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16. ABSTRACT

Findings of the California Division of Highways' study of the properties of concrete made with shrinkage compensated cement are reported. Also, data obtained from laboratory tests and a summary of experience with field applications are presented. Aspects of shrinkage compensated cement concrete included are volume change, resistance to freezing and thawing, crack resistance and the resistance to sulfate attack of restrained and unrestrained specimens. Measurements on concrete specimens in which restraint was minimized as much as possible indicated that shrinkage compensated cement concrete expands for approximately seven days under moist curing conditions. When subjected to drying conditions, shrinkage is similar to that of regular concrete. Test results indicated very little difference in behavior between concretes made with shrinkage compensated cement and Type II Portland cement with respect to resistance to freezing and thawing damage, crack resistance to freezing and thawing damage, crack resistance as determined by axially restrained beams, and crack occurrence on nonreinforced concrete pavement test sections. A significant finding of this project is the extremely low resistance to sulfate attack of concrete made with shrinkage compensated cement. When exposed to alternate wetting and drying in a sodium sulfate solution, beams made with the shrinkage compensated cement showed considerably less resistance to sulfate attack than that exhibited by comparable beams made with Type II cement.

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HIGHWAY RESEARCH REPORT

SHRINKAGE COMPENSATED CEMENT IN HIGHWAY CONCRETE

FINAL REPORT

68-03

STATE OF CALIFORNIA

TRANSPORTATION AGENCY

DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

NO. M & R 635140

68-03

Prepared in Cooperation with the U.S. Department of Transportation, Bureau of Public Roads June, 1968

STATE OF CALIFORNIA—TRANSPORTATION AGENCY RONALD REAGAN, *Governor*

DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS
MATERIALS AND RESEARCH DEPARTMENT
5900 FOLSOM BLVD., SACRAMENTO 95819

June, 1968
M&R 635140
D-3-24

Mr. J. A. Legarra
State Highway Engineer

Dear Mr. Legarra:

Submitted herewith is a research report entitled:

SHRINKAGE COMPENSATED CEMENT IN
HIGHWAY CONCRETE

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Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

Reference: Spellman, D. L., Ames, W. H., and Stoker, J. R. "Shrinkage Compensated Cement in Highway Concrete" State of California, Department of Public Works, Division of Highways, Materials and Research Department.
Research Report No. 635140, June, 1968

Abstract: Findings of the California Division of Highways' study of the properties of concrete made with shrinkage compensated cement are reported. Also, data obtained from laboratory tests and a summary of experience with field applications are presented. Aspects of shrinkage compensated cement concrete included are volume change, resistance to freezing and thawing, crack resistance and the resistance to sulfate attack of restrained and unrestrained specimens. Measurements on concrete specimens in which restraint was minimized as much as possible indicated that shrinkage compensated cement concrete expands for approximately seven days under moist curing conditions. When subjected to drying conditions, shrinkage is similar to that of regular concrete. Test results indicated very little difference in behavior between concretes made with shrinkage compensated cement and Type II portland cement with respect to resistance to freezing and thawing damage, crack resistance as determined by axially restrained beams, and crack occurrence on nonreinforced concrete pavement test sections. A significant finding of this project is the extremely low resistance to sulfate attack of concrete made with shrinkage compensated cement. When exposed to alternate wetting and drying in a sodium sulfate solution, beams made with the shrinkage compensated cement showed considerably less resistance to sulfate attack than that exhibited by comparable beams made with Type II cement.

Key Words: Cements, shrinkage compensated cements, concretes, freeze-thaw durability, shrinkage, cracking, sulfate resistance

ACKNOWLEDGMENTS

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The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those held by the Bureau of Public Roads.

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SHRINKAGE COMPENSATED CEMENT IN HIGHWAY CONCRETE

INTRODUCTION

With the commercial availability of shrinkage compensated cement, the California Division of Highways initiated a study to evaluate the potential benefits of this material in concrete construction. Studies were conducted both in the laboratory and in the field. Two reports on our experience with using compensated shrinkage cements in concrete pavements have been previously published. The first report[1*], dated September 1964, covers the Antelope Valley Freeway experimental pavement. The second report[2] dated June 1965, covers the Lodi Freeway experimental pavement. This report summarizes findings and observations obtained in the field and in laboratory studies to date, with pertinent conclusions.

Early research reported by Klein, Karby and Polivka[3] indicated that a cement developed by them containing about 15% of an expansive component (primarily calcium sulfoaluminate), would be appropriate for nonreinforced concrete slab work. Our preliminary tests of this concrete, although limited in scope, provided encouraging indications of its potential success. This work, coupled with that reported by the Concrete Research and Development Corporation[4] lead to the construction of two pavement test sections.

The new type concrete appeared to offer the possibility of constructing nonreinforced concrete pavements without joints, which would have few if any transverse cracks. Hopefully, such a pavement, in addition to being essentially crack-free, would provide superior riding qualities by minimizing or eliminating the usual slab curling or warping due to differential drying shrinkage and thermal changes. It was theorized that the monolithic pavement slab expansion would be adequately restrained by subgrade friction in the lateral direction and by a combination of subgrade friction and depressed anchorages in the subgrade

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*Refers to references listed at end of report.

near the end of each day's paving in the longitudinal direction. Restraint of expansive forces ideally would build up moderate biaxial compressive stresses in the concrete during the curing period. Then upon drying, instead of the concrete entering a state of tension, the compressive stresses would only be reduced and the normal development of crack-producing tensile stresses would be eliminated. Unfortunately, the performance of these pavement sections has shown no advantage in the use of shrinkage compensated cement in nonreinforced highway construction. (Details of the performance of shrinkage compensated cement in pavement are covered in the previously mentioned reports.)

In addition to the pavement applications, shrinkage compensated cement was investigated further by laboratory tests and used in the deck of a reinforced concrete box girder bridge. Early observations of the bridge showed no apparent difference in performance when compared to a parallel structure constructed under comparable conditions using Type II cement. Restraint was provided in two directions by the reinforcing steel.

CONCLUSIONS

Measurements of unrestrained laboratory specimens of concrete made with the various lots of shrinkage compensated cement supplied to the State, show that expansion will take place for as long as seven days if the specimens are kept saturated. Upon drying, shrinkage compensated cement concrete contracts at a rate and amount comparable to conventional concrete. Crack resistance of restrained specimens and performance in freeze-thaw testing indicates that shrinkage compensated cement concrete is comparable to conventional concrete.

The resistance of shrinkage compensated cement concrete to attack by sulfate solutions was found to be very poor, whether restrained or not.

Observations so far of full scale applications in two experimental nonreinforced pavements and one bridge deck show that shrinkage compensated cement concrete offers no advantage in performance over conventional concrete in structures of this type.

LABORATORY TEST PROGRAM

Length Change of Laboratory Specimens

This phase of the project evaluated certain factors of expansion and subsequent drying shrinkage that occurred in concrete made with shrinkage compensated cement at various cement contents. The tests were performed using unrestrained 3x3x11-1/4-inch specimens. Concrete was made using the cement reported in Column 1, of Table 1 (Lab. No. 17709), and a 1-inch maximum size American River aggregate in 5 and 7-sack per cubic yard mixes. The properties of the fresh concrete are given in Table 2. Specimens were removed from the molds at an age of about 17 hours to insure adequate strength for obtaining accurate measurements. Under these test conditions no expansion measurements during the first 17 hours were made. After stripping from the molds, some of the specimens were stored in a moist curing room at 100% relative humidity; the remaining specimens were treated with curing compound on all surfaces except the top and were placed top down in moist, sandy top soil out-of-doors. The soil was banked up along the sides of the specimens flush with the exposed surface.

Specimens placed in the moist curing room were cured for time intervals of 7, 10, and 14 days before being placed in the drying room at 50% relative humidity and 73°F. Length measurements on the bars were made daily during the wet curing period, and it was found that very little if any expansion took place after 7 days of moist curing. Specimens cured for 10 and 14 days in the fog room had essentially the same drying shrinkage as those cured for 7 days. A graph showing the indicated expansion and shrinkage of the specimens cured for 14 days is shown in Figure 1.

The specimens cured in moist top soil out-of-doors also expanded up to 7 days as long as the soil was kept moist. If the soil was allowed to dry, the bars started shrinking, but expansion could be started again by rewetting during the 7-day period. After 7 days however, expansion could not be resumed by additional wetting.

In an attempt to measure the expansion which takes place during the first few hours after mixing, two specimens were equipped with SR4 strain gages cast in the concrete near the center of the specimen. The sides of the molds were released about one hour after mixing to minimize restraint as much as possible. The data from the strain gage measurements is incorporated into Figure 1 as a dotted line.

The results of this program indicated that unrestrained concrete made with shrinkage compensated cement would expand for approximately 7 days, if the concrete was kept moist. The increased volume would remain relatively constant until drying began. During drying the concrete would shrink in a manner comparable to concrete made with conventional portland cement.

At the end of 14 days of drying, measurements indicated that the specimens were slightly longer than their initial length, a net increase of 0.021% for the 5-sack mix, and 0.033% for the 7-sack mix. The maximum increase in length was 0.062% for the 5-sack mix and 0.078% for the 7-sack mix as indicated in Figure 1. Evidently the richer mixes expand more than leaner ones.

Crack Resistance

In this program, a comparison was made of the cracking resistance of concrete specimens that were positively restrained in one direction. Concrete using shrinkage compensated cement and Type II cement was cast into 5x5x40-inch long specimens. The specimens were restrained internally with a 1-1/4-inch diameter steel bar heavily threaded at each end to provide bond to the concrete. The central 32-inch length of the steel bar was covered with a rubber sleeve to prevent bond between the concrete and the steel (see Figure 2). The physical properties of the fresh concrete are given in Table 2. The cements used are those shown in Columns 2 and 3 of Table 1.

The specimens were placed in the moist curing room for 7 days, then were stored in laboratory air at approximately 73°F and 50% relative humidity. Initial length measurements were made on the steel bars prior to placing the plastic concrete into the molds. Length measurements were taken after the forms were stripped, and daily during the moist curing period. After the specimens were placed in the drying area, length and temperature measurements were taken every other day during the drying period except on weekends. After the concrete had dried for 84 days, it was assumed that the concrete would not shrink enough under the existing drying conditions to crack in tension within a reasonable time. To accelerate drying, the beams were placed in an oven in pairs, a control beam with Type II cement, and a corresponding shrinkage compensated cement beam. The oven was maintained at approximately 100°F and 30% relative humidity. The accelerated drying test in the oven induced earlier cracking of the specimens made with shrinkage compensated cement than those made with Type II cement. Total days drying, days in oven, and calculated stress at failure are tabulated in Table 3. Also see Figures 3 through 6 for the graphs of this data.

The shrinkage of the concrete was determined from length measurements after applying corrections for standard bar readings and temperature changes. Corrections were made accordingly from the initial measured length of the steel bar. Stresses in the concrete were computed from the shrinkage data and the following equation:

$$S_c = \left(\frac{\Delta^1}{L}\right)\left(\frac{A_s}{A_c}\right) E_s$$

Where S_c = Stress in the concrete

Δ^1 = Change of length in the restraining bar (shrinkage)

L = Gage length of the restraining bar (assumed to be 36 inches)

A_s and A_c = Area of the steel and concrete respectively

E_s = Modulus of elasticity for the steel bar

Freeze-thaw Resistance

A comparison was made of the effects of freeze-thaw action on concrete containing shrinkage compensated cement and Type II cement using the same aggregates for both types of concrete. The coarse aggregate used was of good quality but the sand was considered slightly substandard as determined by the mortar strength and the sand equivalent test. Properties of the cements are shown in Columns 4 and 5 of Table 1. Each mix contained 5-1/2 sacks of cement per cubic yard and a nominal 4-1/2% entrained air. Fresh concrete properties are given in Table 2. All specimens were subjected to 40 freeze-thaw cycles as described in Test Method No. Calif. 528.

At the end of the test period there was no visual difference in the specimens made with the two cements. Several specimens from each group showed slight indications of scaling, but this could be attributed to the relatively low quality sand. The average weight loss and the permanent length change due to the freeze-thaw action for all specimens in this program was negligible. The results of this single testing program indicate that the two concretes had comparable resistance to freeze-thaw action.

Resistance to Sulfate Attack

With the relatively high percentage of calculated C_3A in shrinkage compensated cement, it was expected to be vulnerable to attack by sulfate solutions. Findings of other researchers have confirmed this vulnerability[5,6]. To evaluate the effects of concrete exposed to sulfate attack, the Sacramento plot of the Portland Cement Association Long-Time Study was utilized. This exposure involves placing concrete specimens out-of-doors in a shallow pond filled with a 2-1/2% $\pm$ solution of $NaSO_4$ and soil. The solution is allowed to evaporate periodically and after all free water disappears, the pond is filled to the desired level and $NaSO_4$ is added as necessary. The cycling of the evaporation and flooding with water is carried on throughout the summer months with the time required for a cycle varying depending on drying conditions. A cycle during summer months normally takes about two weeks.

The initial testing program involved the use of non-reinforced concrete beams made using 1-1/2-inch maximum size aggregate from the American River near Sacramento. Comparable mixes containing shrinkage compensated cement and Type II cement were made with 5 sacks per cubic yard, 7 sacks per cubic yard, and 5 sacks per cubic yard with air entrainment. Two 6x6x20-inch beams were fabricated from each concrete mix. The beams were cured in a moist room for 14 days, then dried in laboratory air for 14 days. After the drying period the beams were placed in the sulfate exposure pond.

After 6 months of exposure, the beams were removed, cleaned, photographed, and returned to the exposure pond. At the end of 1-1/2 years, the beams were again removed, surveyed in the same manner as they were initially, and weighed and returned to the exposure pond. At the end of the 1-1/2 year period, the beams made from 5-sack, non-air-entrained, shrinkage compensated cement concrete mix were almost completely disintegrated. At the end of 2-1/2 years, the remaining beams were again removed and surveyed. At this time the 5-sack, air-entrained, shrinkage compensated cement beams were over 50% disintegrated; therefore, they were also removed from the study. The survey made after the beams had been subjected to sulfate exposure for 3 years showed one of the 7-sack shrinkage compensated cement concrete beams to be excessively disintegrated and it was removed from the study. The companion 7-sack shrinkage compensated cement concrete beam was removed from the study at the 3-1/2-year survey - also the first 5-sack, non-air-entrained Type II cement concrete beam was removed from the study during this survey. When the beams had been subjected to sulfate exposure for 4 years, the second 5-sack, Type II cement beam and one of the 7-sack Type II cement beams were removed due to excessive disintegration of the concrete.

The results of the surveys are shown in Table 4 and Figures 7 through 24. It is interesting to note the added sulfate resistance obtained from the use of air entrainment. This improvement has been noted in the Long-time Study of Cement performance carried on by the Portland Cement Association.

From the photographs and weight data, it is obvious that shrinkage compensated cement concrete is quite vulnerable to sulfate attack under the test conditions.

Sulfate Resistance of Restrained Concrete

As the indications of low sulfate resistance of expanding cement concrete became evident from the specimens in the exposure pond, the theory was advanced that if the specimens had been constructed by some method that would provide restraint to the expansion, the concrete would likely be much less vulnerable to sulfate attack. This theory was immediately questioned since sulfate attack is primarily a chemical reaction. However, since the concrete in the nonrestrained beams admittedly did not simulate conditions encountered in a reinforced structure, it was decided further testing should be done on restrained specimens.

Two methods of providing restraint to the expansive forces were used (see Figure 24). In one method, internal restraint was provided by the use of four No. 3 reinforcing bars 18 inches long. They were placed in the 6x6x20-inch beam in a manner that provided 1-3/8-inch of cover on the sides and 1 inch on each end. Five evenly spaced hoop ties provided the vertical and transverse reinforcement. The percentage of steel in the longitudinal direction was 1.22 and in the vertical and transverse direction 0.92. The second method used involved externally restrained beams using 6x6x3/8-inch steel plates welded to a No. 6 reinforcing bar. The steel bar is positioned in the center of the plates giving a percentage of steel in the longitudinal direction of 1.22. Concrete mixes with 5-1/2 and 7 sacks per cubic yard were used. Companion reinforced and nonreinforced specimens were made. After 14 days of curing and 7 days of drying, the beams were placed in the sulfate exposure ponds.

The data obtained from the first three surveys on these beams are given in Table 5. These beams had been in the sulfate exposure ponds 14, 20, and 26 months when the respective surveys were made. The internally restrained beams have not shown any advantage over the unrestrained beams. The externally restrained beams have shown an increased resistance to sulfate attack over the unrestrained beams. This is believed to be due to the protection the end plate provides for the corners of the beam, however. Sulfate attack normally starts at the beam corners and with a steel plate covering the beam end, resistance to disintegration might be increased. Photographs showing the beams during the first four surveys of the 5-1/2-sack beams are Figures 25 through 32.

FIELD APPLICATIONS

The two experimental pavements in which shrinkage compensated cements were used, were similar in layout, and each included six test sections as follows:

Antelope Freeway

Test Section	Cement Type	Cement Factor	Air Ent.	Curing Methods
A	II	6	No	7-day polyethylene sheet
B	Exp.	6	No	"
C	Exp.	6-1/2	No	"
D	Exp.	6	Yes	"
E	Exp.	6-1/2	Yes	"
F	II	6	Yes	"

Lodi Freeway

Test Section	Cement Type	Cement Factor	Air Ent.	Curing Methods
A	II	5-1/2	No	7-day polyethylene sheet
B	Exp.	6	No	"
C	Exp.	6	No	7-day wet earth
D	Exp.	6	Yes	"
E	Exp.	6	Yes	7-day polyethylene sheet
F	II	5-1/2	Yes	"

Each of the individual test sections (A, B, C, etc.) was approximately 1/4-mile long and were cast 24 feet wide and 8 inches thick. Contraction joints were omitted from all experimental sections. Special efforts were required to maintain the presence of free water on the concrete surface during the curing period. This was satisfactorily done by both methods shown above, and an excellent cure resulted.

Data obtained from the two experimental pavements indicated that there was expansion in the vertical and transverse directions and virtually none in the longitudinal direction. Transversely, the expansion was greatest at the edges of the pavement and negligible near the center, but vertically, the expansion was greatest near the center.

The most significant findings with respect to the performance of the experimental pavements have been obtained from the crack surveys taken at various time intervals during construction. At the end of the curing period, there were no visible cracks in any of the test sections. The crack surveys began when pavements were 7 to 10 days old and have been made at increasing intervals for about five years. The cracking pattern that has finally developed on both types of the experimental pavements are very similar in nature and indicate no significant difference in the performance of the two types of cement. An interesting finding on these projects is that the air-entrained concrete has a much closer crack interval than the non-air-entrained concrete. Since most air-entraining agents are known to increase drying shrinkage and decrease strength in laboratory tests, this might explain the observed behavior of the pavement in the field, and support the contention that shrinkage differences as measured in the laboratory are related to field performance.

Tables 6 and 7 show the development of cracking on the two experimental pavements.

In January 1967, shrinkage compensated cement was used in the construction of the bridge deck of a reinforced concrete box girder bridge in the Sacramento Valley near Arbuckle, over IS-5. A similar bridge deck was constructed at the same time period using Type II cement. Both decks were constructed under the same control, using the same aggregate, equipment, and crew. Observations of these bridge decks indicate about the same amount and degree of cracking had occurred in both decks at the age of 15 months.

Perhaps one of the more valuable aspects of the research done under fullscale field conditions is that of having reliable "control" sections with which to make comparisons. Control concretes are a necessity in analyzing variables involved in concrete work and the use of them is normal practice in laboratory programs. Inclusion of valid control sections in the field is sometimes difficult to achieve. On both the concrete pavements and the bridge in which shrinkage compensated cement was used (as reported herein) control sections provide an excellent comparison of the cement variable, as placement and curing variables were nearly equal for both the control and "test" sections. Replication can also be effective in field research work.

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Washington, D. C. (1960), Vol. II, pages 3 - 40

TABLE 1

Report of Tests on Cement

Column Number Cement Type Laboratory No.	1 Shrink.Comp. 17709	2 Shrink.Comp. 2101	3 Type II 2681A	4 Shrink.Comp. 19759	5 Type II 20346A
SiO_3, %	20.5	21.2	22.4	21.5	22.5
Al_2O_3, %	5.8	6.3	4.7	5.7	4.5
Fe_2O_3, %	2.5	2.5	3.5	2.5	2.8
CaO, %	63.7	62.8	64.4	62.7	65.0
MgO	0.6	1.0	1.1	2.2	1.7
SO_3	4.16	4.21	2.18	3.60	1.83
Ig. Loss, %	2.3	1.6	1.2	1.4	1.0
Insol. Res. %	0.1	0.3	0.6	0.2	0.21
Na_2O, %	0.06	0.29	0.21	0.17	0.31
K_2O, %	0.13	0.24	0.40	0.39	0.32
Equiv. Na_2O, %	0.15	0.45	0.47	0.43	0.52
C_3A, %	11.2	12.0	6.0	10.9	7.0
Compressive Strength, psi - 3 days	2038		2788	2203	2328
7 days	3110		3870	3153	3145
Surface Area, Blaine CM	3804		3567	3247	3179
Autoclave Expansion, %	10.0		0.01	6.9	+0.07
Initial Set, Gilmore, Hrs:Min.	3:10		4:20	1:55	3:00
Final Set, Hrs:Min.	5:20		6:05	4:50	4:20
Expansion	0.16		0.006	0.027	0.0028
Contraction	0.053		0.039	0.050	0.0382

TABLE 2

Physical Properties of Fresh Concrete

Mix	Slump Ins.	Air %	Unit Wt. Lbs./CF	W/C Lbs./Sk.
For Length Change Specimens*				
5-sack, shrinkage compensated	2.2	2.2	149.0	63.1
7-sack, shrinkage compensated	2.5	1.8	150.1	43.9
For Crack Resistance and Internally Restrained Sulfate Exposure Beams**				
5-1/2-sack, Type II	3.0	1.1	150.1	59.5
5-1/2-sack, shrinkage compensated	2.8	2.2	150.8	55.1
7-sack, Type II	3.8	---	151.7	49.2
7-sack, shrinkage compensated	3.5	---	150.8	45.1
For Freeze-thaw Resistance Specimens*				
5-1/2-sack, shrinkage compensated	1.8	4.6	142.3	48.9
5-1/2 sack, Type II, air-entrained	1.9	4.2	143.1	52.6
For Nonrestrained Sulfate Resistance Specimens**				
5-sack, shrinkage compensated	1.8	1.5	155.9	50.2
5-sack, Type II	1.8	1.2	155.8	51.0
7-sack, shrinkage compensated	1.8	1.4	155.7	38.1
7-sack, Type II	2.0	1.0	156.0	38.8
5-sack, shrinkage compensated, air-entrained	1.5	4.3	152.2	46.5
5-sack, Type II, air-entrained	1.8	3.8	153.6	47.5
For Externally Restrained Sulfate Exposure Beams**				
5-1/2-sack, shrinkage compensated	3.5	1.1	155.6	46.5
7-sack, shrinkage compensated	4.0	1.3	156.1	39.9

* Averages of tests from three mixes
** Averages of tests of two mixes

TABLE 3

Stress in Restrained Shrinkage Beams at Failure

Beam Designation		Failure Total Days Drying	Failure Days in Oven	Calculated Tensile Stress (psi) at Failure
1 - Control	5.5	85	1	283
1 - Shrink. Comp.	5.5	86	1	331
1 - Control	7.0	92	2	362
1 - Shrink. Comp.	7.0	92	2	409
2 - Control	5.5	99	9	374
2 - Shrink. Comp.	5.5	91	1	384
2 - Control	7.0	105	8	453
2 - Shrink. Comp.	7.0	99	2	419

TABLE 4

Disintegration of Beams Subjected to Sulfate Attack

Beam Identification Nonrestrained	11-6-63	5-9-65		4-1-66**		11-1-66		5-25-67		11-17-67	
	Orig. * Wt. Lbs.	Wt. Lbs.	% Wt. Loss	Wt. Lbs.	% Wt. Loss	Wt. Lbs.	% Wt. Loss	Wt. Lbs.	% Wt. Loss	Wt. Lbs.	% Wt. Loss
5.0-AE-Cal 1-2	65.2	64.6	1		3	63.3	3	63.1	3	60.2	8
5.0-AE-Cal 2-2	64.7	64.0	1		3	63.0	3	62.8	3	61.2	5
5.0-AE-Exp 1-2	64.8	58.4	10		50+		***				
5.0-AE-Exp 2-2	63.8	56.0	12		50+		***				
5.0-Cal 1-2	66.2	65.4	1		5	48.1	27		***		
5.0-Cal 2-2	66.0	65.2	1		5	53.2	19	26.8	60		***
5.0-Exp 1-2	66.0	42.5	36		***						
5.0-Exp 2-2	66.0	36.2	45		***						
7.0-Cal 1-2	65.5	65.3	0		2	61.8	6	52.9	19		***
7.0-Cal 2-2	65.6	65.1	1		2	63.1	4	61.4	6	56.7	14
7.0-Exp 1-2	66.3	62.6	6		20		***				
7.0-Exp 2-2	66.5	63.3	5		20	32.4	51		***		

* Weight at end of curing cycle when beam was probably close to saturation
** Estimated percent weight loss
*** Beams removed from test on date indicated

Note: "Cal" designates Type II modified cement conforming to California Standard Specifications
"Exp" designates shrinkage compensated cement
"AE" designates air-entrained concrete

TABLE 5

Disintegration of Restrained Beams Subjected to Sulfate Attack

Beam Identification	Original Weight, Lbs. *	11-1-66 (14 mos.)		5-25-67 (20 mos.)		11-17-67 (26 mos.)	
		Weight Lbs.	Percent Weight Loss	Weight Lbs.	Percent Weight Loss	Weight Lbs.	Percent Weight Loss
	8-24-65						
1 - Exp-5.5	64.1	59.8	7	55.8	13	49.9	22
2	63.1	58.6	7	52.2	17	47.1	25
1 - Exp-IR-5.5	66.9	60.4	10	54.9	18	50.6	24
2	65.8	61.6	6	56.3	14	51.2	22
1 - Exp-7.0	64.2	62.0	3	59.9	7	58.5	9
2	63.1	61.7	2	60.7	4	59.5	6
1 - Exp-IR-7.0	67.2	64.6	4	63.0	6	61.4	9
2	66.3	64.7	2	63.2	5	61.2	8
	10-13-65						
3 - Exp-5.5	65.7	63.9	3	59.2	10	55.7	15
4	65.7	64.8	1	63.5	3	62.1	6
3 - Exp-ER-5.5	73.3	72.7	1	72.9	1	72.5	1
4	74.3	73.6	1	73.8	1	73.5	1
3 - Exp-7.0	65.6	65.0	1	64.8	1	64.2	2
4	65.4	64.7	1	64.4	2	63.6	3
3 - Exp-ER-7.0	72.7	72.1	0	72.4	0	72.0	1
4	72.4	71.9	0	72.2	0	71.8	1

Note: IR = Internally restrained
ER = Externally restrained
Others nonrestrained

*Weight at end of curing cycle when beam was probably close to saturation

TABLE 6

Antelope Freeway Experimental Pavement
(All Plastic Sheet Cured)

Average Crack Interval in Feet, by Unit

Cement	Cement Factor	Air	Unit	Age in Days 7	14	21	28	Age in Months 2	3	5	8	17	40
Type II	6	No	A		122	122	122	64	42	42	42	38	27
Shrink. Comp.	6	No	B		175	175	175	69	40	40	40	30	24
" "	6-1/2	"	C		216	180	180	78	33	28	28	21	19
" "	6	AE	D		161	138	138	49	34	26	26	23	17
" "	6-1/2	AE	E		169	169	169	46	30	24	24	20	15
Type II	6	AE	F		93	93	93	49	26	24	24	21	16

Average Crack Interval in Feet, by Mix Category

Category	7	14	21	28	2	3	5	8	17	40
Type II Cement, A & F		107	107	107	56	34	33	33	30	20
Shrink. Comp. Cement, B,C,D, & E		180	166	166	60	34	29	29	24	18
Non air-entrained, A, B, & C		171	159	159	70	38	36	36	30	23
Air-entrained D, E, & F		141	133	133	48	30	25	25	22	16
Combined all		156	146	146	59	34	31	31	26	19

TABLE 7

Lodi Freeway Experimental Pavement

Average Crack Interval in Feet, by Unit

Cure	Type Cement	Cement Factor	Air	Unit	Approximate Age: Days 10	Days 14	Days 28	Days 42	Months 6	Months 11	Months 15	Months 21	Months 37
Plastic	Type II	5-1/2	No	A	123	90	71	71	71	71	59	37	27
	Shrink. Comp.	6	No	B	130	93	62	62	54	54	48	30	18
Wet Earth	Shrink. Comp.	6	No	C	300	86	75	75	67	63	57	39	24
	" "	6	Yes	D	240	109	67	63	57	52	32	30	16
Plastic	Shrink. Comp.	6	Yes	E	125	96	83	69	59	54	30	21	14
	Type II	5-1/2	Yes	F	101	82	73	69	57	52	24	21	13

Average Crack Interval in Feet, by Mix Category

Category	Days 10	Days 14	Days 28	Days 42	Months 6	Months 11	Months 15	Months 21	Months 37
Type II Cement - A,F	112	86	72	70	64	62	42	29	18
Shrinkage Compensated Cement, B,C,D,E	199	96	72	67	59	56	42	30	17
Nonair-entrained, A,B,C	184	90	71	71	64	63	55	35	22
Air-entrained, D,E,F	155	96	74	67	58	53	29	24	14
Combined All	170	93	72	68	61	58	42	30	17
Plastic cured, shrinkage compensated, B,E	128	95	73	66	57	54	39	26	16
Earth cured, shrinkage compensated, C,D	270	98	71	69	62	58	45	35	19

Figure 1

EXPANSION AND SHRINKAGE OF SHRINKAGE COMPENSATED CEMENT CONCRETE

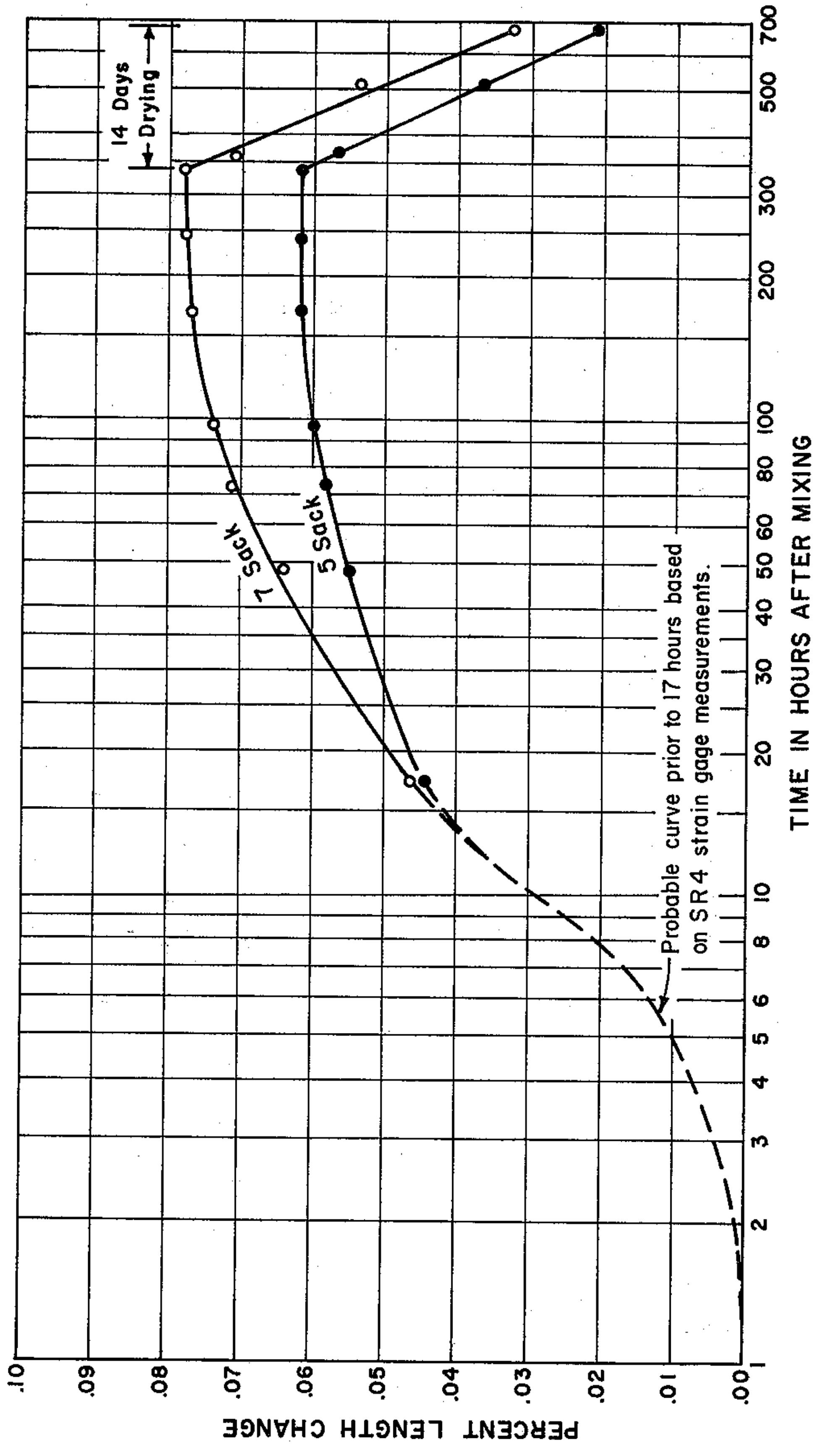
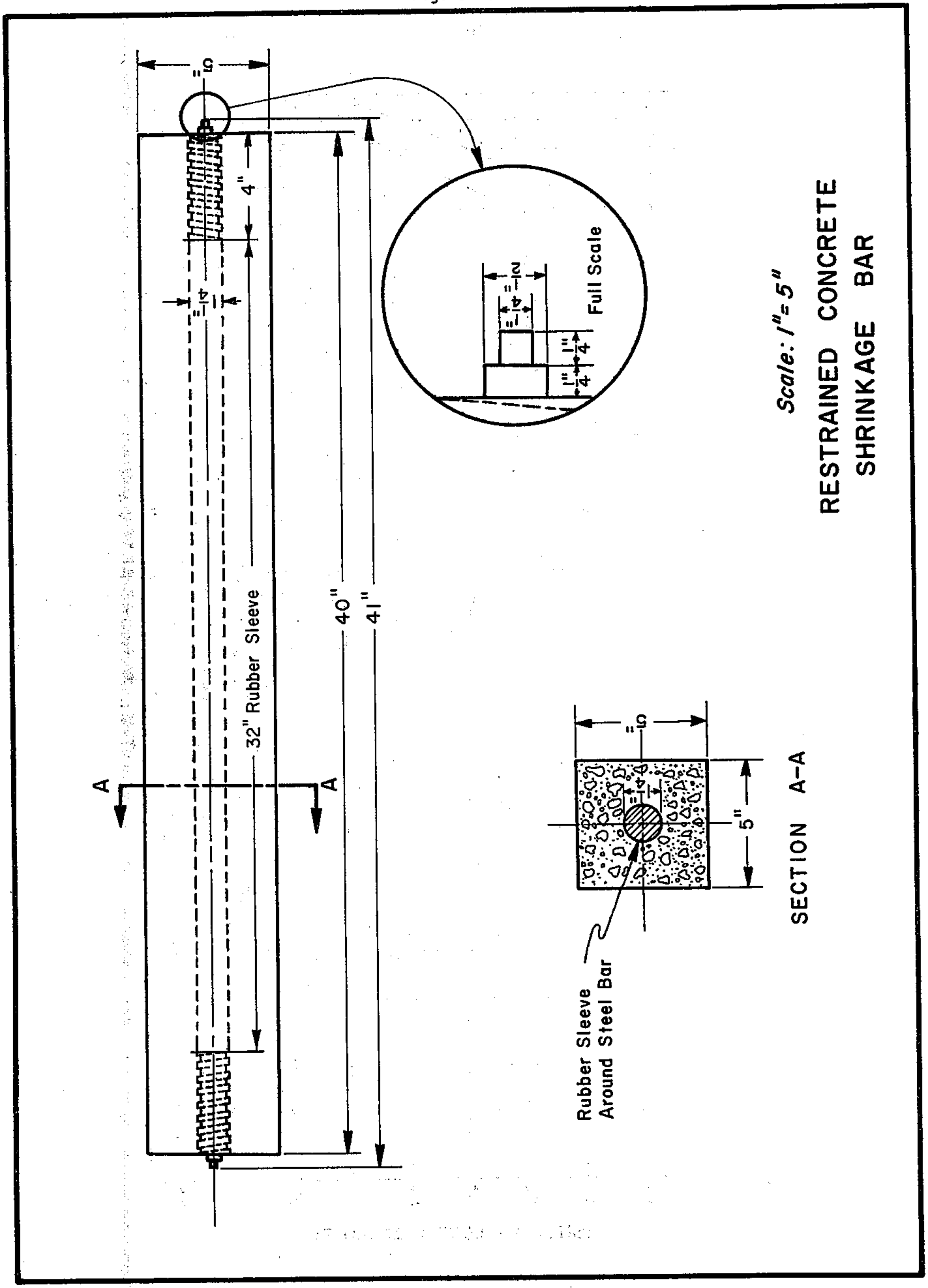


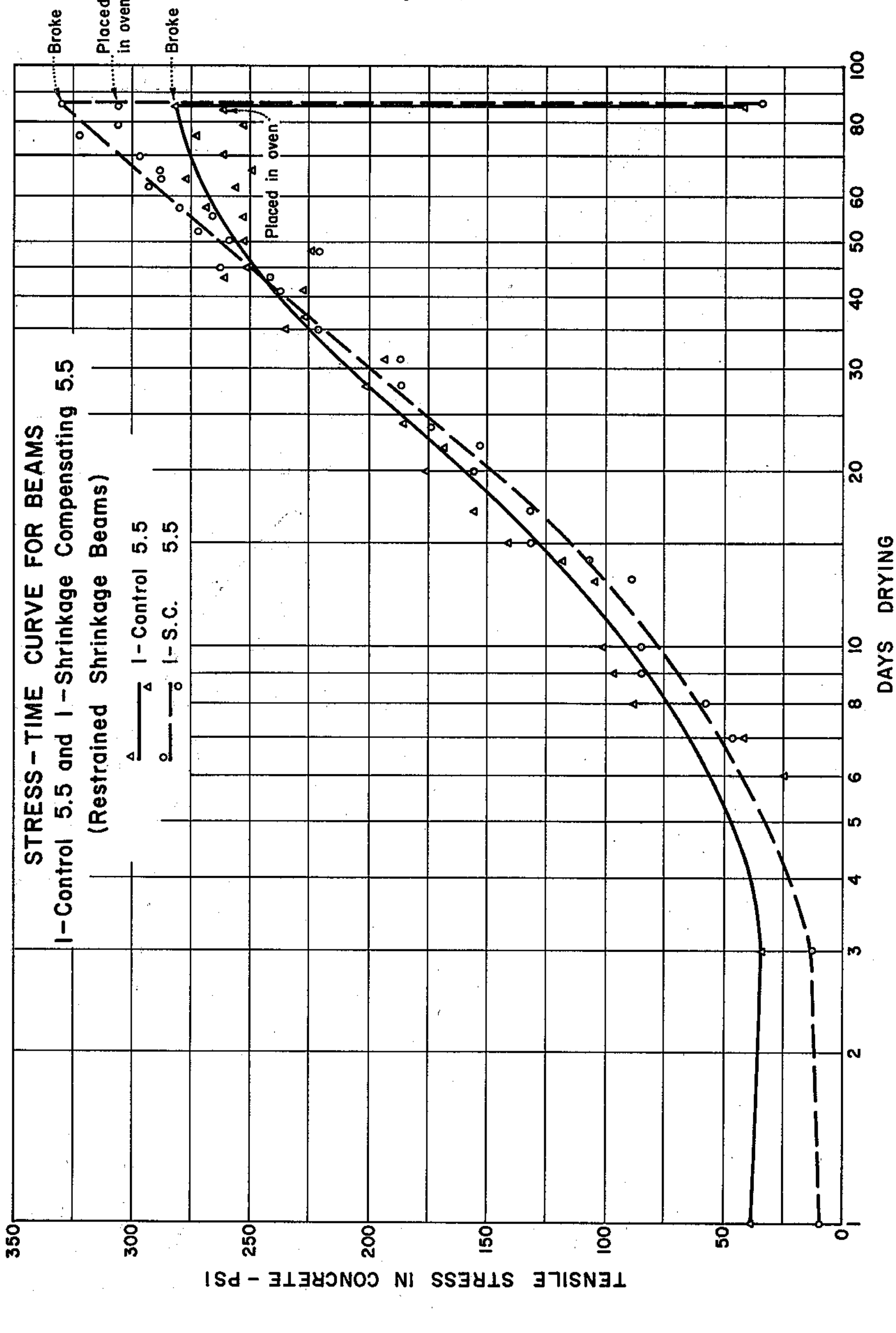
Figure 2



RESTRAINED CONCRETE SHRINKAGE BAR

Scale: 1" = 5"

Figure 3



STRESS-TIME CURVE FOR BEAMS
I-Control 5.5 and I-Shrinkage Compensating 5.5
(Restrained Shrinkage Beams)
I-Control 5.5
I-S.C. 5.5
Broke
Placed in oven
Broke
Placed in oven
TENSILE STRESS IN CONCRETE - PSI
DAYS DRYING
350
300
250
200
150
100
50
0
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100

Figure 4

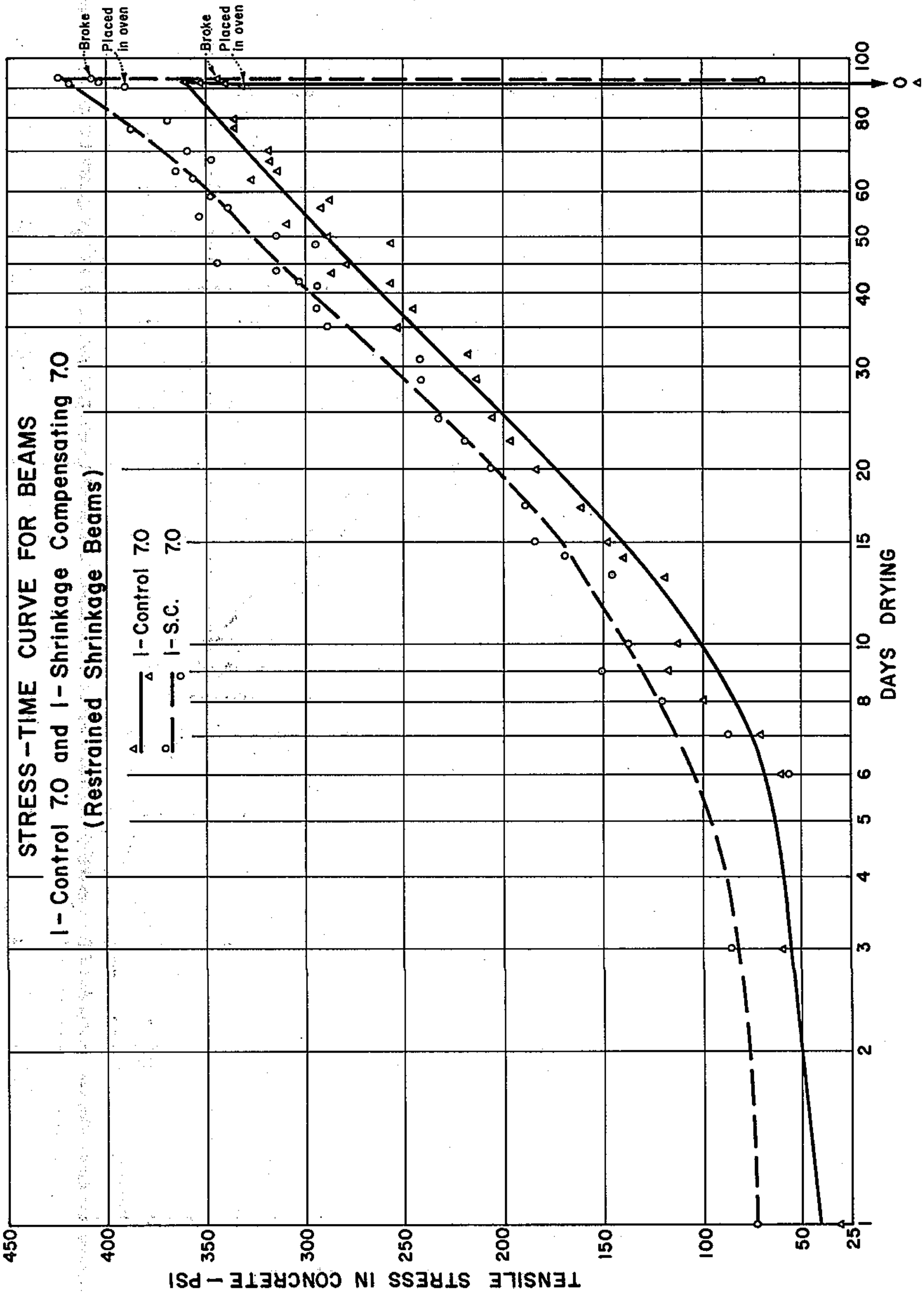
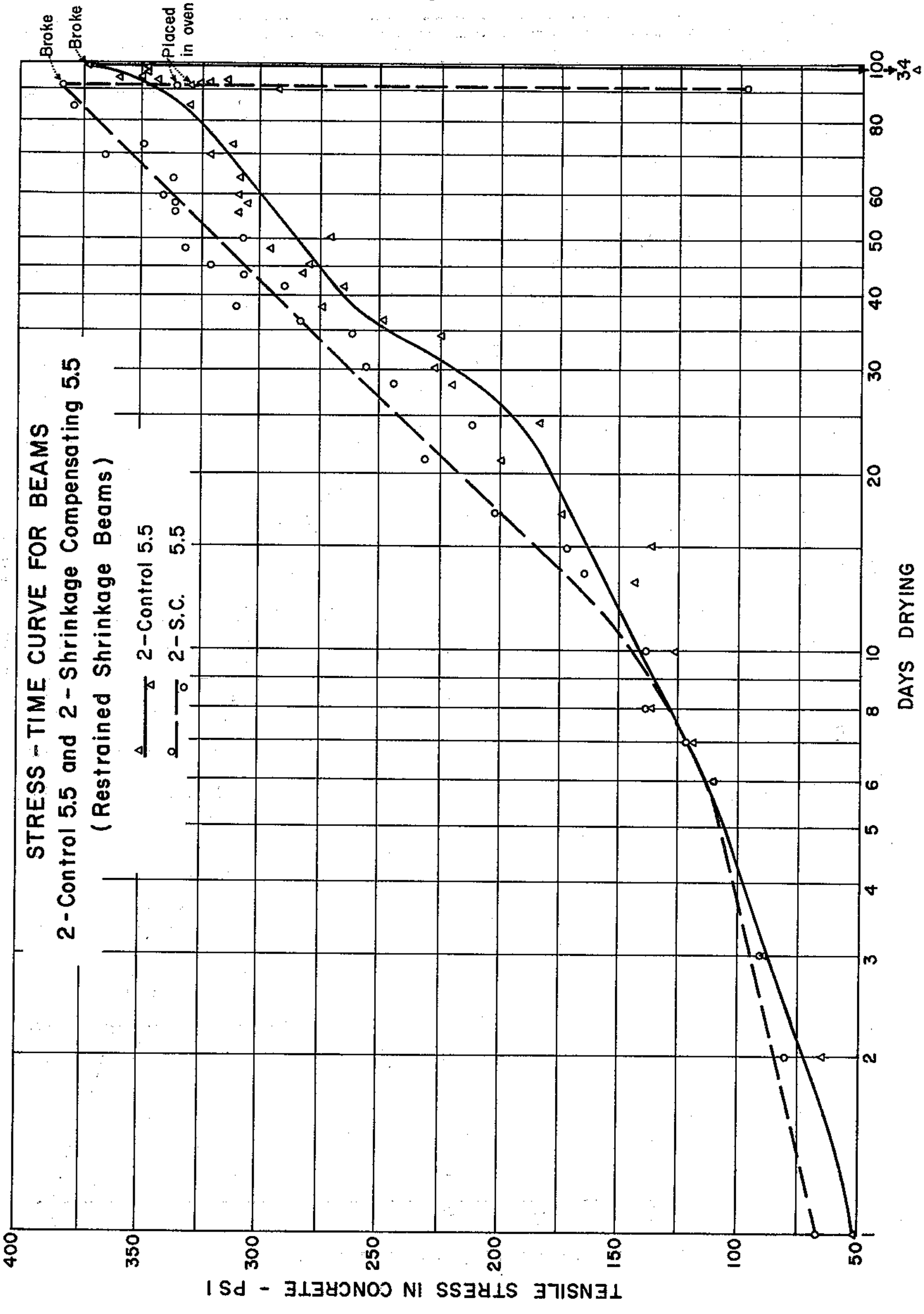
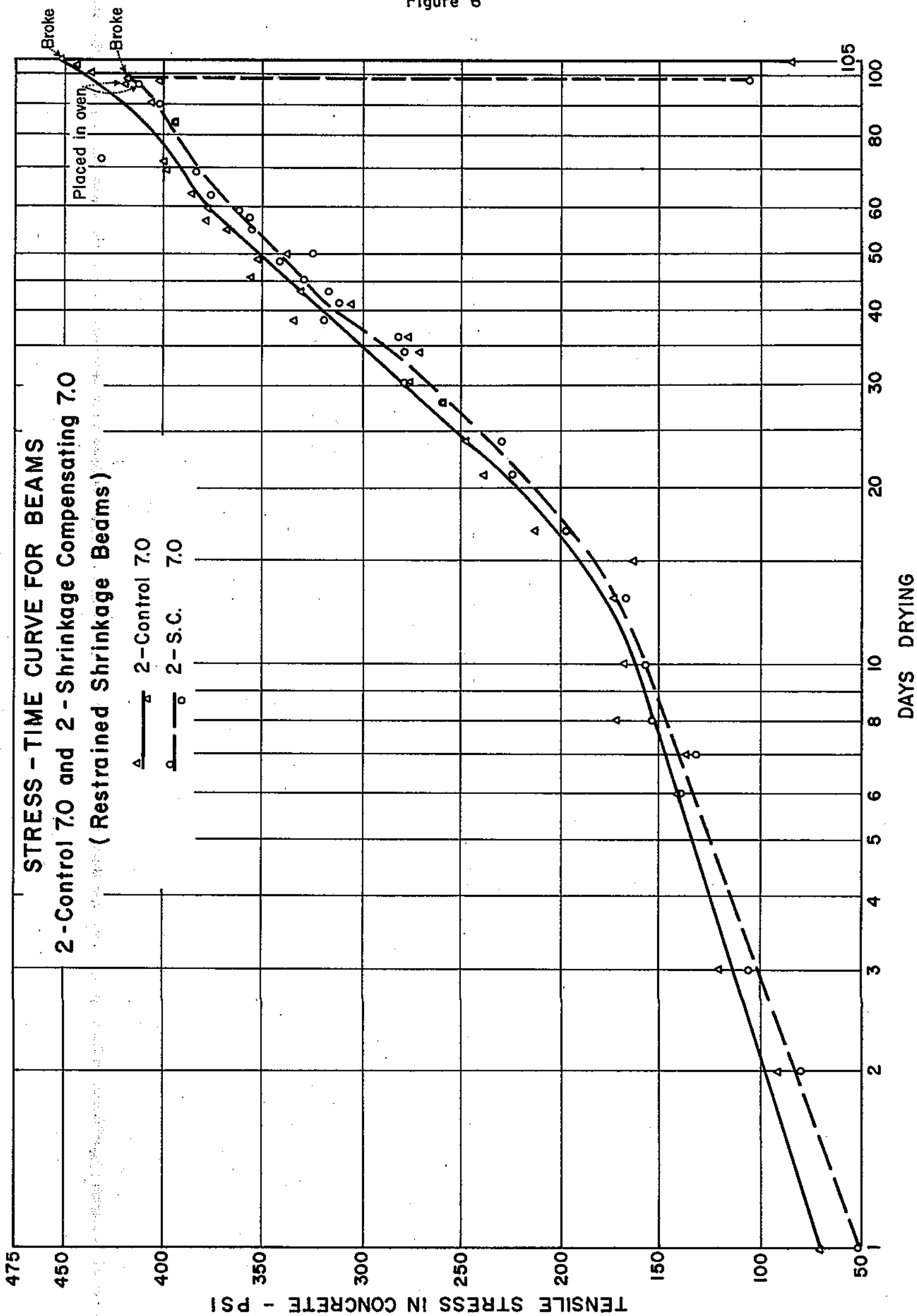

STRESS-TIME CURVE FOR BEAMS
I-Control 7.0 and I-Shrinkage Compensating 7.0
(Restrained Shrinkage Beams)
I-Control 7.0
I-S.C. 7.0
Broke
Placed in oven
Broke
Placed in oven
TENSILE STRESS IN CONCRETE – PSI
450
400
350
300
250
200
150
100
50
25
DAYS DRYING
1
2
3
4
5
6
8
10
15
20
30
40
50
60
80
100

Figure 5



STRESS - TIME CURVE FOR BEAMS
2-Control 5.5 and 2-Shrinkage Compensating 5.5
(Restrained Shrinkage Beams)
2-Control 5.5
2-S.C. 5.5
Broke
Broke
Placed in oven
TENSILE STRESS IN CONCRETE - PSI
DAYS DRYING
400
350
300
250
200
150
100
50
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
34

Figure 6



STRESS - TIME CURVE FOR BEAMS
2 - Control 7.0 and 2 - Shrinkage Compensating 7.0
(Restrained Shrinkage Beams)
2 - Control 7.0
2 - S.C. 7.0
Broke
Broke
Placed in oven
TENSILE STRESS IN CONCRETE - PSI
DAYS DRYING
475
450
400
350
300
250
200
150
100
50
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
105

Figure 7. 5-sack concrete at 6 months exposure. Type II cement left, shrinkage compensated cement right.

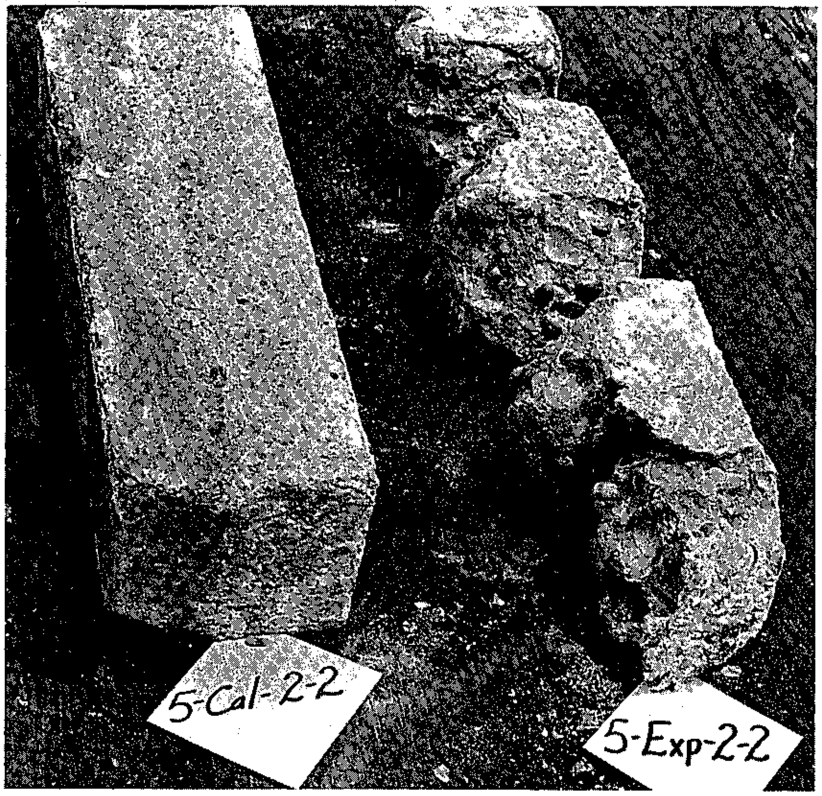


Figure 8. 5-sack mix from Round 2 at 18 months exposure. Type II cement left, shrinkage compensated cement right. Shrinkage compensated cement beams removed from study.

Figure 9. 5-sack, nonair-entrained shrinkage compensated cement concrete beam before removal after 18 months exposure. (Note disintegration of lower portion of beam.)

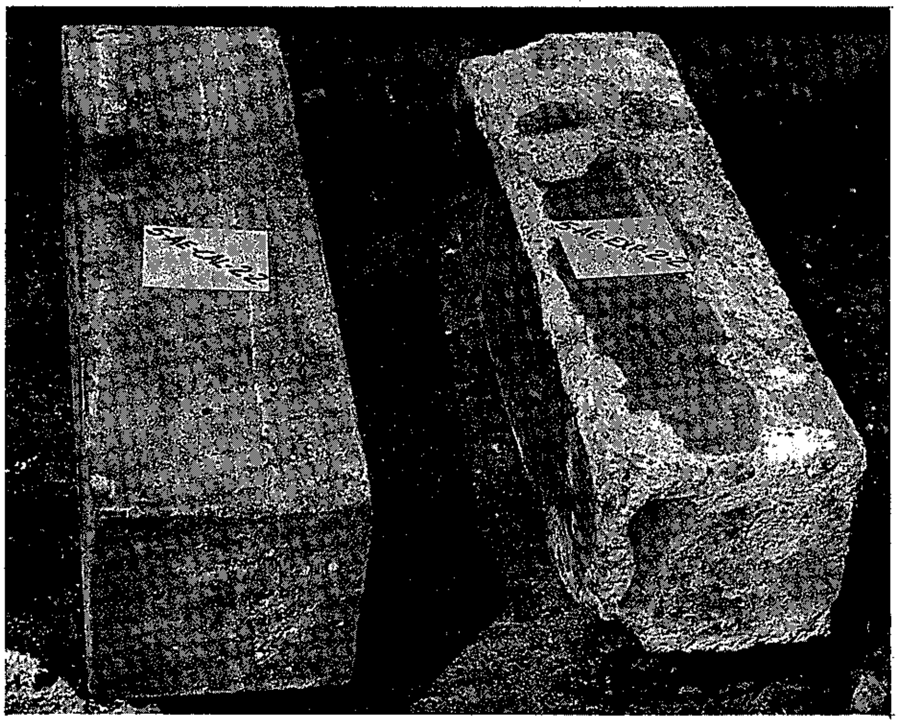


Figure 10. 5-sack, air-entrained concrete at 6 months sulfate exposure. Type II cement left; shrinkage compensated cement right.

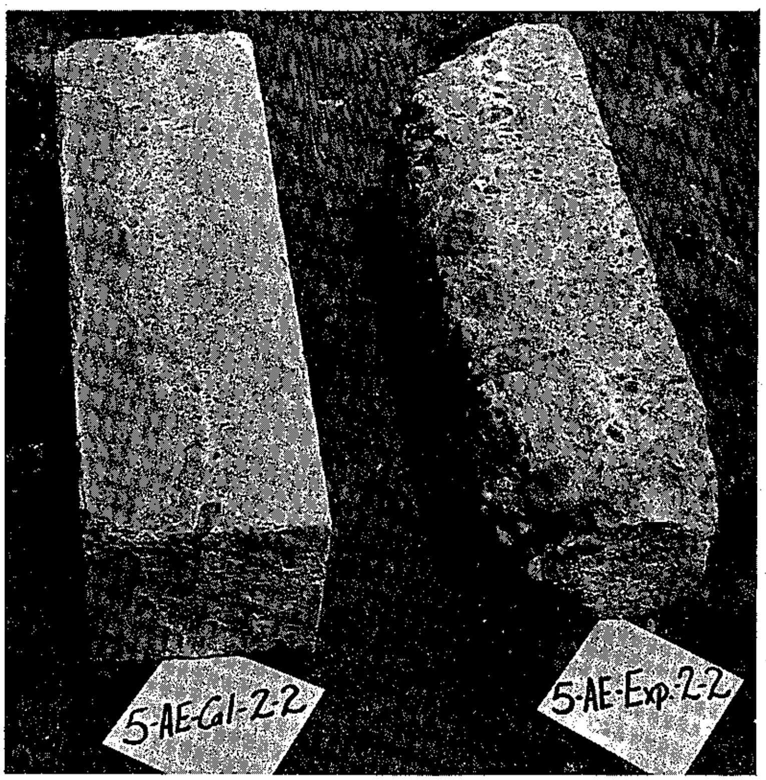


Figure 11. 5-sack, air-entrained concrete at 18 months sulfate exposure. Type II cement left; shrinkage compensated cement right.

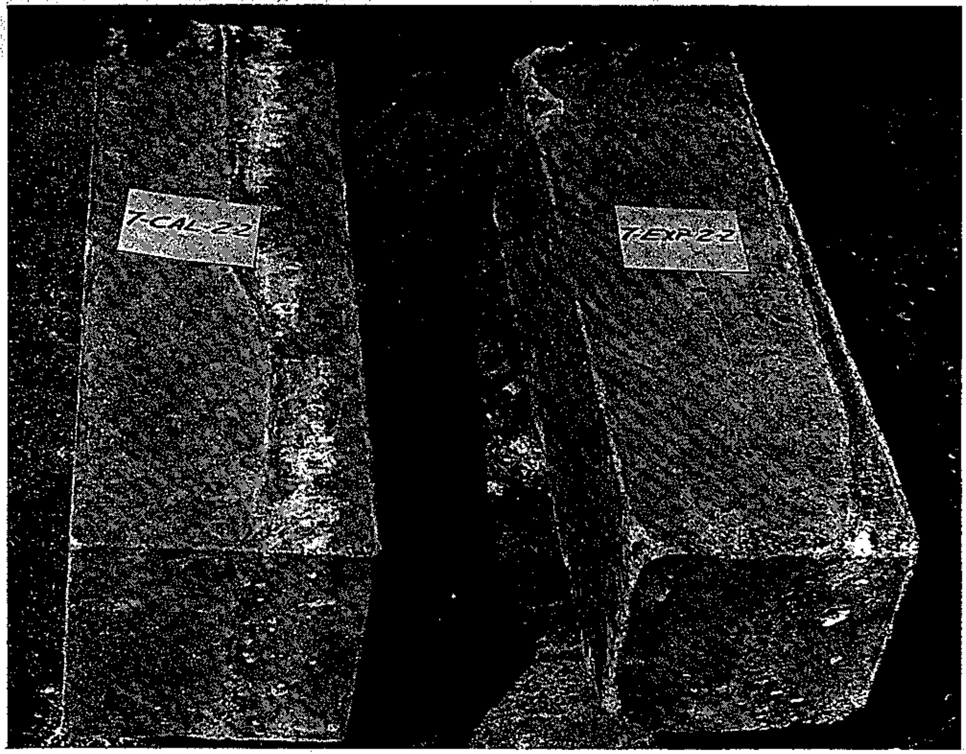


Figure 12. 7-sack concrete after 6 months exposure. Type II cement left; shrinkage compensated cement right.

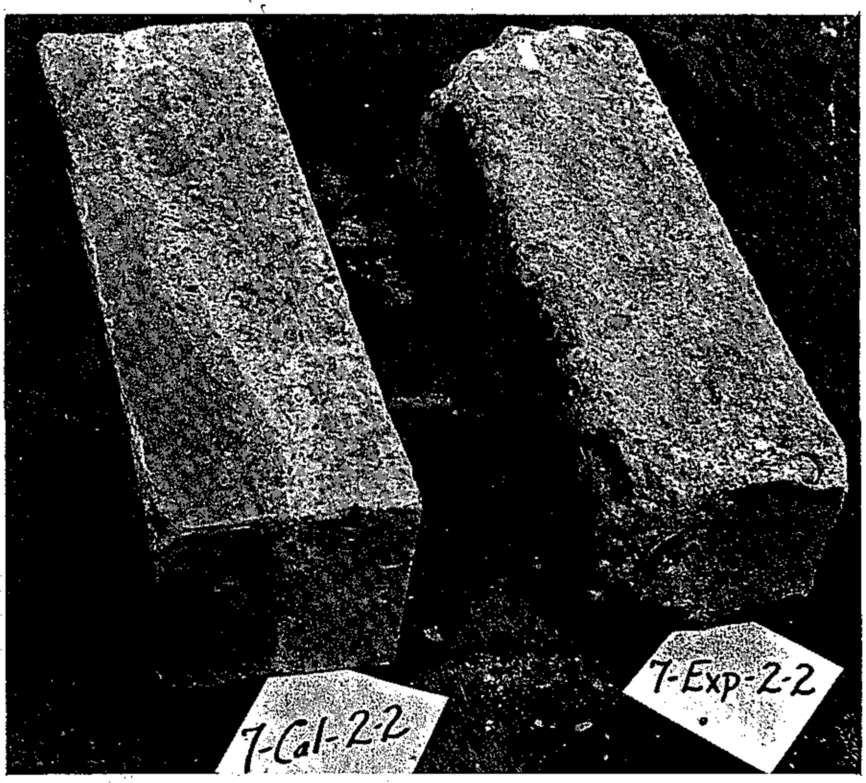


Figure 13. 7-sack concrete after 18 months exposure. Type II cement left; shrinkage compensated cement right

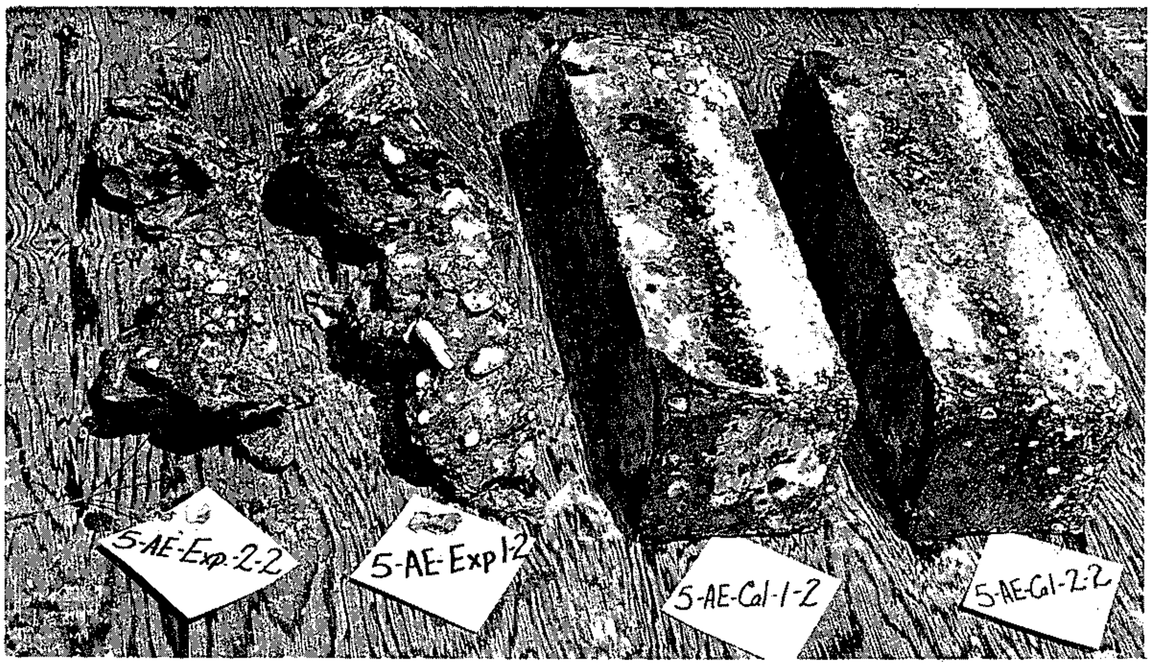


Figure 14. 5-sack, air-entrained concrete at 30 months sulfate exposure. Shrinkage compensated cement left; Type II cement right. Shrinkage compensated cement concrete removed from test.

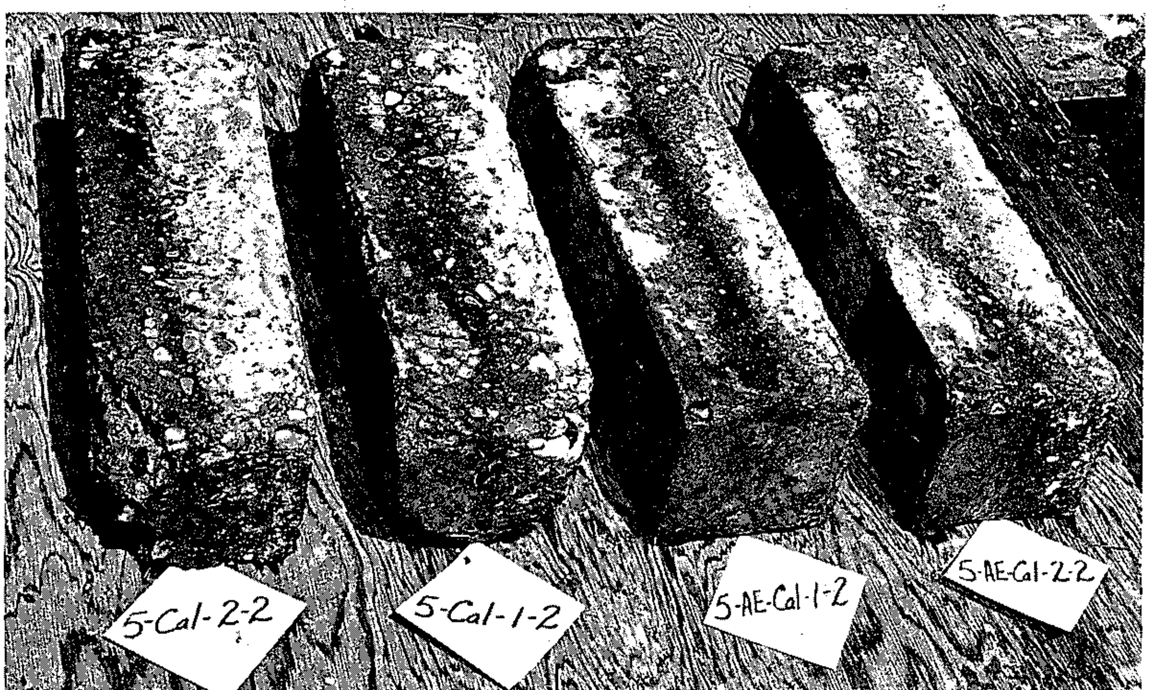


Figure 15. 5-sack concrete after 30 months sulfate exposure. All four beams are from Type II cement. The beams on the left are nonair-entrained, and the beams on the right are air-entrained.

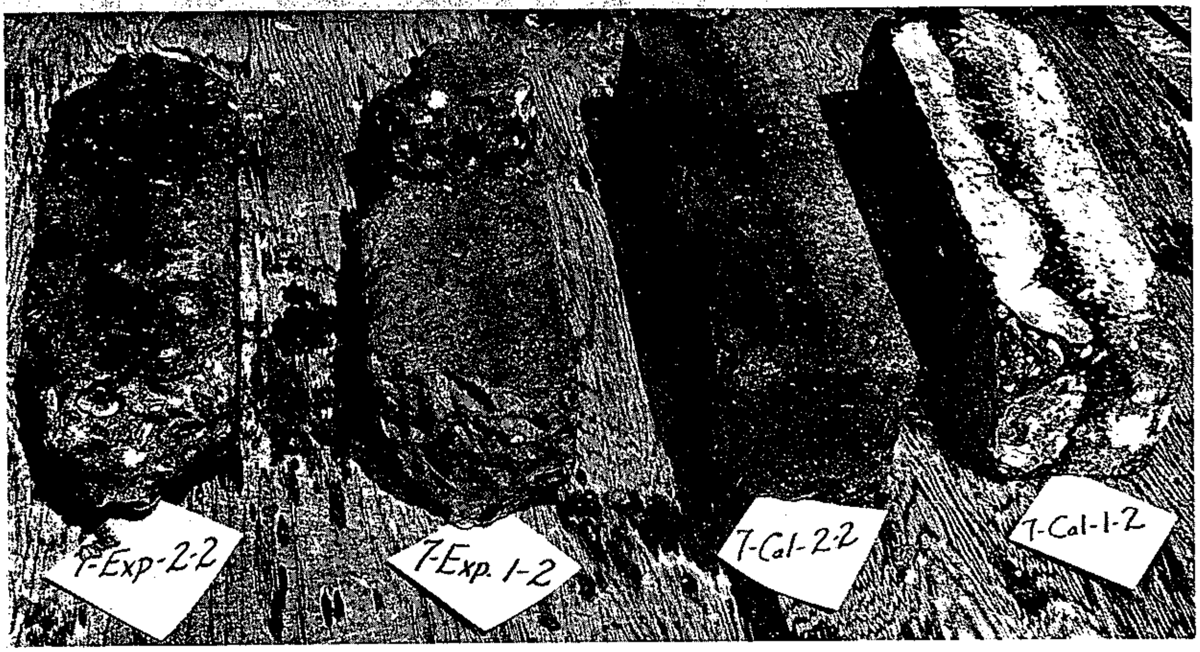


Figure 16. 7-sack concrete after 30 months sulfate exposure. Shrinkage compensated cement beams on left; Type II cement beams on right.

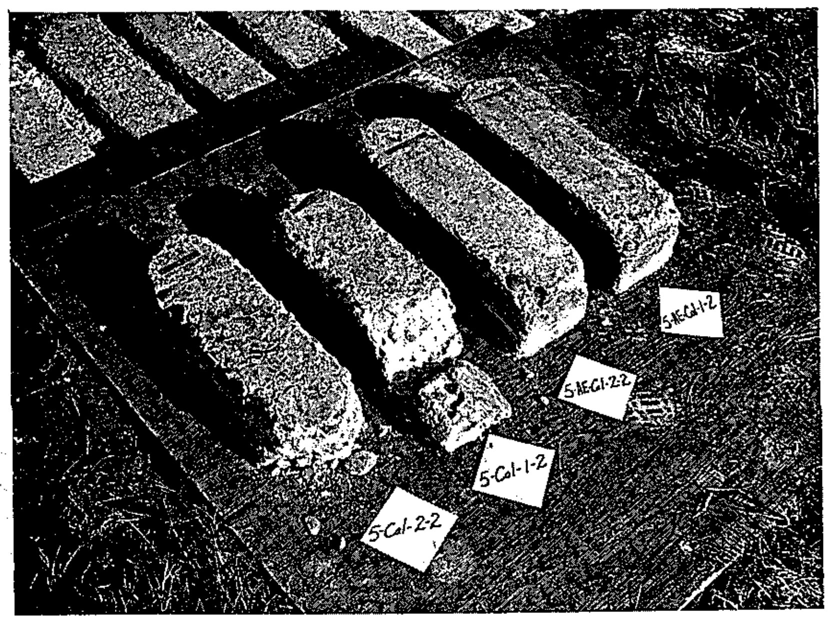


Figure 17. 5-sack, Type II cement concrete after 36 months of sulfate exposure. Nonair-entrained concrete on left and air-entrained concrete on right.

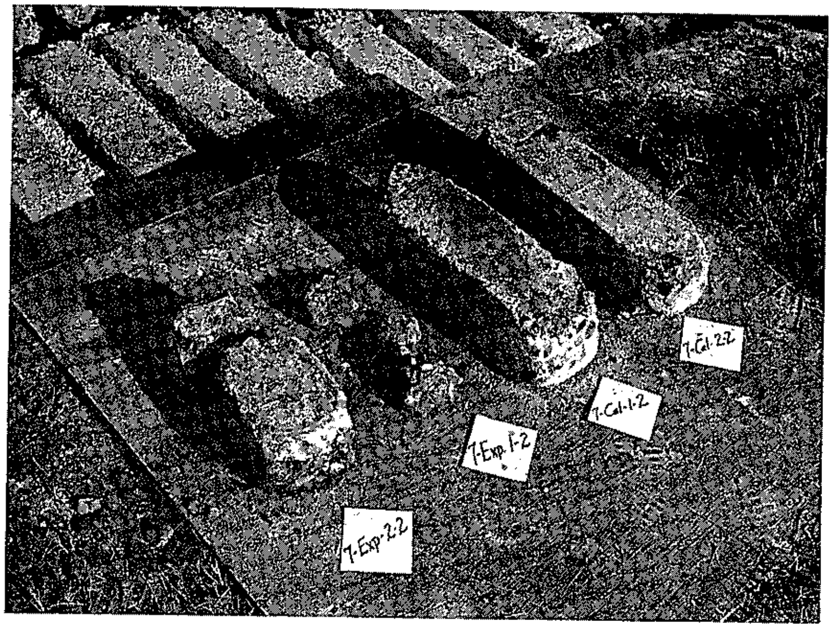


Figure 18. 7-sack concrete after 36 months of sulfate exposure. Shrinkage compensated cement beams on left and Type II cement beams on right. Specimen 7-Exp-1-2 removed from test.

Figure 19. 5-sack, Type II cement concrete specimen after 42 months of sulfate exposure. Both 5-sack, nonair-entrained, Type II cement beams removed from study.

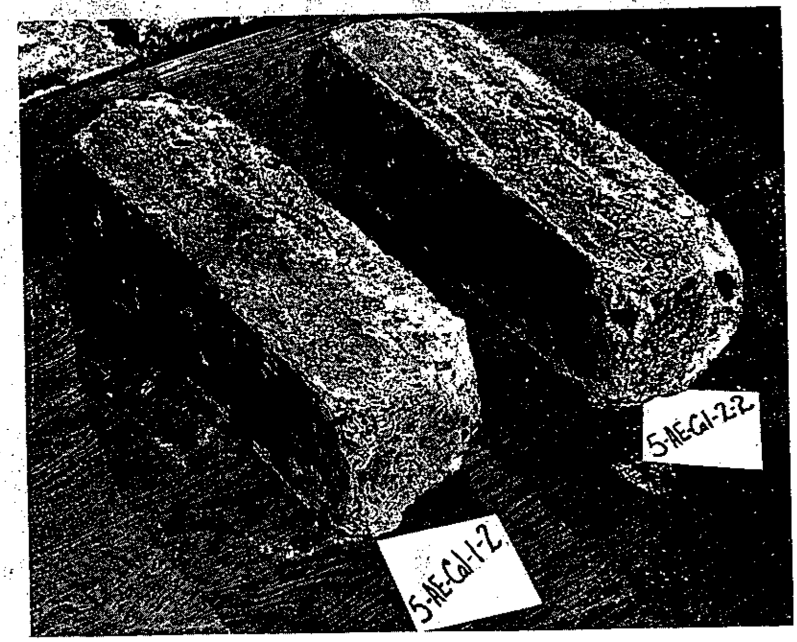


Figure 20. 5-sack, air-entrained, Type II cement concrete beams after 42 months of sulfate exposure.

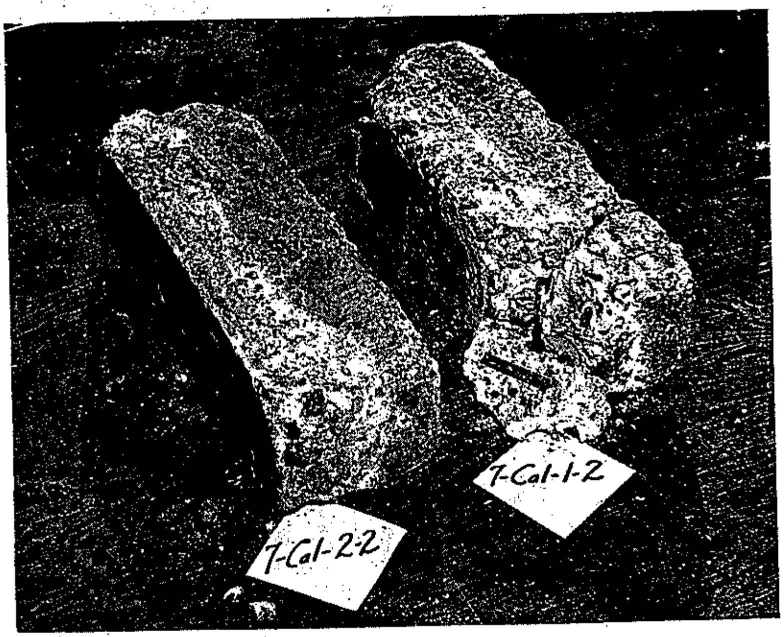


Figure 21. 7-sack, Type II cement concrete beam after 42 months sulfate exposure. 7-sack shrinkage compensated cement beam was reduced to rubble and was removed from test at 42 months exposure.

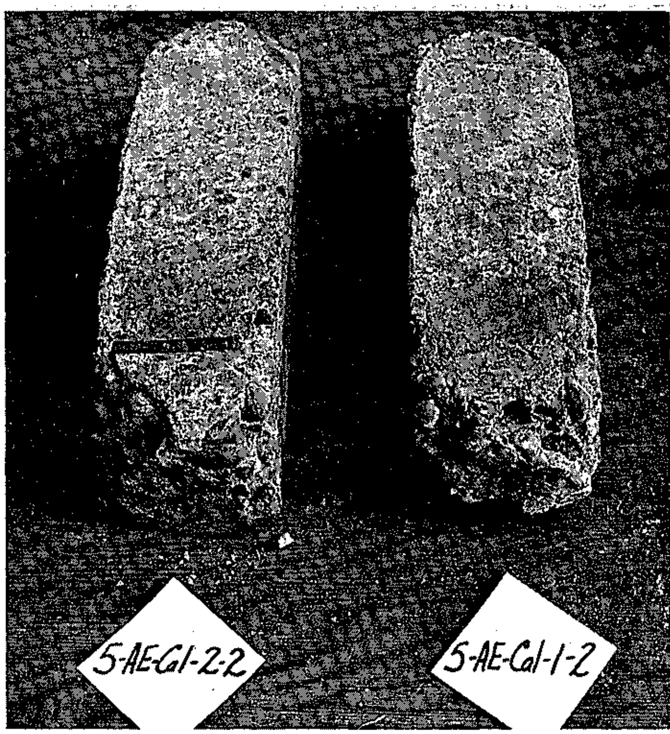


Figure 22. 5-sack, air-entrained, Type II cement concrete beams after 48 months sulfate exposure.

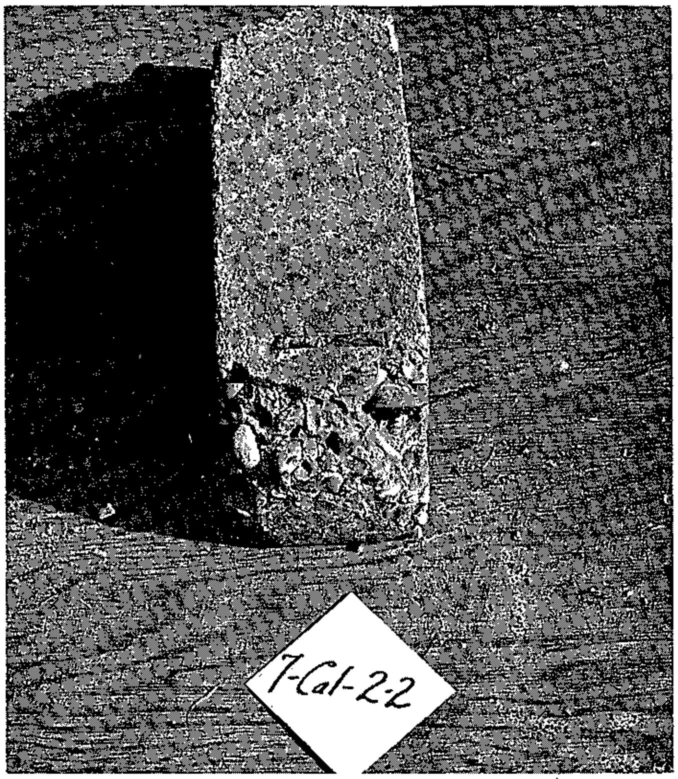
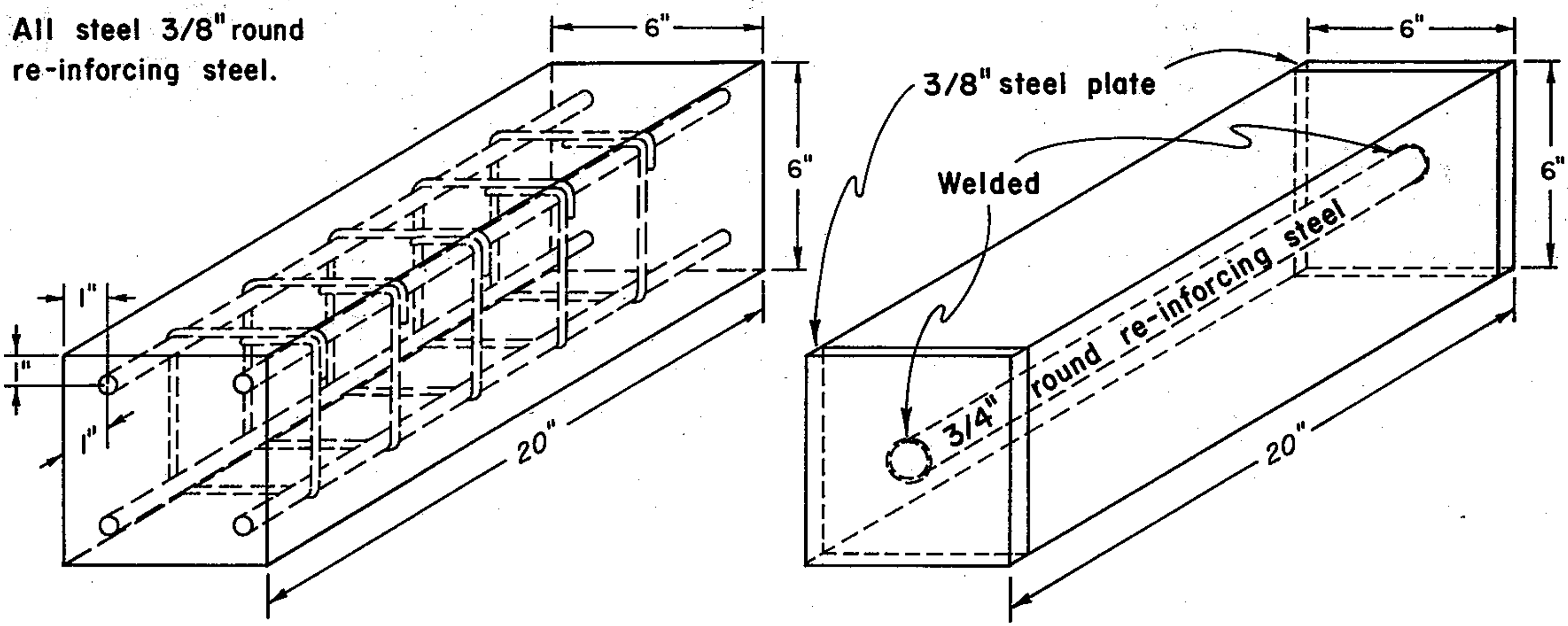


Figure 23. 7-sack, Type II cement concrete beam after 48 months sulfate exposure. The companion beam, 7-Cal-1-2, was reduced to rubble and removed from the test.

Figure 24

SKETCH OF RESTRAINED SULFATE EXPOSURE BEAMS



INTERNALLY RESTRAINED

EXTERNALLY RESTRAINED

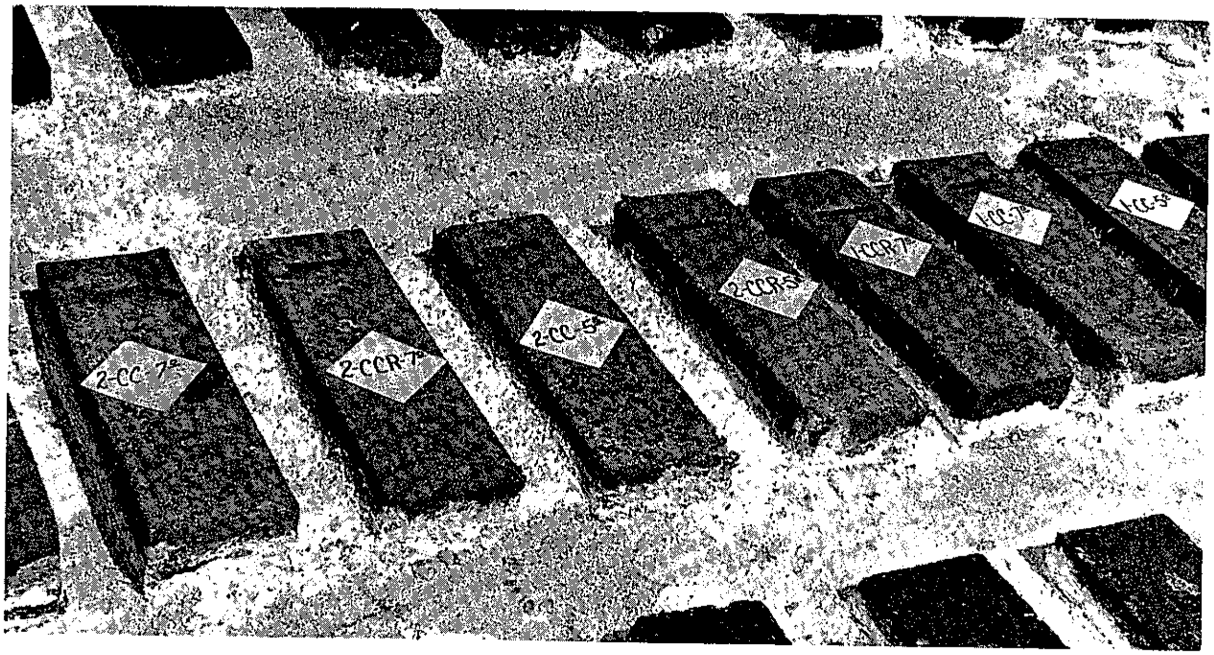


Figure 25. Concrete beams made with shrinkage compensated cement after 8 months sulfate exposure. Beams with "R" at end of designation are internally restrained. Note corners of beams where degradation has started.

Figure 26. Concrete beams made with shrinkage compensated cement after 8 months sulfate exposure. Beams with "R" at end of designation are externally restrained. Note corners of unrestrained specimens.

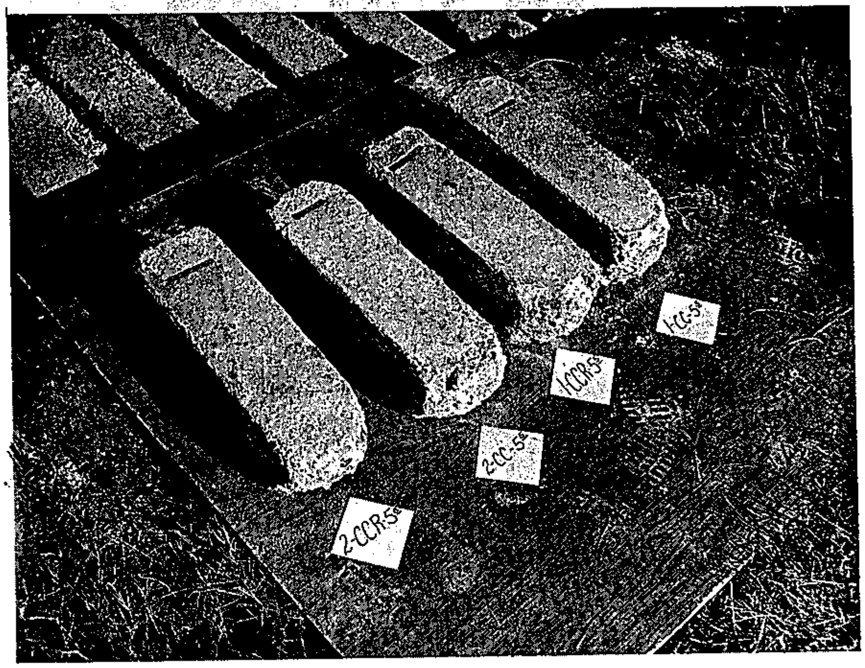


Figure 27. 5.5-sack shrinkage compensated cement beams after 14 months sulfate exposure. Beams with "R" in the identification are internally reinforced.

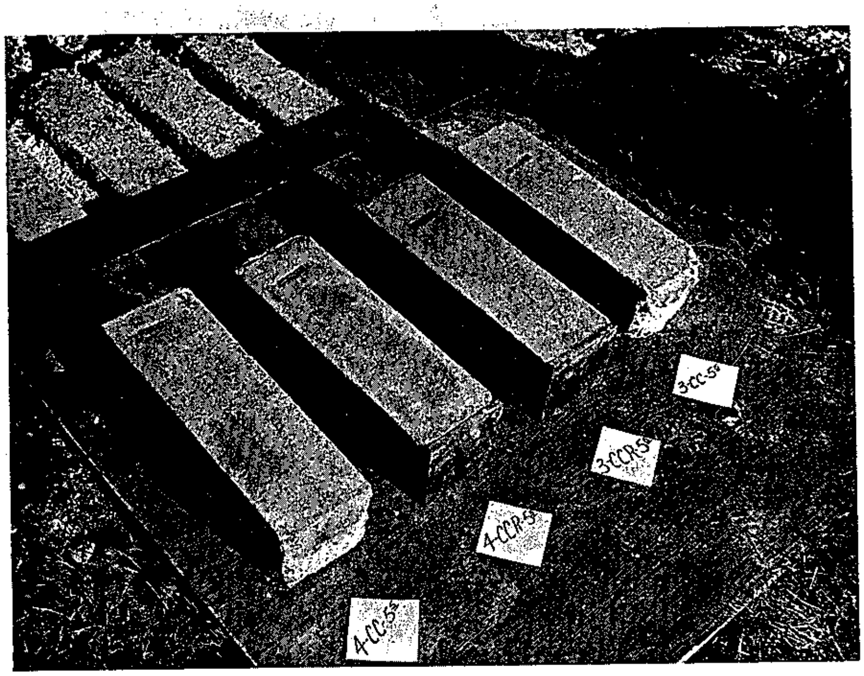


Figure 28. 5.5-sack shrinkage compensated cement concrete beams after 14 months sulfate exposure. Middle two beams are externally restrained.

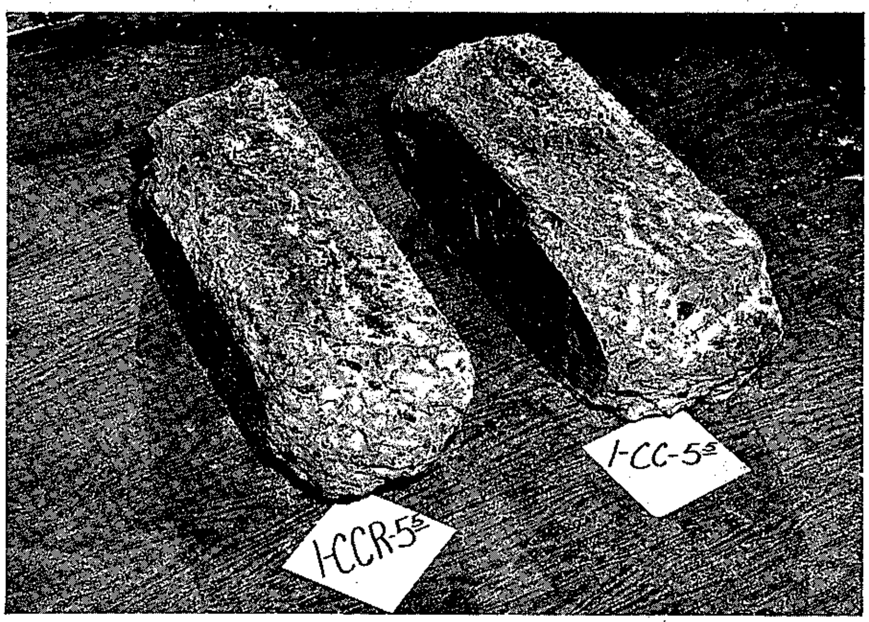


Figure 29. 5-1/2-sack shrinkage compensated cement beams after 20 months sulfate exposure. Beam on left is internally reinforced.

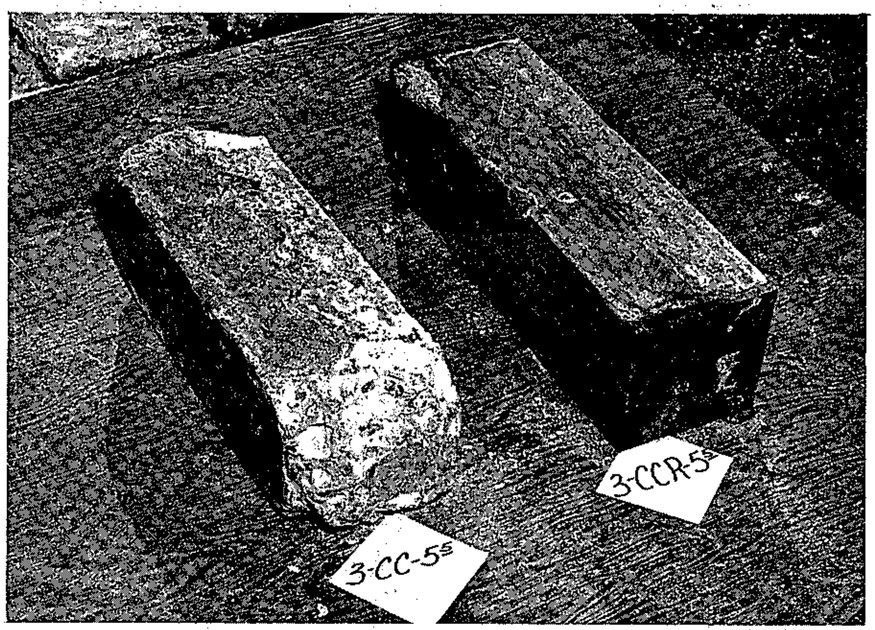


Figure 30. 5-1/2-sack shrinkage compensated cement beams after 20 months sulfate exposure. Beam on right is externally restrained.

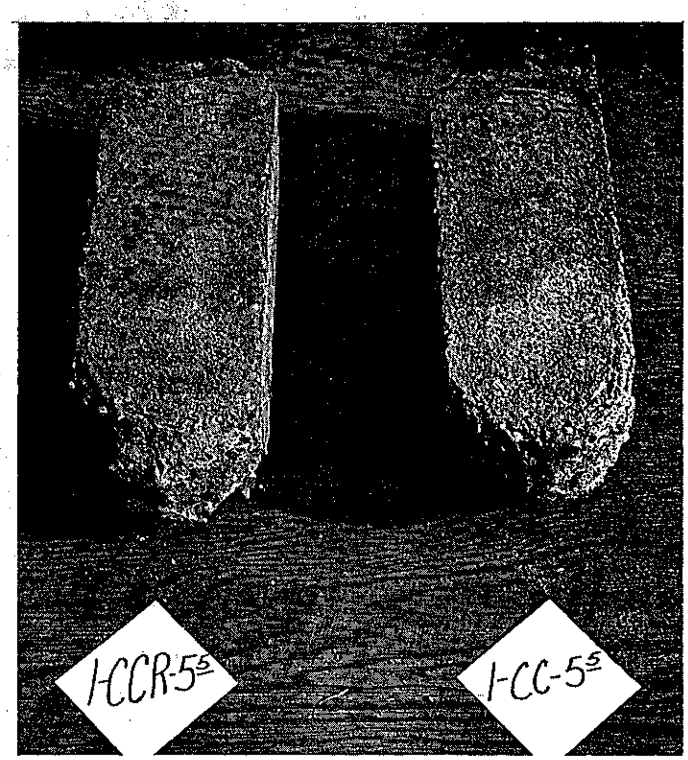


Figure 31. 5-1/2-sack shrinkage compensated cement concrete beams after 26 months sulfate exposure. Beam on left is internally reinforced.

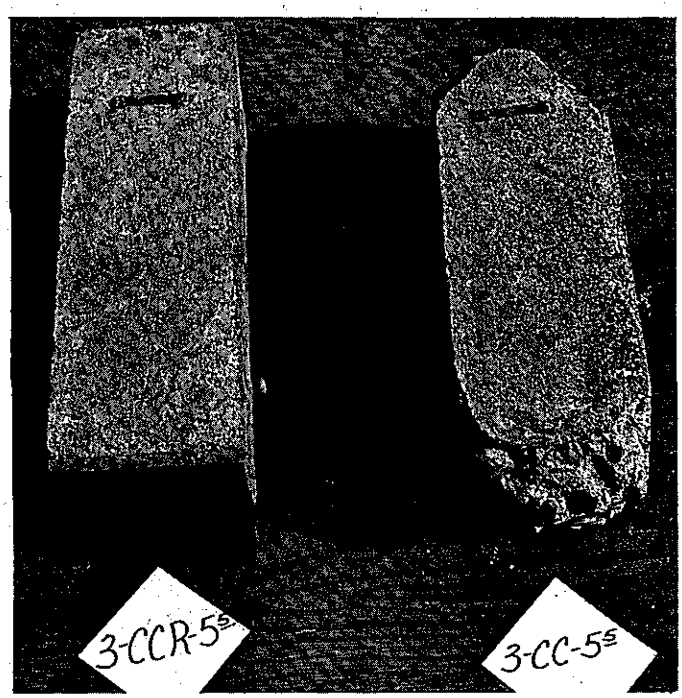


Figure 32. 5-1/2-sack shrinkage compensated cement concrete beams after 26 months sulfate exposure. Beam on left is externally restrained.