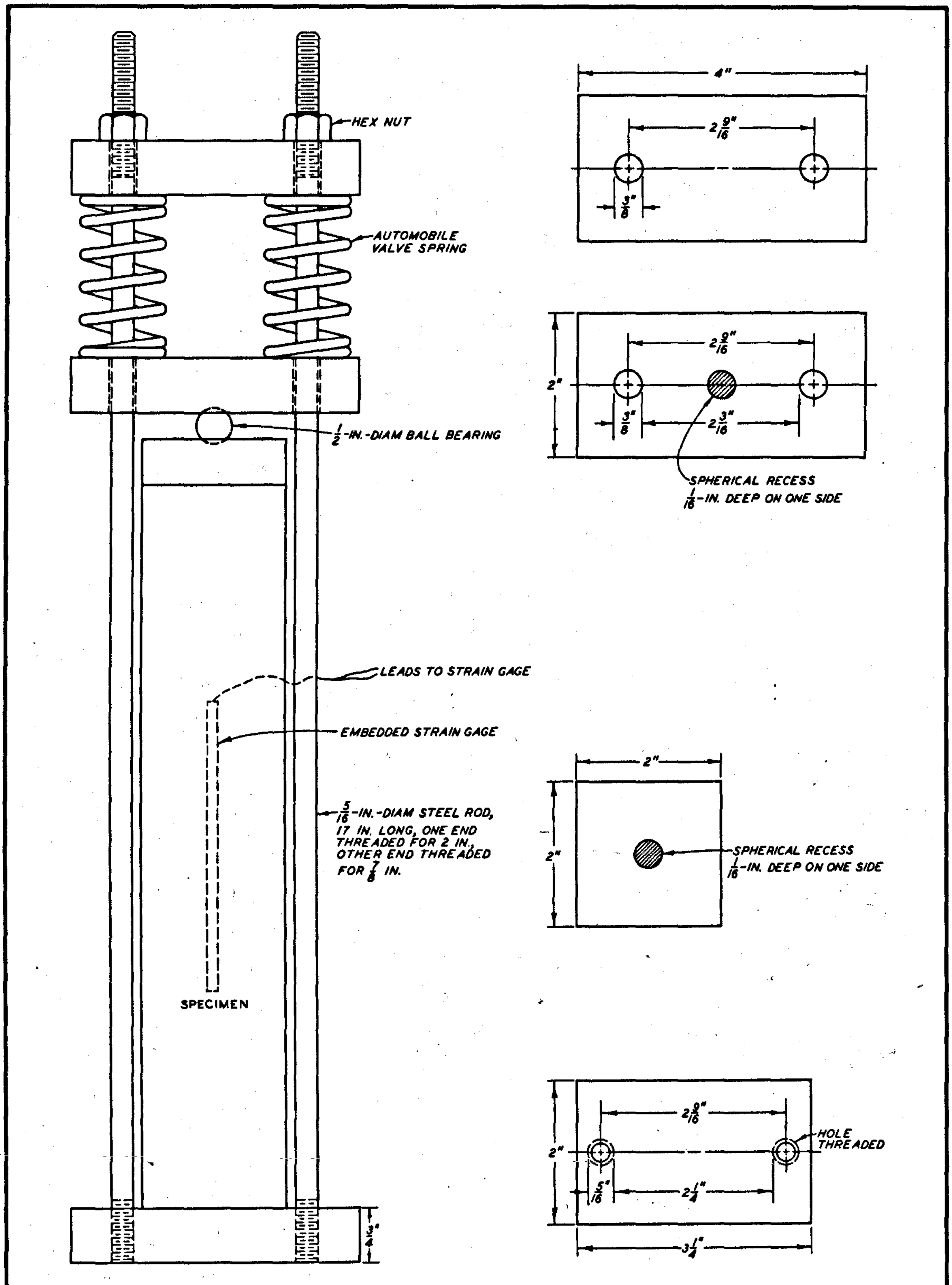


b. Making a measurement

Photograph 8. Equipment and procedure for determining creep in a stressed mortar prism; Phase IV

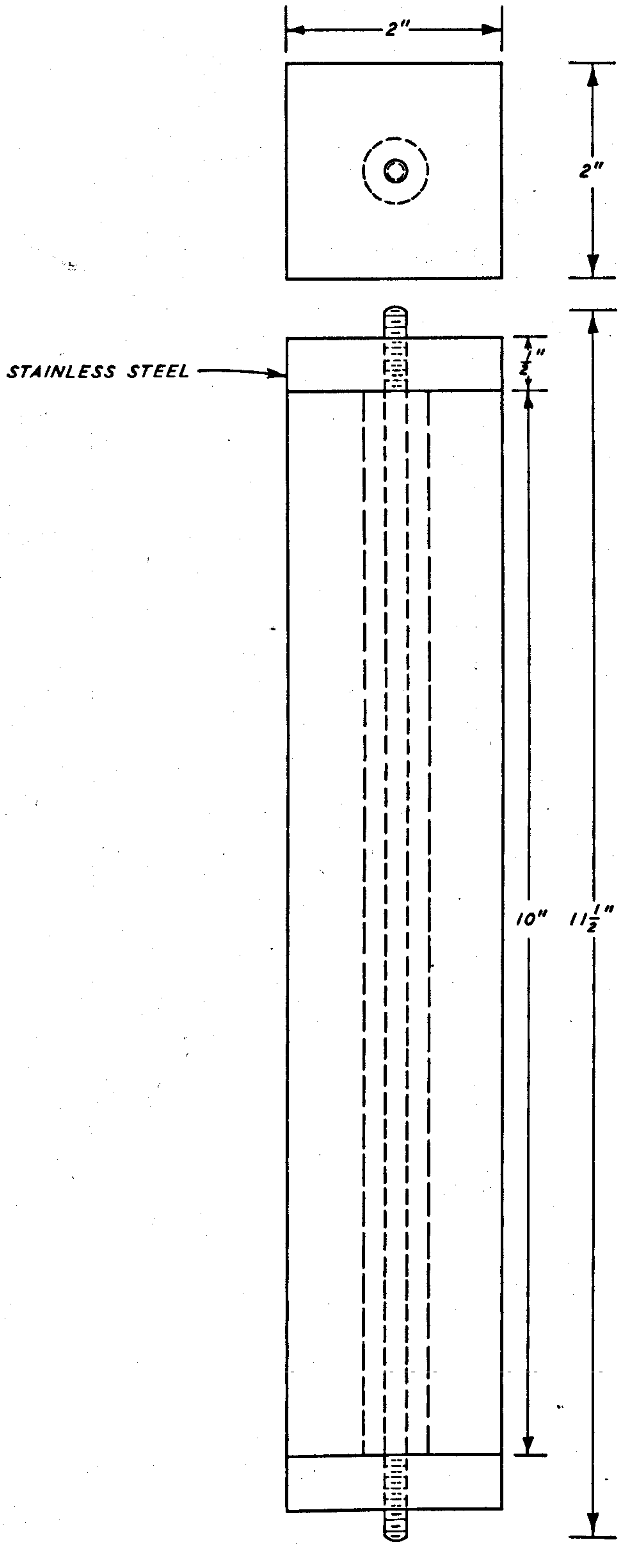


APPARATUS FOR APPLYING RESTRAINT TO ALKALI-AGGREGATE REACTION SPECIMEN
PHASE I

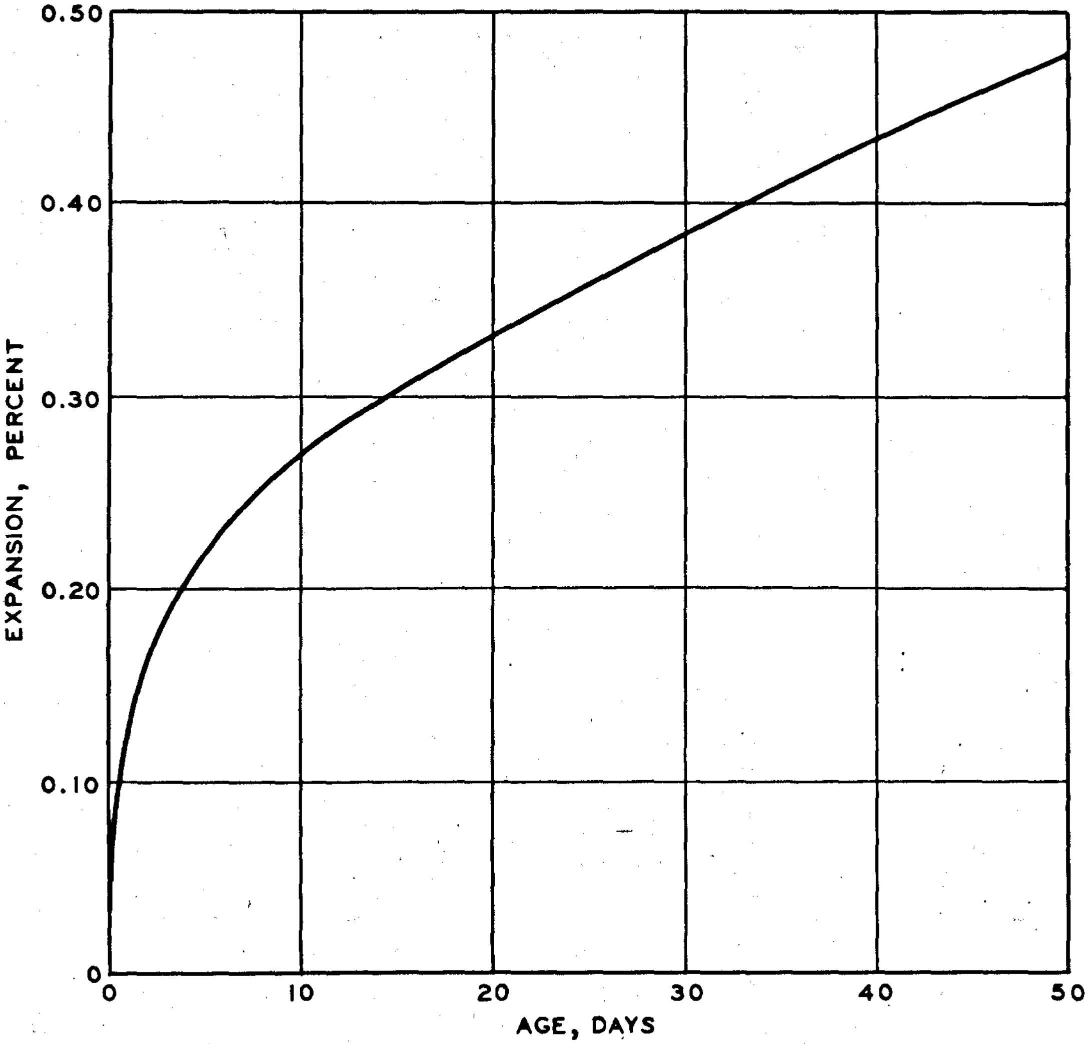


APPARATUS FOR
APPLYING RESTRAINT
ON BARS CONTAINING
EMBEDDED STRAIN GAGES
PHASE II

PLATE 2



MORTAR BAR WITH EMBEDDED
RESTRAINING ROD
PHASE IV

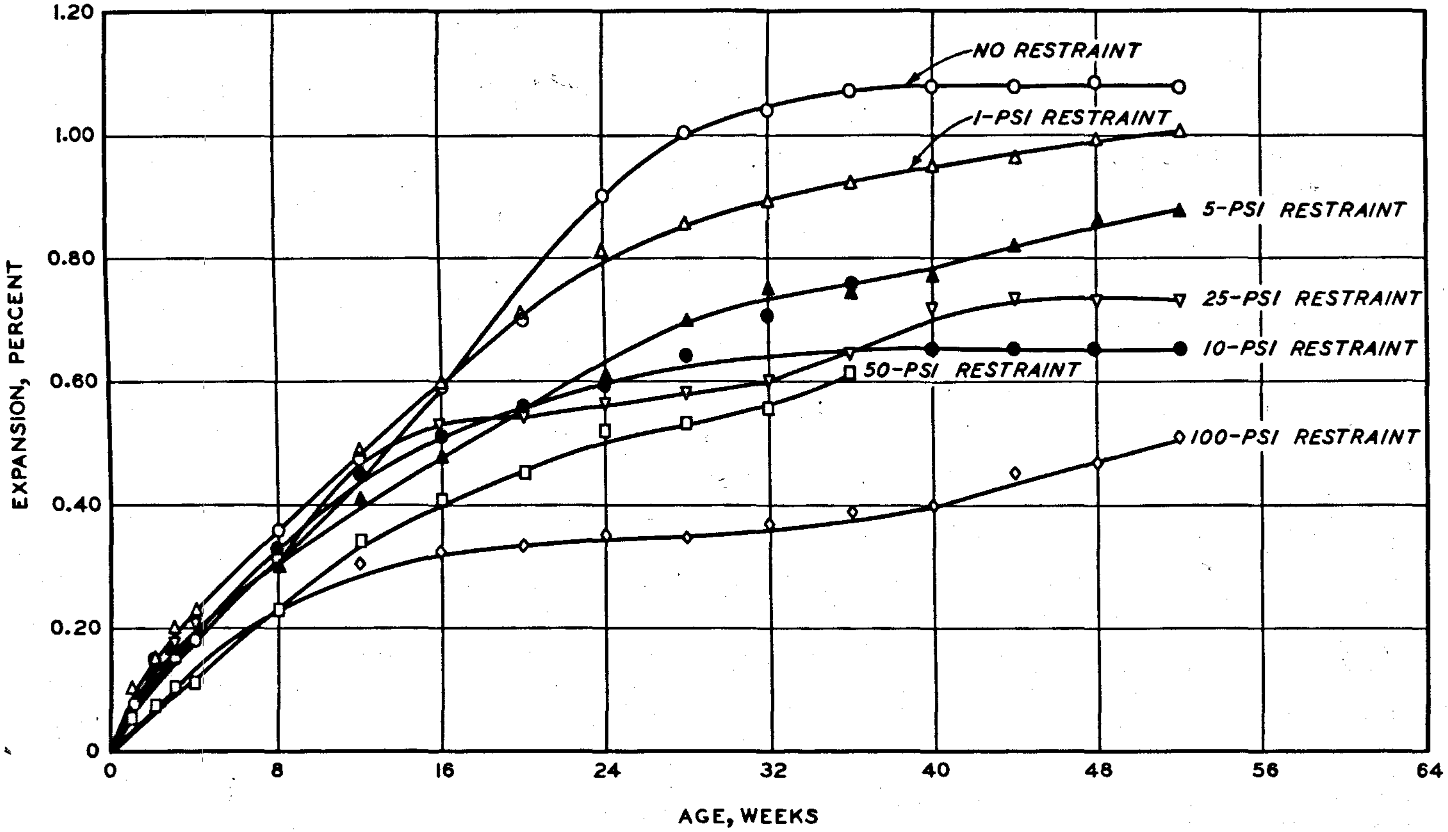


NOTE: GAGE EXPOSED TO 100 F
AND 100 PERCENT HUMIDITY.

EXPANSION OF UNCONFINED POLYESTER-COVERED STRAIN GAGE WITH TIME

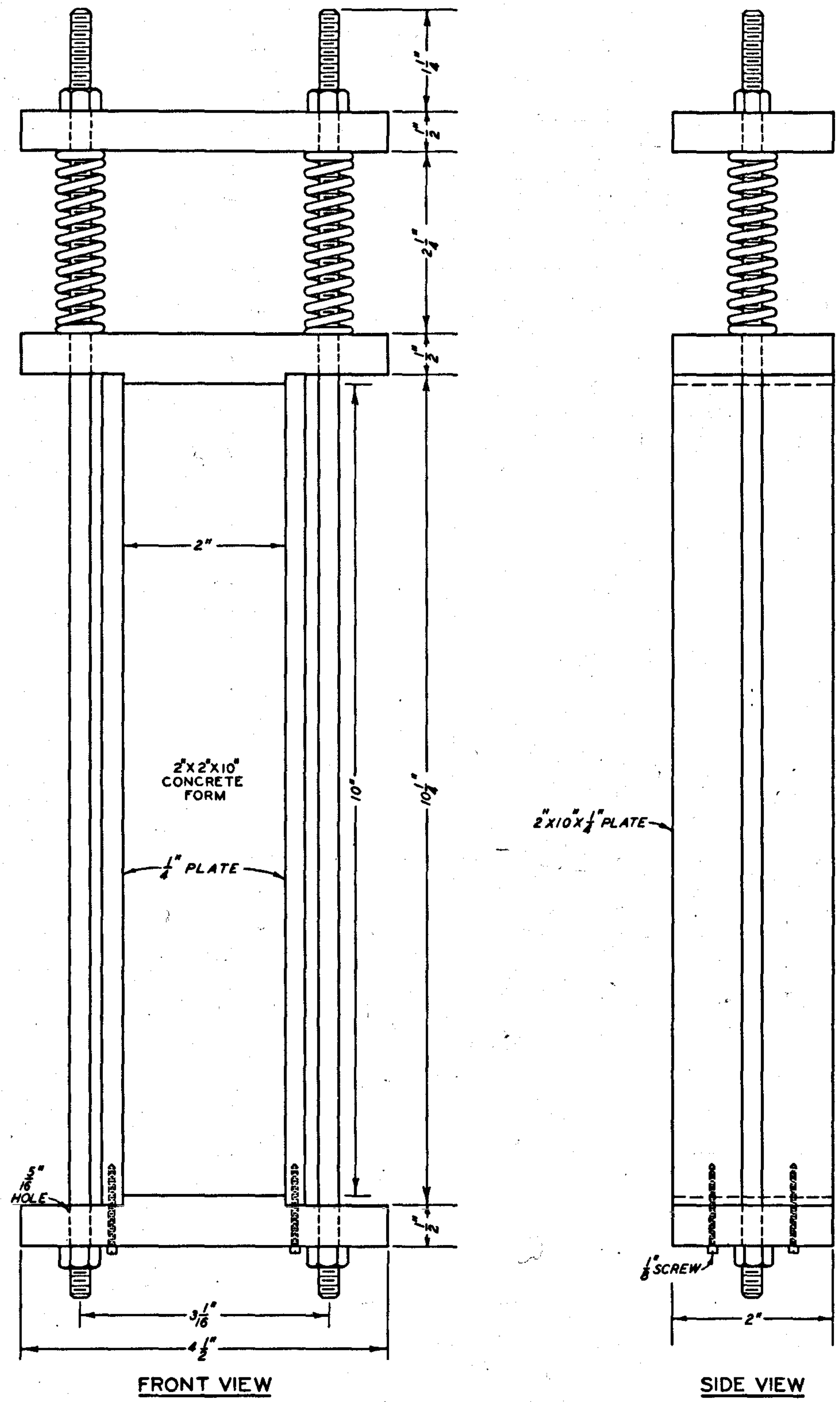
PHASE II

PLATE 4



EFFECT OF EXTERNAL RESTRAINT
ON EXPANSION OF BARS
CONTAINING EMBEDDED STRAIN GAGES
PHASE II

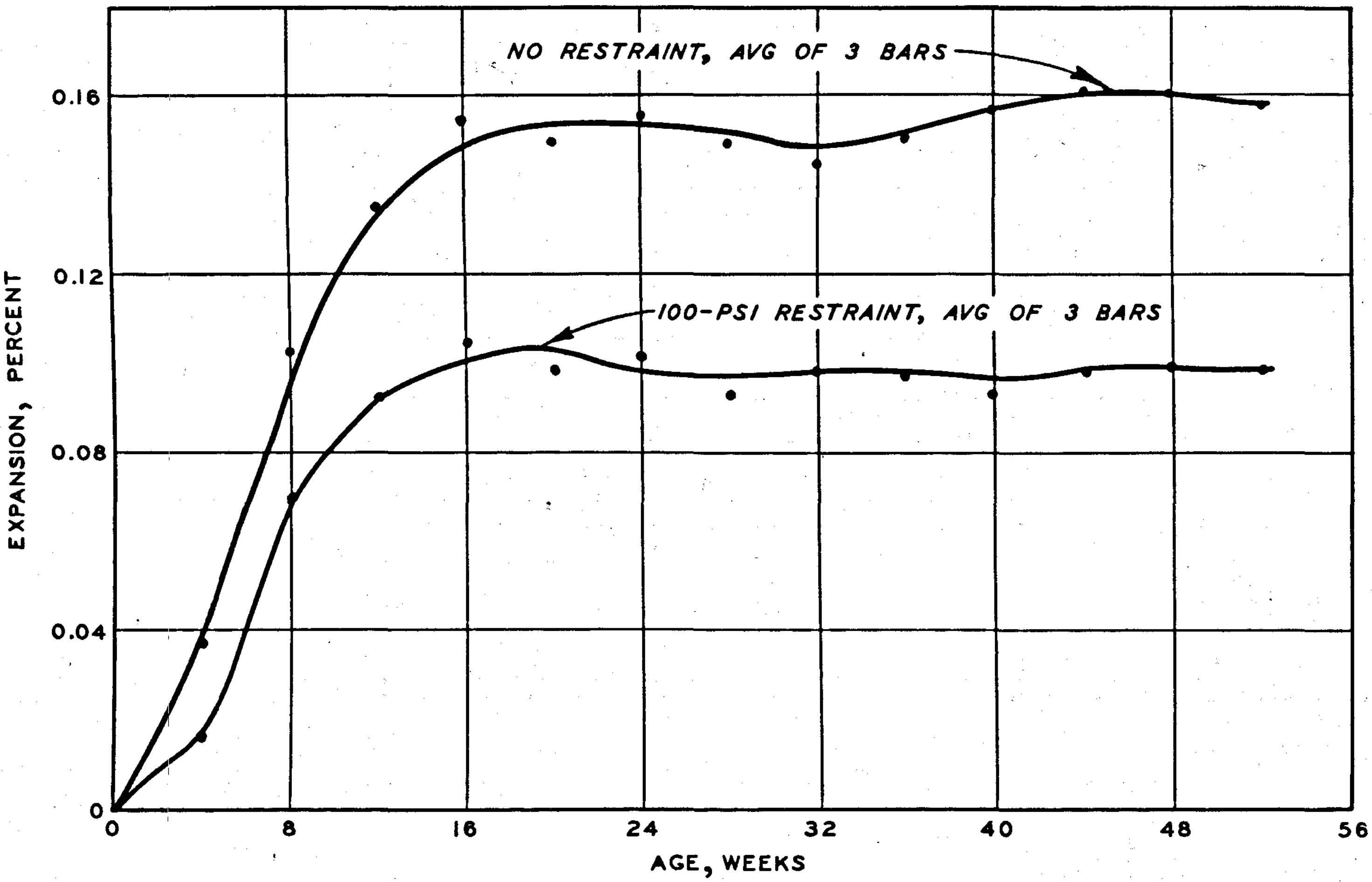
PLATE 5



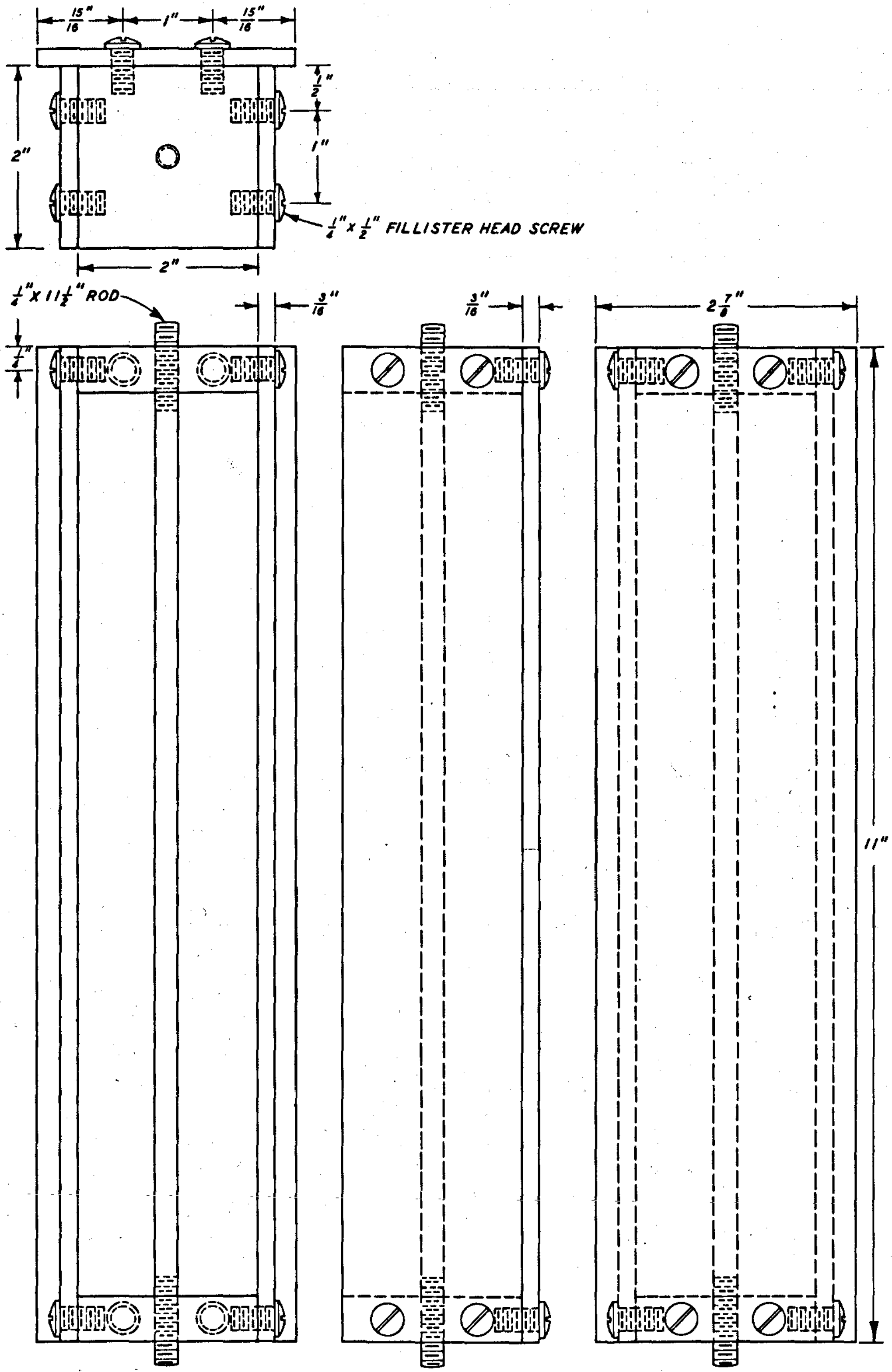
PRESTRESSED MOLDS
PHASE III

PLATE 6

PLATE 7

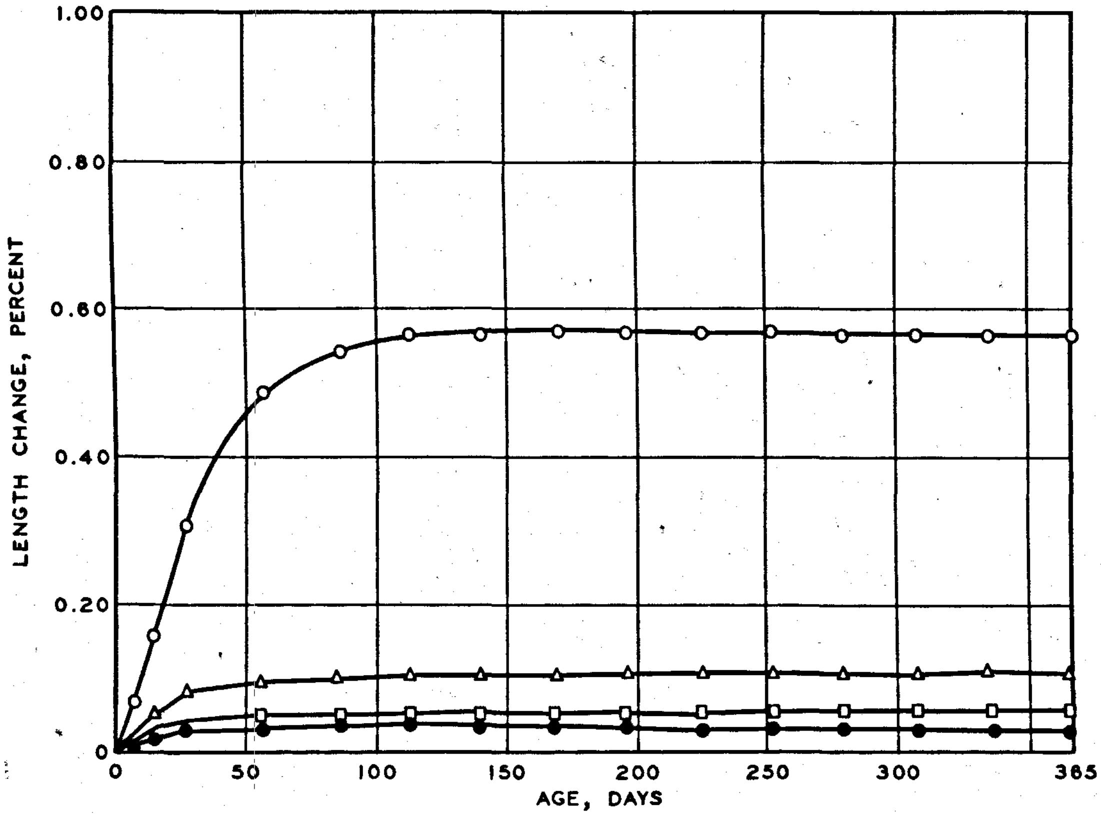


EFFECT OF
PRESTRESSED MOLDS
PHASE III



BAR MOLD AND RESTRAINING ROD
PHASE IV

PLATE 8



AGGREGATE

PYREX

CEMENT

RC-167

0.95 % Na_2O EQUIVALENT

LEGEND

COMBINATION

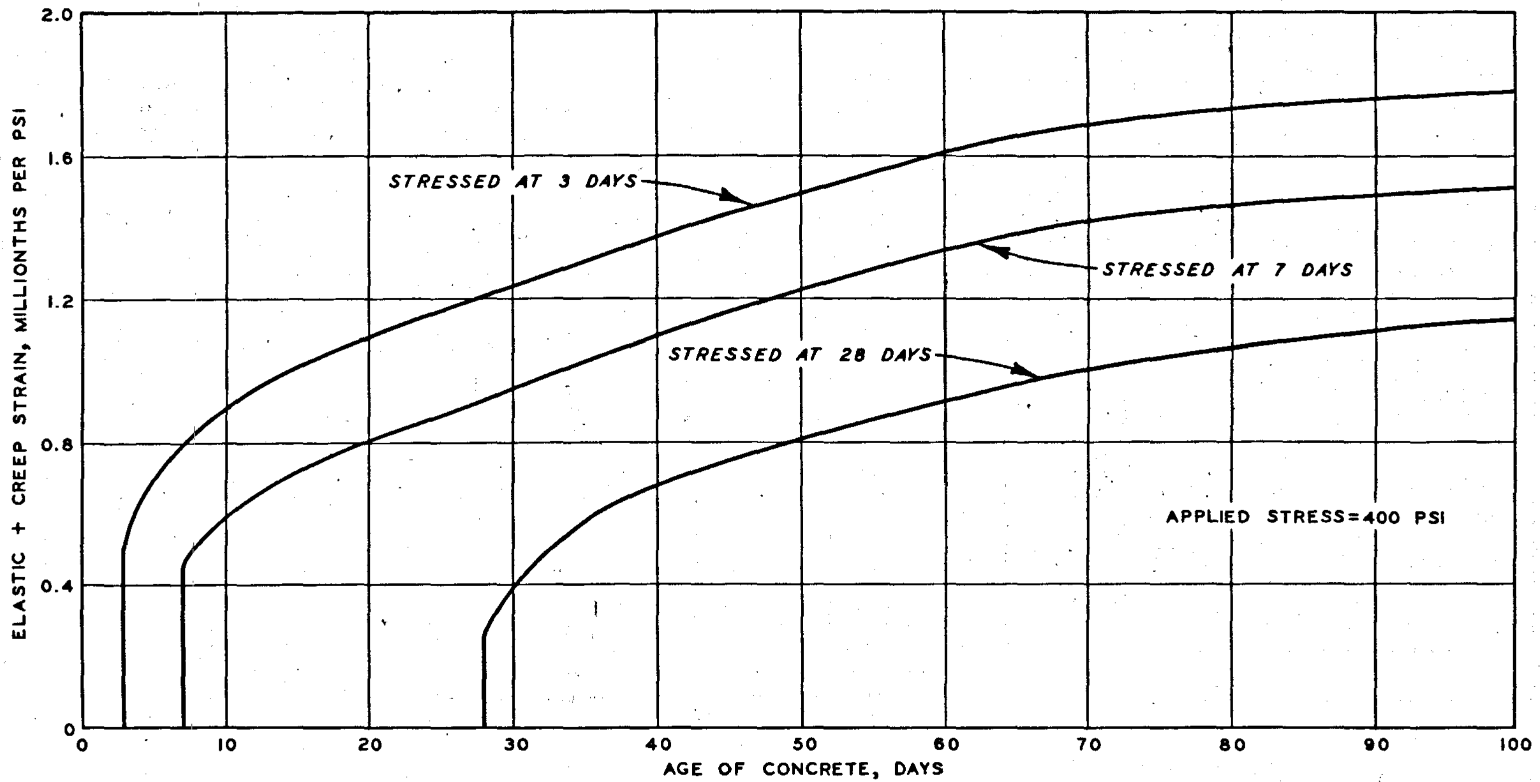
	Combination
O———O	NO RESTRAINT
Δ- - - - -Δ	1/4" RESTRAINT ROD
□———□	3/8" RESTRAINT ROD
●———●	1/2" RESTRAINT ROD

	LENGTH CHANGE	EXPANSION REDUCTION
O———O	0.568 %	0 %
Δ- - - - -Δ	0.111 %	80 %
□———□	0.055 %	90 %
●———●	0.035 %	94 %

NOTE: RESULTS OF TEST FOR LENGTH CHANGE DUE TO CHEMICAL REACTION IN CONCRETE MATERIALS.

EFFECT OF AXIALLY EMBEDDED RESTRAINING RODS

PLATE 10



ELASTIC PLUS CREEP STRAIN IN CEMENT-PYREX PRISMS

PHASE IV

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13. ABSTRACT An investigation was conducted to determine the effects of axial restraint on length change of mortar prisms tending to expand due to alkali-silica reaction. Three approaches were taken. The first involved use of external restraint on expansive mortar prisms. Restraining rigs consisted of aluminum rods held in place by steel header plates and load cells for determining stress caused by expansion. Results were questionable for a number of reasons. The next approach involved use of polyester laminated strain gages embedded axially in expansive prisms for determining stress. Restraint was provided by external frames giving restraining loads of 0-100 psi. Prisms were stored at 100 F and 100% RH. Results indicated that restraint does act to reduce expansion; however, accuracy was doubtful because it was discovered that the polyester cover of the strain gages expanded when exposed to 100 F and 100% RH even with no external stress transferred to it. The third approach involved use of axially embedded calibrated steel restraining rods (1/4-, 3/8-, and 1/2-in.-diam) with end plates screwed on the ends of each rod. Stress developed on the end plates at 1-yr age was greater with the larger rods because the smaller rods elongated more under tensile stress and relieved some of the end-plate pressure. Linear expansion was reduced 80, 90, and 94% by the three restraints. Tests of cubes sawed from the prism after 1-yr exposure indicated that restraint had little or no effect on compressive strength. Strains and stresses expected in the restrained specimens were estimated by an approximative analysis involving linear superposition of measured unrestrained expansion values and elastic and creep behavior of nonexpanding reference prisms. Measured strains ranged only between 16 and 52% of the calculated or theoretical values, indicating that such calculations are at best only useful in giving a very conservative estimate.

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Mortar bars						

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