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JOINT HIGHWAY RESEARCH PROJECT

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EXPANSIVE (SELF-STRESSING)
CEMENTS: IN REINFORCED
CONCRETE

Hanume Gowda

PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

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Interim Report

EXPANSIVE (SELF-STRESSING) CEMENTS: IN REINFORCED CONCRETE

TO: J. F. McLaughlin, Director August 3, 1976
Joint Highway Research Project
Project: C-36-58D
FROM: H. L. Michael, Associate Director
Joint Highway Research Project File: 5-13-4

The attached is an Interim Report on the HPR Part II Research Study titled "Expansive (Self-stressing) Cements: In Reinforced Concrete". This report was prepared by Mr. H. Gowda under the direction of the co-principal investigators Professors C. F. Scholer and E. C. Ting.

This report describes the work conducted to develop a satisfactory and reliable expansive cement, a cement where expansion was reproducible in the laboratory conditions. The report also describes the evaluation of the concrete and the structural behavior of self-stressed concrete members.

Self-stressing expansive cements are not recommended for immediate use since many questions remain concerning their long term performance and applicability in field situations. Nevertheless, the indicated 20% reduction in steel, based upon equal deflections, holds promise of economics if otherwise feasible.

The report is submitted for approval. Copies of the Report will also be submitted to ISHC and FHWA for review, comment and acceptance as partial fulfillment of the objectives of the Study. A final report will be submitted at a later date.

Respectfully submitted,

Harold L. Michael

Harold L. Michael
Associate Director

HLM:ss

Attachment

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Interim Report
EXPANSIVE (SELF-STRESSING) CEMENTS:
IN REINFORCED CONCRETE

by

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Project No.: C-36-58D

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The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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EXPANSIVE (SELF STRESSING) CEMENTS: IN REINFORCED CONCRETE

HIGHLIGHT SUMMARY

The objectives of this investigation were to gain a better understanding of the behavior of self-stressing reinforced concrete structures and to determine the economic savings possible with the effective use of expansive cement under practical construction conditions. This report is primarily concerned with the first of the above objectives although potential economic savings in beams is briefly discussed.

This report describes the evaluation of expansive cements by means of free expansion of mortar bars, effects of longitudinal as well as lateral restraints on self-stress development and mechanical properties, effects of eccentric restraints, and effects of different curing conditions. It also describes the structural behavior of self-stressed concrete members and the determination of economic savings possible with the effective use of expansive cement under practical construction conditions.

The length change measurements of mortar bars were made in a length comparator. The expansive cement evaluated was a blend of portland cement, calcium aluminate cement, and gypsum. The calcium aluminate cement contents were varied from 10 to 25 percent and the gypsum contents were in the range of 10 to 20 percent. Two expansive cements, giving a medium and a high amount of expansion were selected for the remainder of this investigation.

The self-stress development, longitudinal expansion, and lateral expansion measurements were made on 3 x 3 x 11 inch beams. Four different percentages of unbonded longitudinal steels were used. The studies were made on uniaxially restrained specimens, triaxially restrained specimens (with two different percentages of lateral steel and eccentrically restrained specimens). Water curing was used and measurements were made at a regular interval of time. Study was also made to find the effect of different curing procedure in triaxially restrained beams with 0.56 percentage of lateral steel. In this case the beams were placed in a hot water bath at 80°C for six hours and then water cured.

The 6 x 12 inch cylinders were used to study the mechanical properties of triaxially restrained self-stressed concrete. Five different percentages of longitudinal steel were used. The lateral steel percentages of 0.56 in the form of spirals were used in all the cylinders. The triaxially restrained and free expansion cylinders were tested in compression at the age of 28 days.

The structural behavior of self-stressed concrete was studied by using 3 x 4 x 24 inch beams. Beams were tested in flexure using a third point loading. For comparison purposes, the ordinary reinforced concrete beams were also tested. Using the equal deflection criteria, the savings in steel of self-stressed concrete compared to conventional reinforced concrete beams was calculated.

Results of the free expansion studies indicate that for any given gypsum content, the rate of expansion was increased as the calcium aluminate cement was increased. Even though the rate increased, the ultimate expansion decreased as the calcium aluminate cement was increased. In triaxially restrained specimens the self-stress development was increased as the degree of lateral steel was increased in addition to preventing the longitudinal cracks which were observed in a uniaxially restrained specimen. It is possible to achieve different magnitudes of self-stress at the top and the bottom of the beam by placing the longitudinal steel eccentrically. The less self-stress development was measured for the 80°C water curing procedure. The compression test results indicate a significant improvement in mechanical properties of the triaxially restrained specimen compared to the free expansion specimen. The structural behavior of self-stressed concrete beam was similar to the ordinary reinforced concrete beams except less deflection and fewer cracks occurred in the self-stressed concrete beams. A significant reduction in the total quantity of reinforcing steel of about 20 percent was found possible based upon equal deflection criteria. This 20 percent reduction could have significant economic benefits.

CHAPTER I

INTRODUCTION

Statement of the Problem

Self-stressing cements have long been recognized as materials which might be beneficial for some reinforced concrete structures. It is a well known fact that self-stressing can be achieved if the cements have the potential of producing large expansions and if the concretes are restrained properly by steel reinforcement. Such a combination can produce compressive stresses in the concrete and high tensile stresses in the steel.

Unrestrained expansion of concrete produces a volumetric strain which is of sufficient magnitude to be disruptive and results in poor mechanical properties, such as compressive strength and modulus of elasticity (1, 2). The basic function of restraint in self-stressing concrete is the utilization of potential expansion to produce a favorable state of stress in the concrete. This state of stress is beneficial in resisting the tensile stresses induced by externally applied loads and in bringing about changes of internal structure of concrete in a manner that favorably affects its properties. There is a loss of self-stress, due to creep and

drying shrinkage, as in conventional prestressed concrete (3). However, the residual self-stress is significant from the structural point of view (4).

From the point of view of practical application of an expansive cement of the self-stressing type, it would be logical to investigate the potentialities of the cement in developing adequate states of self-stress when expansion is restrained. For simplicity, the structural elements were restrained uniaxially (1, 4). From the results of uniaxially restrained structural elements, it was concluded that the earlier microfissures, due to the expansions perpendicular to the direction of restraint, detrimentally affect the mechanical properties of the resulting concrete (1).

It is seen from the previous studies that the mechanical properties of a structural concrete element containing self-stressing cement depends greatly upon the amount of restraint and the manner in which it was restrained. So, a promising application of self-stressing cement concrete lies in the utilization of its three dimensional expansion to provide three dimensional prestressing of concrete and to achieve better mechanical properties.

The energy requirements for producing self-stressing cements are not greatly different than those for conventional hydraulic cements. Hence it would be logical to investigate the savings in steel by making use of the self-stress developed in a triaxially restrained conditions in which improved mechanical properties could be achieved.

Objectives and Scope of the Investigation

The objectives of this investigation were to gain a better understanding of the behavior of self-stressing reinforced concrete structures and to determine the economic savings possible with the effective use of expansive cement under practical construction conditions.

To achieve the objectives, the following studies were made:

1. Study the effects of lateral steel on self-stress development with different percentages of longitudinal steel.
2. Study the effects of eccentric longitudinal steel of different percentages in triaxially restrained conditions.
3. Study the effects of variable curing conditions.
4. Study the mechanical properties of triaxially restrained cylinders.
5. Study the structural behaviors of triaxially restrained self-stressed concrete beams.
6. Determine the possible savings in steel by utilizing the triaxially restrained self-stressed concrete.

The scope of this investigation was limited to one type of concrete proportion. The Type-M self-stressing cement (5, 6) was used throughout the study.

CHAPTER II

REVIEW OF LITERATURE

Expansive Cements

Expansive cements have been researched during the past three decades in France, Russia and the United States. In earlier days efforts were made to find means of compensating for the shrinkage that results when concrete dries. The cement hydration products causing the expansion are calcium sulfoaluminates (7, 8, 9). More recently, to use an expansive cement for self-stress development in the concrete was suggested. To achieve a desired level of self-stress in the concrete over and above stress losses due to creep and drying shrinkage, similar to prestressed concrete, the cement used must have the potential of high expansion and the concrete must be adequately restrained (10). The result of such restrained expansion is a prestressed concrete.

The expansive cement developed in France consisted of a mixture of portland cement, sufoaluminate and a stabilizing agent of blast furnace slag (7). The sulfoaluminate is produced by burning a mixture of gypsum, bauxite and chalk. Blast furnace slag is used to slow down the reaction and enables the expansion to take place over a given period of

time and also subsequently absorbs the excess of calcium sulfate. Since the expansive characteristics of this cement are quite difficult to control and the expansion is not large enough to achieve high self-stress in the concrete, the cement has not been used extensively.

The cement developed in Russia is produced by inter-grinding portland cement, alumina cement, and gypsum, which with water furnish the necessary ingredients for formation of hydrated calcium sulfoaluminates (8). The rate of expansion is controlled by the relative proportions of the components and by the temperature of curing water. Russian literature reports successful use of expanding cements in the casting of concrete pipes, tanks, and thin road slabs (11, 12).

In the United States, Klein and Troxell (9) reported on the development of anhydrous calcium sulfoaluminate, which is used in combination with portland cement in concrete to generate the expansion of the concrete during its early reaction. Anhydrous calcium sulfoaluminate is prepared by burning a mixture containing calcite, aluminum sulfate, and bauxite at about 2400°F. They reported that it is possible to achieve a large expansion in an expansive cement concrete with proper proportions of ingredients. The cements developed in Russia and the United States are commonly referred to as the expansive Type-M and Type-K respectively.

Curing and Uniaxial Restraint

For practical use of self-stressing generated in an expansive concrete, it is required to control the rate of expansion and the degree of restraint (4).

The method of curing of an expansive concrete controls the rate of expansion (4, 13). If the expansion occurs too early, the bond between the particles is not strong enough to hold them together, so the disruption of the concrete occurs (9). On the other hand, if the expansion occurs at the later age, this expansion affects the internal structures of the expansive cement concrete with detrimental effects upon the mechanical properties of such concrete (14). This is significant especially in the case of uniaxially restrained prismatic elements because a greater part of the transverse expansion relative to longitudinal expansion seems to occur at a later stage. Since at this stage the concrete has gained considerable stiffness, any significant lateral expansion that occurs may be detrimental to the mechanical properties of the concrete. The poor mechanical properties was explained by the broken bond between coarse aggregates and expansive cement concrete mortar matrix (14).

Curing controls both the formation of cement gel which contributes towards the strength gain, and of trisulfate hydrate, thus controlling expansion and self-stress (2). The history of curing is important in determining the eventual maximum expansion and self-stress because the two reactions involved do not proceed at the same rate. The expansion

which occurs at a very early age when the concrete is in plastic condition and the structure is still weak, will contribute much less to the self-stress development than the later expansion.

The size effect on the expansion was studied by Bertero (14). It was caused by a moisture gradient developed from the wet surface to the interior when the large specimens subjected to an external moist curing. The initial expansion decreased and the later expansion increased as the size of the specimen increased. Also, as the size of the specimen increased, the time required to reach an equilibrium expansion was increased. However, the size of the specimen did not affect the final total magnitude of longitudinal expansion. The larger the cross-section, the lower the total over-all lateral expansion. The gradient and the magnitude of local transverse strain are greater (hence poor mechanical properties) when the size of the cross-section becomes larger. The non-homogeneity and anisotropy of the resulting expansive cement concrete in uniaxially restrained prismatic elements increased is the size of the cross-section of the specimen increased.

Effects of curing were studied extensively by Klein and Bertero (13). For a unrestrained specimen, they measured higher initial rate and a larger amount of free expansion when specimens were cured in a higher temperature. However, under restraint, a larger expansion occurred when the concrete was cured under water at 45°F rather than the concrete

was cured at 100°F. In the case of a unrestrained specimen, the expansion when cured at 100°F took place at an early age, during a period when the concrete was still weak and subject to plastic deformation. So, in a restrained specimen, the concrete was not capable of exerting adequate pressure against the end plates, in an early expansion period, the expansion did not contribute to the longitudinal restrained expansion.

In order to control the rate of expansion, Mikhailov suggested a method of curing (5). The structural elements were coated with paraffin and immersed in water at 20°C until the strength development was adequate to resist self-destruction of the concrete through stresses imposed by restraint under conditions of high and rapid expansions. Thereafter, the structural elements were placed in a water bath at 70° to 80°C, the paraffin melted off, and the expansion took place under the action of the thermal curing. The curing was continued until the expansive reaction completed after which the final curing was carried out under water at 20°C.

Klein, Karby and Polivka (4) used a different method of controlling the rate of expansion. The concrete is covered, after stripping the mold, with a loose fitting membrane in a fog room for about one day, and subsequently cured in water.

Recently Mikhailov (6) studied the chemical reactions due to the curing conditions of expansive cement concrete. The main idea in controlling the reaction rate is to retard and

hamper the formation of $C_3A(\overline{CS})_3H_{31}^*$ (calcium trisulfate) until the concrete develops adequate strength and then speeds up its formation in a short time. At high temperature conditions the existence of $C_3A(\overline{CS})_3H_{31}$ is impossible, and therefore $C_3A(\overline{CS})H_{12}$ (calcium monosulfate) is generally formed. By the end of 12 to 18 hours after casting $C_3A(\overline{CS})H_{12}$ and possibly small amount of $C_3A(\overline{CS})_3H_{31}$ are formed. Submerging the specimen in a hot water at 90° to 100°C , $C_3A(\overline{CS})_3H_{31}$ (expansion giving compound) disappears and the formation of $C_3A(\overline{CS})H_{12}$ (strength giving compound) takes place due to the high temperature. After gained adequate strength, the concrete is cured in water at room temperature during which the expansion takes place.

In the earlier study of the effect of restraints upon the self-stress development, a uniaxially restrained specimen was used by Bertero (1). He showed that the longitudinal expansion of the concrete depends on the amount of longitudinal steel reinforcement. The self-stress developed in concrete increases as the percentage (by volume) of the longitudinal restraint increases from 0.22 to 3.23. However, for a further increase of steel percentage, the development of self-stress decreases.

The lateral expansion of a uniaxially restrained specimen was also studied in Ref. (1). Bertero showed that the expansion decreased as the percentage of restraints increased (1).

* $C = CaO$, $A = Al_2O_3$, $H = H_2O$, and $\overline{S} = SO_3$.

However, for a restraint greater than 1.76 percent of steel, the lateral expansion started to increase. In the latter report, Polivka and Bertero (15) further demonstrated the effect of the degree of restraint in a uniaxially restrained concrete specimen where an increase in the amount of expansive component above a certain percentage might cause a large expansion in the lateral direction thereby weakening the structure of the concrete sufficiently to prevent the development of higher self-stress in the longitudinal direction.

For the range of steel percentage between 0.90 and 3.23, the compressive strength and modulus of elasticity remained constant, but an increase of steel percentage beyond 3.23 percent seemed to affect these properties detrimentally (15).

Based upon the above results, Bertero and Polivka (1, 15) concluded that it is possible to achieve the maximum self-stress with improved mechanical properties by using optimum degree of longitudinal restraint which lies between 1 to 2 percent of steel in a uniaxially restrained specimen.

In the two other investigations, Bertero (14, 16) reported that the longitudinally restrained prismatic structural element does not seem to hold great promise for practical application because of the detrimental effects of lateral expansion on the mechanical properties of the concrete.

Triaxial and Eccentric Restraints

A limited amount of work has been done on triaxial restrained (reinforced) self-stressing concrete. In Bertero's

investigation (16), it was found that the presence of even a small amount of lateral restraint, provided as a spiral reinforcement during the complete period of curing, produces a concrete with improved mechanical properties. From the structural elements tested (17, 18, 19) which are uniaxially and biaxially restrained, the cracking load and the ultimate load can be predicted by the usual elastic and plastic theories for structural analysis.

The self-stress development in a triaxially restrained beam were made by Iida and Monji (20). They theorized that the self-stress along the longitudinal direction of the beam increases as the degree of lateral restraint increases. However, contradictory experimental results were obtained. Within the range of lateral restraint they used, the self-stress along the longitudinal axis decreased as the degree of lateral restraint increased.

Bertero and Montero (21) reported that the longitudinal expansion in a triaxially restrained structural element was greater, when compared with a uniaxially restrained specimen. This implies that the self-stress increases in a triaxially restrained specimen and also it offers another possibility of increase in strength and ductility of concrete due to the confinement in the lateral direction and thereby improvement in the bond between the longitudinal reinforcement and the concrete.

Practically no work has been done on eccentrically restrained specimens. Tso (18) tested a beam with eccentric reinforcement and without any lateral steel. He was not able to predict the curvature of the beam due to insufficient data. However, he concluded that the cracking load and deflection can be approximately predicted by the conventional theory of elasticity and the principles of prestressing.

CHAPTER III

MATERIALS

Cements and Gypsum

A Type I portland cement from a single clinker batch was used throughout this investigation. The physical and chemical properties of this cement are listed in Table 1. The calcium aluminate cement for the entire project was obtained in one shipment. The gypsum (calcium sulfate, reagent grade) was received periodically from a chemical supply house.

Aggregates

The lime stone aggregate, laboratory designation 53-2S, size No. 11 of Indiana State Highway Standard Specifications, was used as coarse aggregate. The lime stone aggregate was selected in order not to have any possible reactions with cement. The fine aggregate used was a local glacial-alluvial sand. The gradation, dry rodded unit weight, specific gravities and absorption were performed according to ASTM Standard Tests for both coarse and fine aggregates. Their results are presented in Tables 2 and 3. The coarse and fine aggregates were sieved separately and the materials from each sieve were stored in a separate container. The aggregates

Table 1. Physical and Chemical Properties of Cement*

<u>Physical Properties</u>	
Fineness, No. 325 Sieve	84.1 percent
Specific Surface; Blaine	3720 sq. cm. per gm.
Initial Set; Gilmore	2 hrs., 30 min.
Vicat	100 min.
Final Set; Gilmore	4 hrs., 15 min.
Vicat	160 min.
Normal Consistency	23 percent
Expansion	0.007 percent
Air Entrained	8.5 percent

<u>Chemical Analysis</u>	
<u>Compound</u>	<u>Percent Present</u>
Silicon dioxide, SiO_2	21.42
Aluminum oxide, Al_2O_3	5.62
Ferric oxide, Fe_2O_3	2.34
Calcium oxide, CaO	64.41
Magnesium oxide, MgO	1.07
Sulfur trioxide, SO_3	2.84
Loss on ignition	1.22

* The portland cement is designated No. 322 in the Joint Highway Research Project Concrete Laboratory at Purdue University.

Table 1 (Cont'd)

Calculated Compound Composition

<u>Compound</u>	<u>Percent Present</u>
Tricalcium Silicate, C_3S	49.9
Dicalcium Silicate, C_2S	23.9
Tricalcium Aluminate, C_3A	11.1
Tetracalcium Alumino-ferrite, C_4AF	7.1

Table 2. Gradation and Properties of Coarse Aggregate

<u>Gradation</u>	
<u>Sieve Size</u>	<u>Accumulative % Retained</u>
3/8"	5.5
#4	68.7
#8	99.4
Passing #8	100.0

Properties

Dry rodded unit weight = 95 lb/cuft.

Bulk specific gravity = 2.54

Bulk specific gravity (SSD) = 2.6

Apparent specific gravity = 2.69

Absorption = 2.0%

Table 3. Gradation and Properties of Fine Aggregate

Gradation

<u>Sieve Size</u>	<u>Accumulative % Retained</u>
#4	0.4
#8	15.2
#16	35.8
#30	58.7
#50	90.1
#100	98.4
Passing #100	100.0
F.M. = 2.98	

Properties

Dry rodded unit weight = 110 lb/cuft.

Bulk specific gravity = 2.32

Bulk specific gravity (SSD) = 2.5

Apparent specific gravity = 2.66

Absorption = 2.5%

are batched for each mix by component fraction in accordance with accumulative batch weight formula (Tables 2 and 3). The aggregates were batched in this way to eliminate any possible changes in the gradation.

Water

The ordinary tap water was used as mixing water in all the mixes. It was thought that the purity of tap water was sufficient for the purpose of this project.

Steel

For small beams (3 x 3 x 11-in.), the unbonded type of longitudinal stainless steel bars were used. The 5/8 in., 1/2 in. and 3/8 in. diameter bars of AISI-303 Type stainless steel and 1/4 in. diameter bar of 17-4PH high strength stainless steel were used as longitudinal restraints. The high strength stainless steel was selected in order to keep the stress level within the yield strength in a 1/4 in. diameter bar. The end plates are also made up of stainless steel, 3 inch in square and 3/8 inch in thickness were used. The purpose of using stainless steel rather than an ordinary steel was not to have rusting which might affect the results. The stress-strain relationships of AISI-303 and 17-4PH steels are given in Figures A1 and A2 in Appendix I. The stirrups consisted of 1/16 in. diameter steel wire which was able to bend easily and stiff enough to restrain the expansion. The mechanical characteristics of this steel is illustrated in Figure A3 in Appendix I.

The AISI-303 Type stainless steel unbonded bars were used in 6 in. x 12 in. cylindrical specimens. The circular end plates of 6 inch in diameter and 1/2 inch in thickness of ordinary steel were used. From the economy point of view the ordinary steel plates were selected, but the rusting was prevented by spraying WD-40. The cylinders were restrained laterally by means of spirals of 1/16 in. diameter steel wire.

The bonded type of No. 3 reinforcing 50 grade steel bars were used for beams of 3 in. x 4 in. in cross-section and about 24 inch in length. The lateral steel consisted of stirrups of 1/8 inch wire. This particular diameter was used in order to have 1.3 percent of lateral restraint with a reasonable spacing of one inch. It was able to bend easily in making stirrups. The mechanical characteristics of No. 3 reinforcing bar and the steel wire are illustrated in Figures A4 and A5 in Appendix I.

CHAPTER IV

EXPERIMENTAL WORK

A-Free Expansion of Mortar Specimens

Preparation of Expansive Cement

Due to the limited supply of commercially manufactured expansive (self-stressing) cements, it was decided to prepare the cement in the laboratory. For the materials available, Type-M expansive cement was selected (5, 6). The ingredients (the portland cement, calcium aluminate cement and gypsum) were mixed for 3 minutes at slow speed with a mechanical mixer. It was observed that the 3 minutes of mixing time was sufficient in order to achieve uniform mix.

From the previous investigations, it was reported that the expansive power decayed due to the long period of storage of an expansive component (10, 14). So, it was decided to prepare the expansive cement immediately prior to preparation of mortar and concrete, thus eliminating any possible reactions due to the long period of storage.

Mix Design

All mortar mixes were prepared using a water to expansive cement ratio of 0.4 and sand to expansive cement ratio of 2.

The mix design data is shown in Table 4. The ingredients of expansive cement were varied for each mix. In order to achieve a high expansion it was thought of investigating free expansion measurements by using calcium aluminate cement of 10, 15, 20 and 25 percent at a gypsum content of 10, 15, and 20 percent.

Apparatus

The molds for casting test specimens and the length comparator for measuring length change were in accordance to the requirements of ASTM Specifications C 490. The mechanical mixer for mixing mortar was in accordance with ASTM Specification C 305. The mold, the length comparator and the mechanical mixer are shown in Figures 1, 2, and 3 respectively.

Preparation and Expansion Measurement of Mortar Specimens

Two mortar bars (1 x 1 x 11 1/4 in.) were cast according to the requirements of ASTM C 157 from each mix of mortar. The casting of specimens took place within 10 minutes after the mixing was completed. As soon as casting was completed the specimens were covered with a plastic sheet and then with a damp cloth to prevent the evaporation of water from the specimens.

Specimens were removed from the mold at an age of about 18 hours from the time of casting. At this time, the initial length measurements of mortar bars were made using the length comparator. The specimens were cured in a fog room and length measurements were made at 48 hours of time interval until

Table 4. Mix Design for Mortar and Concrete

A. Design of Mortar

<u>Materials</u>	<u>Weight of Materials for Single Mix</u>
Expansive Cement	300 gm.
Fine Aggregate	600 gm.
Water	120 gm.

B. Design of Concrete

<u>Materials</u>	<u>Weight of Materials For Cubic Yard</u>	<u>Weight of Materials for Single Mix</u>
Water	400 Lb.	860 gm.
Expansive Cement	855 Lb.	1840 gm.
Coarse Aggregate	1119 Lb.	2400 gm.
Fine Aggregate	1397 Lb.	3000 gm.

Figure 1. Mold for Casting of Mortar Specimens

Figure 2. Length Comparator

Figure 3. Mechanical Mixer

constant readings were observed or until the specimens were cracked and broken.

B - 3 x 3 x 11 in. Beams

Mix Design

Materials were proportioned according to PCA Method (25) of mix design. From the workability point of view, the slump of 2 to 3 inches was assumed in the calculation. The mix design data is shown in Table 4. After allowing water for absorption of coarse and fine aggregates, the water cement to ratio used was 0.40.

After investigating the free expansion measurements of mortar bars and from the preliminary studies on concrete, it was decided to use two types of ingredients of expansive cements to give medium and high expansions in the concrete. The medium expansive cement consists of 15 percent gypsum, 20 percent calcium aluminate cement and 65 percent of portland cement; and the high expansive cement consists of 15 percent gypsum, 17 1/2 percent calcium aluminate cement and 67 1/2 percent portland cement (Table 5).

Table 5. Medium and High Expansive Cement Compositions

Type of Cement	Gypsum, percent	Calcium Aluminate Cement, percent	Type I Portland Cement, percent
Medium Expansive Cement	15	20	65
High Expansive Cement	15	17 1/2	67 1/2

Fabrication

General

Four different percentages of longitudinal steel ($5/8$ in., $1/2$ in., $3/8$ in. and $1/4$ in. diameter) were used in the following series to investigate the effects on self-stress development. These percentages were chosen arbitrarily but they were within the maximum and minimum percentages used by Bertero (1). The end plates were inserted at the ends of each rod and brass nuts were used to prevent the outward movement of the plates. The electrical resistance strain gages of Type EA-09-125AD-120 were mounted at the center of the rods to measure the longitudinal strains. The gage surfaces were protected by gluing a brass channel section to prevent moisture and possible compressions exerted by the expanding concrete. The rubber sleeves were used to prevent bonding between stainless steel rods and the concrete. The inside diameter of rubber sleeves was $1/8$ in. greater than the diameter of the rods. The stirrups were made from $1/16$ in. diameter steel wire and were used as lateral restraints. The shape of the stirrup was a $2\ 1/2$ in. square.

Uniaxially Restrained Beams

The medium expansive cement and high expansive cement were used separately in this series to study the effects of these cements at different percentages of longitudinal restraints. The fabrication for uniaxially restrained beams is shown in Figures 4 and 5.

FIGURE 4 **SCHEMATIC DIAGRAM OF UNIAXIALLY RESTRAINED BEAM.**

Figure 5. Fabrication for Uniaxially Restrained Beam

Triaxially Restrained Beams

Triaxially restrained conditions were created by providing unbonded longitudinal restraint and lateral restraints in the form of stirrups. The four welding rods of 1/16 in. diameter were inserted in the holes which were provided for this purpose in the end plates at four corners. The stirrups were tied using 24 gage soft wire at corners to the welding rods. The fabrication is similar to that shown in the Figure 8 except that the longitudinal restraint is placed at the center of the cross-section. The schematic diagram is shown in Figure 6.

Two series of experiments were conducted. In the first series the medium expansive cement and high expansive cement were used with 0.56 percentages of lateral steel (14 stirrups in a beam). The purposes of this series were to investigate the effects of using medium and high expansive cements in a triaxially restrained condition, and to study the differences between triaxially restrained beams and uniaxially restrained beams. In the second series the high expansive cement with 0.84 percentages of lateral steel (21 stirrups in a beam) were used to study the effects of high lateral percentage.

Eccentrically Restrained Beams

In this series the high expansive cement with lateral restraints of 0.56 percentages (14 stirrups in a beam) were used. The holes in the end plates were 1/8 in. greater than the diameter of the rods in order to prevent bending of the

FIGURE 6

SCHEMATIC DIAGRAM OF TRIAXIALLY
RESTRAINED BEAM.

rods due to the differential restrained expansions at top and bottom of the beams. The fabrication is shown in Figures 7 and 8.

Beams to Study the Effect of Different Curing Conditions

The high expansive cement and 0.56 percentages of lateral steel were used. The fabrication was similar to the one explained under triaxially restrained beams with 0.56 percentage of lateral steel.

Control Specimens

The control specimens were casted in each batch to check the expansion of the concrete among the batches. The molds of plexiglass rings of 4 inch inside diameter, 1/16 in. wall thickness and 1 inch in height were used (Figure 9). This particular size of plexiglass ring was able to withstand the expansive forces without breaking. Two steel balls were glued on the outside surface diametrically opposite to each other to measure the restrained expansion.

Preparation of Beams

A Model A200 Hobart mixer (Figure 10) was used for mixing concrete. Rigid steel molds (Figure 11) were used for casting beams. The Vebe Consistometer vibrating table was used for vibrating concrete.

Materials required for two beams and one control specimen were prepared in a single mix. The expansive cement was prepared as described earlier under the title of free

FIGURE 7 SCHEMATIC DIAGRAM OF ECCENTRICALLY RESTRAINED BEAM.

Figure 8. Fabrication for Eccentrically Restrained Beam

Figure 9. Control Specimen

Figure 10. Model A200 Hobart Mixer for Mixing Concrete

Figure 11. Rigid Steel Mold for Casting Concrete Specimens

expansion of mortar specimens. The coarse aggregate, fine aggregate and water required for absorption were mixed for ten revolutions. The expansive cement and remaining mixing water were then added and mixed for 2 minutes at a slow speed. The mixing was stopped for 1 minute. During this period, all the concrete on the blade of the mixer and the wall of the bowl was scraped down by using a trowel. The mixture was again mixed for an additional 1 minute. The total of three minutes of mixing time was sufficient to mix the concrete completely.

After mixing, the concrete was placed into a mold fixed to the vibrating table. A total of one minute of vibrating time was used for vibrating the concrete. During the first 30 seconds of vibration the concrete was placed into the mold. Then the vibration was stopped for 1 minute and the surface was finished. The concrete was vibrated for another 30 seconds. Another beam and a control specimen were prepared from the same mix. The hand compaction was used in the preparation of control specimens. The entire casting process was completed within 10 minutes after mixing. As soon as casting was completed the specimen was covered with a plastic sheet and then with a damp cloth. In any single day two mixes (four beams of different percentages of longitudinal steel and two control specimens) were made.

Beams for free expansion measurements were cast according to the requirements of ASTM Method C 157.

Beams were removed from the molds at the age of about 18 hours from the time of casting. Gage points were marked to measure the longitudinal restrained expansion. Brass thin plates were glued at the quarter-point and the mid-point of the beam length for the measurement of lateral expansion. All the beams except those were prepared to study the effects of different curing conditions, were cured up to 14 days in a fog room. Control specimens were also cured in the same way. Beams prepared to study the effects of different curing conditions were kept in a hot water bath for 6 hours at 80°C after removing from the molds. Then the beams were taken out and were cured in a fog room up to 14 days.

Measurement of Strains, Longitudinal and Lateral Expansions

Using 120 C Strain Indicator the longitudinal strains of restraining rods were measured. The half-bridge with a compensating gage was used in measuring strains. The accuracy of the strain indicator was 5 µε. The Whittemore gage of least count 0.001 in. was used to measure the longitudinal restrained expansions. Using a 0.001 in. accuracy micrometer, the lateral expansions at the quarter-point and the mid-point were measured. The accuracies of these instruments were sufficient for the present purposes.

Free expansions were measured with a length comparator. The change in diameter of control specimens due to the expansion of concrete were measured with a micrometer.

All the measurements were made at a 48 hour time interval during the 14 days of curing period. The expansions of all the specimens were terminated within this curing period. At 14 days the specimens were kept for drying at the room temperature for an additional 7 days and the 21 day measurements were taken.

C - 6 x 12 in. Compression Cylinders

Fabrication

Five different diameters (1 inch, 7/8 inch, 3/4 inch, 5/8 inch and 1/2 inch) of AISI-303 stainless steel rods were used to study the effects on mechanical properties of self-stressed concrete. The inside diameter of the rubber sleeve was 1/8 inch greater than the diameter of the rod. The electrical resistance gages of Type EA-09-125AD-120 were mounted and the surfaces were protected from the moisture as described earlier under the title of the fabrication of 3 x 3 x 11 in. beams. The circular end plates of 1/2 inch in thickness were inserted at the ends of each rod and brass nuts were used to prevent the outward movement of plates. The lateral steel percentage of 0.56 in the form of helix were used in all the cylinders. The 1/16 inch in diameter wire was used to make stirrups of helical shape. In order to have 0.56 percent of lateral steel but still allowing a reasonable spacing, it was required to use two wires. The diameter of the helix was about 5 1/2 inches. The helical wires were tied to four longitudinal 1/16 inch diameter

welding rods which were inserted to the end plates at an equal distance along the circumference of 5 1/2 inch diameter. The schematic diagram is shown in Figure 12.

Preparation of Cylinders

Due to the presence of end plates in the fabrication, it is necessary to use a horizontal cylindrical mold (Figure 13) to cast cylinders. The materials required to cast one cylinder and one control specimen were selected in each mix. The medium expansive cement was used in all the mixes. The mixing, casting, and curing processes of cylinders were outlined earlier.

Testing of Cylinders

The strains in the longitudinal restraining rods were measured at the end of 28 days of curing period. All cylinders were tested in compression in accordance with ASTM C 39 for obtaining stress-strain relationships. In the compression test, hollow cylindrical steel rings of about 2 inches in height were used at the ends of the cylinder to prevent the load application on longitudinal restraining rods. This arrangement is illustrated in Figure 14.

D - 3 x 4 x 24 in. Bonded Beams

Fabrication

The reinforcing bars, No. 3 of 50 grade steel were used in all the beams. The stirrups from 1/8 inch diameter steel wire were used. The complete reinforcement details and the

FIGURE 12 SCHEMATIC DIAGRAM OF TRIAXIALLY RESTRAINED CYLINDER.

Figure 13. Horizontal Cylindrical Mold for Casting Cylinders

Figure 14. Compression Test of Concrete Cylinder

placement of gages used in the beam are shown in Figure 15.

Preparation of Beams

The Concrete Mixer of capacity of about 3 ft³ was used for mixing concrete. Beams were casted in rigid steel molds.

A total of six beams, two for the ordinary concrete, two for the medium expansive concrete and two for the high expansive concrete, were prepared on the same day. Materials required to cast two beams at a time were selected. Water required to produce 2 to 3 inch slump was used in each mix. The concrete was mixed for 3 minutes. The casting and curing procedures have been outlined in previous sections. Beams were cured up to 21 days and tested in flexure at that time.

Testing of Beams

Before testing the beams in flexure, the strains in the longitudinal restraining rods due to the self-stress development in the concrete beams were measured. The electrical resistance gages (SR₄, Type A-16) were placed on the concrete beams to measure the compressive strains due to bending. One gage was placed on the top side at the center of the beam and two gages were placed on the vertical side at 3/4 in. and 1 1/2 in. measured from the top (Figure 16). Beams were tested in bending using a third point loading setup (Figure 17). During the test the deflection at the center, strains in steel and concrete were recorded. Deflections were measured with a dial gage having a least count of 0.001 in. placed at the center

Side View

Section A-A

FIGURE 15 REINFORCEMENT DETAILS.

FIGURE 16 LOCATION OF CONCRETE GAGES IN FLEXURE TEST.

Figure 17. Experimental Set-up for Flexure Test

of the beam. Strains were measured with an indicator and switching and balancing unit. The beams were tested to failure and the crack patterns in the beam were noted.

CHAPTER V

RESULTS AND DISCUSSION

A-Free Expansion of Mortar Specimens

The expansion-time curves for each expansive mortar as measured with the 1 x 1 x 11 1/4 in. specimens are shown in Figures 18, 19, and 20. The results indicate that the expansion-time curves are dependent upon both the gypsum and calcium aluminate cement.

Figures 18, 19, and 20 show that for any given gypsum content the rate of expansion increases as the calcium aluminate cement content increases, except for the curve of 20 percent calcium aluminate cement at 10 percent gypsum. It is believed that the reaction (there by expansion) between calcium aluminate cement and gypsum was completed within the first 24 hours during which the specimens were in the mold, hence no expansion was measured. From the curves it is apparent that for constant calcium aluminate cement content the rate of expansion increases as the gypsum content increases. For example, for a calcium aluminate cement content of 15 percent and gypsum contents of 10, 15, and 20 percent, at the age of 4 days the approximate expansions of 0.02 inch, 0.035 inch, and 0.04 inch were respectively obtained.

FIGURE 18 INFLUENCE OF CALCIUM ALUMINATE CEMENT AT 10 PERCENT GYPSUM.

FIGURE 19 INFLUENCE OF CALCIUM ALUMINATE CEMENT AT 15 PERCENT GYPSUM.

FIGURE 20 INFLUENCE OF CALCIUM ALUMINATE CEMENT AT 20 PERCENT GYPSUM.

McKee (29) and Monfore (23) studied the influence of calcium aluminate cement on expansion for a constant gypsum content. Their results indicated that for any given amount of gypsum content the rate and magnitude of expansion increased as the calcium aluminate cement content increased. In this study, within the percentages of ingredients of expansive cement that were used, the magnitude of the expansion was decreased as the calcium aluminate cement content increased at a constant gypsum content (Figures 18 and 19) for the specimens were not self destructed. The explanation for this inconsistency of the results will not be given here, but to support the results the free expansions measured on concrete for two different percentages of calcium aluminate cement at a constant gypsum content will be presented under the title of uniaxially restrained beams. Also, it should be noted that the gypsum and calcium aluminate cement contents of expansive cements used by McKee and Monfore were of a lower range compared to the compositions used in this investigation.

The slope of the curve at the end of curing period is of utmost importance. McKee (22) stated:

"Partially hydrated expansive concrete, when re-exposed to a moist environment, have been reactivated even after one year of drying. Similarly, exposure to sulfates at a later date may reactivate partially hydrated sulfoaluminate crystals. Volume changes of this nature are unpredictable and, consequently, undesirable."

So, it is very important that the curing of the specimens should be continued until expansion ceases in order to insure a stable concrete. From Figures 18, 19, and 20 the only

three compositions of expansive cement achieving stability (without self-destruction) were 20 percent and 15 percent of calcium aluminate cement at 10 percent gypsum (Figure 18) and 25 percent of calcium aluminate cement at 15 percent gypsum (Figure 19).

The appearance of the specimens at the end of curing period falls into one of two basic categories. They are: less surface cracks due to low expansion shown in Figure A6; and large surface cracks due to high expansion shown in Figure A7 in Appendix II. Surface cracks were observed even in a low expansion specimens. In high expansion specimens large surface cracks and some spalling at the corners were observed. Self-destructions and in some instances warping also occurred.

During the course of this study, it was interesting to note that the mortar specimens were always warped in the direction of top side of casting regardless of the manner in which the specimens were kept in the process of curing. This means the larger expansion on the bottom side and lesser expansion on the top side of casting of the specimen. It was speculated that this differential expansion was due to the different water cement ratios at top and bottom side of the specimen. Due to the bleeding characteristics of mortar, the water cement ratio at top is higher than the water cement ratio at the bottom. To verify this, as soon as casting was completed, the specimen was covered with a glass plate and the mold was kept upside down. Some of the bleeding water

came out of the specimen. After demolding the specimen was cured in the same way as other specimens. In this particular specimen no warping was observed. From this study, it was concluded that the warping of the specimen was due to the different water cement ratios at top and bottom resulting in differential expansion.

B-Uniaxially Restrained Beams

Longitudinal expansions at the surface of the concrete of uniaxially restrained specimens, measured by the 10 in. Whittemore gage, are shown in Figures 21 and 22. The results are the averages of two tests. The percentage error of the test result is within 10 percent of the average values.

During the analysis of the results, discrepancies were found between the longitudinal strains measured on the surface of the concrete and the strains measured with electrical resistance gages. It was realized that this discrepancy was due to the end plate deflections. Then, the end plate deflections at different levels of self-stress were calculated. After applying the correction of end plate deflection to the measured strains on the surface of the concrete, it was found that these results closely agree to the strains measured by electrical resistance gages. The plotted strains in Figures 21 and 22 are after applying the corrections to the measured values.

If the restraining rods were stressed within their elastic range, indeed they were, then the Figures 21 and 22

FIGURE 21 LONGITUDINAL EXPANSION OF UNIAXIALLY RESTRAINED MEDIUM EXPANSIVE CONCRETE SPECIMENS.

FIGURE 22 LONGITUDINAL EXPANSION OF UNIAXIALLY RESTRAINED HIGH EXPANSIVE CONCRETE SPECIMENS.

represent the variation of steel stresses with time provided that the scale used for the concrete expansion is multiplied by the modulus of elasticity of the steel, E_s . Once the steel stresses have been determined, the self-stress developed in the concrete was calculated by multiplying the steel stress with the ratio of steel to the area of concrete. The variations of these stresses with time are shown in Figures 23 and 24.

Previously, for a uniaxially restrained specimen, it has been reported by Bertero and Polivka (1) that the longitudinal expansion of the concrete decreased as the degree of longitudinal restrained steel increased. They stated:

"The total amount of expansive force developed by the concrete which is proportional to the concrete self-stress increased as the percentage of steel increased from 0.22 to 3.23. However, the rate of increase diminishes rapidly for restraints greater than 0.90 percent of steel."

From the interpretation of Figure 13 of Bertero and Polivka (1), it can be concluded that the self-stress developed in the concrete was increased between the steel percentages of 0.6 and 3.23. The self-stress diminished at a slower rate as the steel percentages increased from 3.23 percent. From the Figures 21 and 22, it can be concluded that as the percentage of longitudinal restrained steel increased, the concrete expansion is decreased. Figures 23 and 24 show that as the percentage of steel increased the self-stress developed in the concrete is increased.

FIGURE 23 SELF-STRESS DEVELOPMENT IN UNIAXIALY RESTRAINED MEDIUM EXPANSIVE CONCRETE SPECIMENS.

FIGURE 24 SELF-STRESS DEVELOPMENT IN UNIAXIALY RESTRAINED HIGH EXPANSIVE CONCRETE SPECIMENS.

In a medium expansive concrete specimen (Figure 23), the self-stress development is increased rapidly in the first two days of curing. However, the self-stress development is increased at a slower rate after two days and almost terminated at 14 days. In the case of high expansive concrete specimens (Figure 24), the self-stress development is increased rapidly in the first four days of curing. Then the self-stress development increased gradually from two to six days. At 14 days, the self-stress development is almost terminated. From this it can be concluded that the high early reaction continues for a longer period in the case of high expansive concrete compared to the medium expansive concrete.

During the course of this study, it was observed that the development of random cracks in free expanded concrete specimens. These cracks were visible at the age of 4 days in the case of high expansive concrete. Figure A8 in Appendix III shows the cracks at the age of 14 days. In the case of a uniaxially restrained specimen of medium expansive concrete, no longitudinal cracks were observed (Figure A10 in Appendix III) due to the low expansion of the concrete. However, in the case of high expansive concrete specimens, the longitudinal cracks were observed (Figure A9 in Appendix III). These cracks were developed at the age between 4 and 6 days. At the age of 6 days, these longitudinal cracks were clearly visible. As soon as the longitudinal cracks developed the lateral expansion started to increase rapidly without increase in longitudinal expansion. Comparison of lateral expansions

of uniaxially restrained specimens (Table 6) of high and medium expansive concrete specimens, shows that about four times greater expansions exist in high expansive specimens. This increase of lateral expansion is not only due to the expansive power of the concrete but also due to the presence of longitudinal cracks of high expansive concrete specimens. So, it can be concluded that the increase of expansion of the concrete, in the case of uniaxially restrained specimens, does not contribute in development of self-stress after the longitudinal cracks developed.

The measurements of free expansion of medium and high expansive concrete specimens are 1.95 and 6 percent respectively. These are the average values of four test specimens. The percentage error of the test result is within 10 percent of the average values. In high expansive concrete specimens less than 10 percent increase in self-stress was measured even though there was as much as three times the free expansion as compared with medium expansive concrete specimens. As discussed before, due to the presence of longitudinal cracks in the case of high expansive concrete specimens, most of the expansion took place in the lateral direction.

Control specimens were cast from each batch and measurements of changes in diameter were made to check the expansive power of the self-stressed concrete among the batches. The measurements of change in diameter of medium and high expansive concrete specimens are 0.027 and 0.049 inches respectively.

At this stage, it is interesting to discuss the free expansion, biaxially restrained expansion (control specimen) and uniaxially restrained expansion of medium and high expansive concretes. As reported earlier, in the case of high expansive concrete, the free expansion is about 3 times, biaxially restrained expansion is about 2 times and uniaxially restrained expansion is 1.1 times greater than the medium expansive concrete specimens. These results indicate that in the case of high expansive concrete in order to achieve high self-stress, the concrete has to be restrained biaxially in surface structural elements and triaxially in prismatic structural members.

C-Triaxially Restrained Beams

Three series of experiments were conducted for triaxially restrained specimens. In the first series, specimens were of medium expansive concrete with a lateral restrained steel of 0.56 percent. The specimens of the second series were of high expansive concrete with 0.56 percent of lateral steel. The third series of specimens were of high expansive concrete with 0.84 percent of lateral steel.

The average observed longitudinal restrained expansion as a function of time for three different series of experiments are shown in Figures 25, 26, and 27. Assuming the restrained longitudinal rods are stressed within their elastic limit, the self-stress development was calculated as explained before. The self-stress development as a function of age are shown in

FIGURE 25 LONGITUDINAL EXPANSION OF TRIAXIALLY RESTRAINED MEDIUM EXPANSIVE CONCRETE SPECIMENS WITH $p' = 0.56\%$.

FIGURE 26 LONGITUDINAL EXPANSION OF TRIAXIALLY RESTRAINED HIGH EXPANSIVE CONCRETE SPECIMENS WITH $p' = 0.56\%$

FIGURE 27 LONGITUDINAL EXPANSION OF TRIAXIALLY RESTRAINED HIGH EXPANSIVE CONCRETE SPECIMENS WITH $p' = 0.84\%$.

Figures 28, 29, and 30. Each curve represents the average of two test results obtained from the two specimens similarly restrained. The range of variation of test results between the two specimens was less than 10 percent in all cases.

From the expansion-time curves (Figures 25, 26, and 27) it can be seen that most of the expansion takes place in the first 4 days after demolding the specimens. Also, most of the self-stress (Figures 28, 29, and 30) was developed in the first 4 days. After 6 days, the expansion as well as self-stress development are almost constant in all the three cases.

Comparison of the curves given in Figures 25 and 26 with those shown in Figures 21 and 22 respectively indicate that the history of triaxially restrained specimen (lateral steel of 0.56 percent) is similar but greater than that obtained for uniaxially restrained specimens. Similarly, the self-stress developed in the case of triaxially restrained specimens was greater compared to the uniaxially restrained specimens. These differences were expected because of the existence of lateral stirrups in the triaxially restrained specimens. The stirrups did not allow the concrete to expand freely in the lateral directions and therefore forced it to expand more longitudinally.

The lateral steel percentage was increased from 0.56 to 0.84 in order to find the effect on longitudinal expansion and self-stress development. Results of this investigation (Figures 27 and 30) indicate that the increase in longitudinal expansion as well as the development of self-stress compared

FIGURE 28 SELF-STRESS DEVELOPMENT IN TRIAXIALLY RESTRAINED MEDIUM EXPANSIVE CONCRETE SPECIMENS WITH $p' = 0.56\%$.

FIGURE 29 SELF-STRESS DEVELOPMENT IN TRIAXIALLY RESTRAINED HIGH EXPANSIVE CONCRETE SPECIMENS.

FIGURE 30 SELF-STRESS DEVELOPMENT IN TRIAXIALLY RESTRAINED HIGH EXPANSIVE CONCRETE SPECIMENS WITH $p_l = 0.84\%$

with triaxially restrained specimens (Figures 26 and 29) having 0.56 percentage of lateral steel. As explained before, these differences were expected since the closely spaced stirrups confined the concrete laterally and forced it to expand more longitudinally resulting with higher self-stress development.

Bertero and Montero (21) studied the effect of the closely spaced ties on expansion and self-stress development of the structural elements. They stated:

"comparison of expansion results shows that the maximum expansion of the structural element (triaxially restrained) was about 25 percent higher than that of the control specimens (uniaxially restrained). This difference was expected due to the fact that whereas the concrete of the control specimens was capable of expanding freely in the lateral directions, in the case of the structural elements the presence of closely spaced ties confined the concrete laterally and forced it to expand more longitudinally. Thus these results pointed out the convenience of prefabricating what can be called three dimensional chemical pre-stressed structural elements rather than merely uniaxial prestressing elements."

Also, they reported that the final magnitude of self-stress developed in a control specimen as 575 psi and in a structural element as 679 psi.

Iido and Monji (20) studied the effects of triaxially restrained specimens on self-stress development of the concrete. The longitudinal steel percentage of 1.01 and lateral steel percentages of 0.63, 0.82, and 1.01 were used in their studies. The size of the beam was 3.9 x 3.9 x 15.7 in. From their results they reported the following two conclusions:

- (i) The self-stress in the concrete along the main axis has a tendency to increase as the ratio of lateral steel ratio perpendicular to the direction of restraint to main axial steel ratio decreases.
- (ii) It is necessary to increase the ratio of lateral steel ratio perpendicular to the direction of restraint to main axial steel ratio for the fabrication of ideal self-stressed concrete. The self-stress along the main axis however, has a tendency to decrease when increasing the said ratio.

From their results (20), the development of self-stress for the lateral steel ratios of 0.63 and 0.82 is almost constant and a decrease of 15 percent of self-stress when the lateral steel percentage increased from 0.82 to 1.01. They have not given any possible reasons for this decreased self-stress with increased lateral steel. But they concluded that the higher percentage of lateral steel is needed for the fabrication of ideal self-stressed concrete in order to achieve a better mechanical properties.

The increase of self-stress development was measured when the lateral steel percentage increased from 0.56 to 0.84 (Figures 29 and 30). These results agreed with the conclusions of Bertero and Montero (21) but not with the conclusions of Iido and Monji (20). The inconsistency between these results and those of Iido and Monji was not resolved.

Comparison of lateral expansions (Table 6) of uniaxially and triaxially restrained specimens of medium expansive concrete indicated a slight decrease in the lateral expansion in the case of triaxially restrained specimens. Due to the presence of lateral, as well as longitudinal steel, the

Table 6. Lateral Expansions of Uniaxially and Triaxially Restrained Specimens

A. Medium Expansive Concrete

Type of Restraint	Longitudinal steel, %	Lateral Expansions, % at 1/4 pt. at 1/2 pt.	
Uniaxial	3.62	0.57	0.68
	2.30	0.61	0.73
	1.25	0.69	0.80
	0.56	0.89	0.96
Triaxial with 0.56 percent of lateral steel	3.62	0.42	0.53
	2.30	0.58	0.66
	1.25	0.67	0.73
	0.56	0.78	0.86

B. High Expansive Concrete

Type of Restraint	Longitudinal Steel, %	Lateral Expansions, % at 1/4 pt. at 1/2 pt.	
Uniaxial	3.62	2.90	3.10
	2.30	2.93	2.96
	1.25	3.26	3.90
	0.56	3.96	4.26
Triaxial with 0.56 percent of lateral steel	3.62	1.66	1.73
	2.30	1.76	1.86
	1.25	2.23	2.26
	0.56	2.46	2.60
Triaxial with 0.84 percent of lateral steel	3.62	1.20	1.26
	2.30	1.40	1.43
	1.25	1.66	1.80
	0.56	1.96	2.06

concrete was confined resulting in improved mechanical behavior.

In the case of high expansive concrete specimens, the lateral expansion was decreased as the lateral steel increased from 0 to 0.84 percent. The considerable decrease of lateral expansion was measured even with a small percentage of lateral steel (0.56 percent). Also, it was observed that the presence of this small amount of lateral steel was capable of preventing the longitudinal cracks (Figure A9 and A10 in Appendix III) by confining the concrete in the lateral direction. So, it was found that considerable improvement in the mechanical behavior of an expansive concrete could be obtained by triaxial restraint of expansion.

Comparison of lateral expansions of triaxially restrained specimens with 0.56 percentage of lateral steel (Table 6) of medium expansive concrete specimens indicate that considerable amounts of lateral steel are needed, in the case of high expansive concrete specimens, in order to keep the lateral expansion equal to the lateral expansion of medium expansive concrete specimens.

D-Eccentrically Restrained Beams

Figure 31 shows the calculated average longitudinal self-stress developed as a function of time. Since the electrical resistance gages were placed at neutral axes, presumably no bending strains were recorded. Also, as a precautionary measure against bending, it was maintained that the holes of

FIGURE 31 SELF-STRESS DEVELOPMENT IN ECCENTRICALLY RESTRAINED HIGH EXPANSIVE CONCRETE SPECIMENS.

the end plates $1/8$ in. greater than the diameter of the rods. Assuming the rods were stressed within their elastic limit, the steel stresses were calculated by multiplying the measured strains with modulus of elasticity of steel, E_s . Then the average longitudinal self-stress developed in the concrete were calculated by multiplying the steel stress with the ratio of area of longitudinal steel to the net cross-sectional area of concrete.

As expected, the self-stress development increases with increase of longitudinal steel percentage. Comparison of curves for eccentrically restrained specimens given in Figure 31 with those of triaxially restrained specimens shown in Figure 29, both having 0.56 percent of lateral steel, indicate that slight difference in self-stress development. The decrease in self-stress development in the case of eccentrically restrained specimens is probably due to the readjustment of the end plates in the early expansion stage.

Tso (18) investigated the effect of self-stress in a uniaxially restrained beam of 6 x 6 x 40 in. The restraint was of 0.3 percent high strength steel wire with an eccentricity of 2 inches at center and zero at the end (curved). The results indicated:

An expansion as high as 1.26 percent was developed at the top fibre. A curvature was produced in the beam as a result of eccentric self-stress. At the age of 65 days a chamber of about 0.79 in. was observed at the center of the beam by direct measurement. Expansion in the bottom fiber was only about 0.1 percent.

Table 7 shows the significant difference between the top and bottom fiber expansion. Also, during this investigation curvature due to eccentricity was observed in the four different percentages of longitudinal steel. From the results it was concluded that the different levels of self-stress could be achieved in a self-stressed concrete structure by reinforcing eccentrically. The different levels of self-stress causes the upward deflection at the center of the beam similar to eccentrically prestressed concrete structures.

E-Study of Different Curing Condition

The purpose of this study is to retard and hamper the formation of calcium trisulfate until the concrete develops adequate strength and speeds up its formation in a short time. When concrete is kept in a high temperature condition, the existence of calcium trisulfate (expansion giving compound) is impossible (6), and therefore calcium monosulfate (strength giving compound) is generally formed. The concrete specimens were cured in a fog room after keeping in hot water at about 80°C for 6 hours during which the concrete gained strength.

Figure 32 shows that the average longitudinal expansion as a function of time. The self-stress developed in the concrete is calculated as explained previously and shown in Figure 33 as a function of time.

Comparison of curves given in Figure 33 with those as shown in Figure 29 indicates about a 20 percent decrease in self-stress development in the specimens which were kept in

Table 7. Longitudinal Expansion of Eccentrically
Restrained Specimens

Longitudinal Percent- age of Steel	Top Fibre Expansion, Percent	Bottom Fibre Ex- pansion, Percent
3.62	+0.610	-0.260*
2.30	+0.655	-0.258
1.25	+0.710	-0.254
0.56	+0.786	-0.244

* Negative sign indicates contraction

FIGURE 32 LONGITUDINAL EXPANSION OF TRIAXIALLY RESTRAINED SPECIMENS WITH DIFFERENT CURING CONDITION.

FIGURE 33 SELF- STRESS DEVELOPMENT OF TRIAXIALLY RESTRAINED SPECIMENS WITH DIFFERENT CURING CONDITION.

hot water (80°C) for 6 hours. The reason for this is not fully understood. However, when the specimens were kept in hot water at about 80°C , the white powder was deposited on the surface of the specimen. X-ray diffraction was run for this powder and found that the powder is calcium carbonate. Presumably the gypsum reacted with water at high temperature and calcium hydroxide is formed. Since the precaution against carbonation of the specimen was not taken, this calcium hydroxide converted to calcium carbonate. Again why gypsum came out from the specimen is unknown at this time.

In order to find the effects of different curing conditions on unrestrained concrete, the high expansive concrete specimen was kept in hot water at 80°C for 6 hours and cured in a fog room up to 14 days. The free expansion measurement of this specimen was about 1.7 percent which was less than $1/3$ of free expansion of concrete with a regular water curing. The appearance of specimens which were cured under two different curing conditions are shown in Figure All in Appendix III. There are no visible cracks in the specimen which was kept in hot water at about 80°C and then cured in a fog room up to 14 days.

F-Compression Tests

Since the cylinders were tested without removing the lateral restraints (helix), the strength contributed from the helix towards the compressive strength of the concrete was investigated. This was done on a ordinary portlant cement

concrete cylinders with and without helix. The stress-strain relationship of the compression test of these cylinders are shown in Figure 34. The stress difference between these two curves is taken as the strength contributed by helix. The stress-strain relationship of the compression test of cylinders along with modified curves for different percentages of longitudinal steel are shown in Figures A12 - A16 in Appendix III. Each curve represents the average values obtained for two specimens tested. The variation of results obtained in these two tests was within 5 percent of the average values. The modified curves are obtained by taking into account the strength contributed from helix found from ordinary portland cement concrete cylinders tested with and without helix. All modified stress-strain curves of compression test are replotted and shown in Figure 35. In this figure, the stress-strain relationship of free expanded concrete cylinder is also shown.

The secant modulus of elasticity is calculated at $0.45 f'_c$ as illustrated in Figure A17 in the Appendix. The final magnitude of self-stress developed, the compressive strength and secant modulus of elasticity are shown in Table 8.

Figure 35 and Table 8 indicate that the increase in compressive strength and secant modulus of elasticity at $0.45 f'_c$, in the case of triaxially restrained specimens was about 4 times greater compared to the free expanded concrete. Thus significant improvement in the mechanical properties was obtained even with presence of small percentages of lateral and longitudinal steels. These improved mechanical properties

FIGURE 34 CONCRETE STRESS-STRAIN DIAGRAM FOR CYLINDERS WITH AND WITHOUT HELIX.

FIGURE 35 MODIFIED STRESS-STRAIN DIAGRAM OF COMPRESSION TEST CYLINDERS.

Table 8. Analysis of Compression Test Cylinders

Percentage of Longitudinal Restraint, P, Percent	Self-Stress Developed, psi	Compressive Strength f'_c at 28 days, psi	Secant Modulus of Elasticity, E, at $0.45 f'_c$, million psi
0	0	1460	0.91
0.71	183	5660	3.75
1.11	200	5770	3.82
1.59	219	6130	3.94
2.18	228	6200	4.10
2.9	246	6310	4.18

in a triaxially restrained specimens were little lower compared to the ordinary concrete due the expansion of the self-stressed concrete.

For cylinders with 0.56 percent of lateral restraints, the different percentages of longitudinal steel did not significantly change the modulus of elasticity or the compressive strength. But, as expected, the modulus of elasticity and the compressive strength were increased as the percentage of longitudinal steel increased.

Bertero and Polivka (1) studied the effect of degree of restraint on the mechanical properties of uniaxially restrained specimens. From the results they concluded:

The degree of restraint had a significant effect on the mechanical characteristics of the self-stressed concrete. Compressive strength and modulus of elasticity, in the direction of restraint increased as the degree of restraint is increased. However, for the range of restraint between about 0.90 and 3.23 percent of steel, these properties remained constant and an increase beyond 3.23 seemed to affect these properties detrimentally.

Their results showed that the measured lateral expansion of the concrete decreased as the percentage of longitudinal restraint increased. However, for restraints greater than 1.76 percent of steel, the lateral expansion started to increase. Also, they concluded that the increased lateral expansion due to higher percentage of longitudinal restraint had a significant effect on the mechanical characteristics of the self-stressed concrete. They stated:

- (a) A very rapid improvement in the mechanical properties would be observed when 0.22 to 0.90 percent of steel;

- (b) some improvement would be obtained when the degree of restraint is increased from 0.90 to 1.76 percent of steel; and
- (c) no improvement could be expected for a degree of restraint greater than 1.76 percent of steel, because any improvement in mechanical properties that might occur due to a slight increase in the self-stress might be canceled by the detrimental effect of the larger lateral expansion.

From the results presented in Figure 35 and Table 8, the continuous increase of compressive strength and modulus of elasticity, as longitudinal steel percentage increases, is apparent. Presumably, the lateral restraint controlled the higher lateral expansion due to the increased longitudinal restraint, thereby improved mechanical characteristics of the self-stressed concrete. So, it can be concluded that the lateral restraints confined the concrete to improve considerably its strength and ductility.

In another investigation, Bertero (16) reported considerable improvement in the mechanical behavior of triaxially restrained cylinder compared with uniaxially restrained cylinder. Further, their results of compressive strength and secant modulus of elasticity for triaxially restrained cylinders (5/8 in. diameter longitudinal steel and 0.5 percent lateral restraint) are higher compared to the results reported in Table 8. The reason for this is due to the medium expansive cement that was used in preparation of compression test cylinders. From the results and observation during compression tests, considerable improvement in the mechanical behavior of prismatic structural elements of self-stressing concrete was

expected when restraining the expansion triaxially.

G-Structural Behavior of Beams

The purpose of this study was to compare the structural behavior of an expansive concrete beam with that of an ordinary concrete beam, and thus determine the economic savings in steel with effective use of self-stressed concrete. The structural behavior was studied by testing the beams of ordinary reinforced and self-stressed concrete beams in flexure. The savings in steel of self-stressed concrete was calculated by using the equal deflection criteria.

Figure 36 shows the load versus the calculated deflection for the ordinary portland cement concrete, medium expansive and the high expansive concrete beams. The deflections were calculated in the following order: first, the curvature of the beam was calculated by dividing the sum of the measured strains of concrete and steel by the structural depth. Then by using the conjugate beam method, the central deflections were calculated. The details of calculation are given in Appendix V.

Figure 37 shows the load versus measured deflection for ordinary concrete and self-stressed concrete beams. The deflections were measured at the center of the beam during the test with a dial gage having a least count of 0.001 in. The deflections are also tabulated in Table 9. The data given are the average values of two tested beams and the variation in these two tests was within 10 percent of the average value.

FIGURE 36 LOAD VS CALCULATED DEFLECTION CURVES.

FIGURE 37 LOAD VS MEASURED DEFLECTION CURVES.

Table 9. Comparison of Calculated and Measured Deflections

Load Kips	Portland Cement Concrete Deflections, Calculated, in. Measured, in.		Medium Expansive Concrete Deflections, Calculated, in. Measured, in.		High Expansive Concrete Calculated, in. Measured, in.	
	Calculated	Measured	Calculated	Measured	Calculated	Measured
2.5	0.013	0.014	0.011	0.012	0.0045	0.004
5	0.025	0.026	0.018	0.022	0.015	0.016
7.5	0.030	0.040	0.023	0.030	0.020	0.024
10	0.037	0.053	0.03	0.043	0.026	0.034
12.5	0.043	0.065	0.037	0.053	0.033	0.046
15	0.069	0.152	0.049	0.077	0.043	0.058
16	-	-	0.089	0.130		
17.5	-	-	-	-	0.071	0.085
18	-	-	-	-	0.124	0.135

In view of the behavior of the tested beams, two distinctly different stages can be defined. The first stage defined the part of the load deflection curve upto the yielding of the steel which is linear for all beams. It is designated as the elastic range. The second stage of the load deflection relationships is characterized by an increase of deflection without the load increment. Thus, the steel is in a plastic range.

A comparison of the measured and calculated deflections shows a close agreement in the early stage of the loading. However, the difference is significant when the steel strains are in the plastic range. This is probably due to the errors in strain measurements generated by the micro-cracks in the concrete.

At the failure of the beam, the strains in the steel were calculated by using the concrete strains at the failure load. This procedure was followed because the gages were failed in recording the strains in the steel. The change in position of neutral axis was neglected. The strains measured in concrete and steel are shown in Table 10. The depth of the neutral axes for ordinary, medium expansive and high expansive concrete beams at yield are 1.43, 1.51 and 1.45 inches respectively.

Comparison of curves for different concretes shows that the measured deflections as well as the calculated deflections for ordinary concrete were larger than those for self-stressed concrete as contemplated before the investigation

Table 10. Measured Strains in Concrete and Steel

Load Kips	Portland Cement Concrete Strains in Millionths Concrete	Portland Cement Concrete Strains in Millionths Steel	Medium Expansive Concrete Strains in Millionths Concrete	Medium Expansive Concrete Strains in Millionths Steel	High Expansive Concrete Strains in Millionths Concrete	High Expansive Concrete Strains in Millionths Steel
2.5	455	520	405	415	158	172
5.0	870	1008	669	701	540	560
7.5	908	1387	734	986	651	864
10.0	1102	1663	938	1302	843	1145
12.5	1295	1930	1185	1610	1081	1452
15.0	2090	--	2250	--	1338	1930
16	--	--	2745	--		
17.5	--	--	--	--	2190	--
18	--	--	--	--	3825	--

(Figure A18 in Appendix V). Furthermore, the appearance of crack patterns of ordinary and self-stressed concrete beams are significantly different (Figure 38). The differences in deflection and crack patterns are apparently due to the presence of longitudinal self-stress. The self-stress development in medium and high expansive concrete beams were 520 psi and 644 psi respectively. They were measured before the beams were tested.

Higher failure loads were recorded in the self-stressed concrete beams as compared to the ordinary concrete beams. This higher strength was due to the existence of pre-stresses and the higher steel stress at failure strain.

The elastic limits of the load-deflection curves are approximately within the range of 12.5 kips and 15 kips (Figures 36 and 37). From the Figure 36, the corresponding deflection for the load of 12.5 kips in ordinary concrete was 0.043 inches. The corresponding load for this deflection in high expansive concrete beam is about 15 kips. Therefore, the increase in the ultimate load is about 20 percent. The increase in the ultimate load shown in Figure 37 for the measured values is about 24 percent. The agreement appears to be excellent.

It should be noted that the same amount of steel was used in all beams. Hence, it was concluded that the savings in steel was about 20 percent in the case of self-stressed concrete for the same limiting deflection.

Figure 38. Comparison of Concrete Beams for Crack Pattern

P.C: Ordinary Portland Cement Concrete Beams

B: Medium Expansive Concrete Beams

A: High Expansive Concrete Beams

CONCLUSIONS

The conclusions drawn are pertinent only to the conditions of tests and the materials employed in this investigation. From the results obtained the following generalizations can be made:

1. The results of free expansion mortar bars indicate that for any given gypsum content, the rate of expansion is increased as the amount of calcium aluminate cement increases, but the magnitude of expansion decreases. A laboratory self-stressing cement can successfully be made which will be reproducible in the expansion characteristics.
2. The self-stress development is higher in the triaxially restrained specimens, when compared with that of the uniaxially restrained specimens, in addition to preventing the longitudinal cracks. The presence of lateral steel confine the concrete in the lateral direction and forced it to expand more longitudinally. The lateral confinement prevents the formation of longitudinal cracks. In a triaxially restrained specimen, the self-stress development increases as the lateral steel increases. The eccentric restraints can be used in order to achieve different magnitudes of self-stress at top and bottom of the beams.

3. It is possible to produce self-stressing concrete having compressive strength and modulus of elasticity suitable for structural work. The detrimental effects of free expansion on the compressive strength and modulus of elasticity can be overcome by confining the concrete triaxially.

4. In self-stressed concrete structures, smaller deflections and fewer cracks can be achieved due to the presence of longitudinal self-stress. The savings in steel of about 20 percent can be achieved in a self-stressed concrete as compared to conventional reinforced concrete for an equal deflection criteria.

LIST OF REFERENCES

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1. Bertero, V. V., and Polivka, M. "Effects of Degree of Restraint on Mechanical Behavior of Expansive Concrete", Proceedings, ASTM, V. 64, 1964.
2. Klein, A., and Bresler, B., "A Review of Research on Expansive-Cement Concretes", Proceedings, International Conference on the Structure of Concrete (London, 1965), pp. 467-472.
3. Aroni, S., Bertero, V. V., and Polivka, M. "Chemically Prestressed Concrete", PCI Journal, V. 13, No. 5, Oct. 1968, pp. 22-35.
4. Klein, A., Karby, T., and Polivka, M., "Properties of an Expansive Cement for Chemical Prestressing", Proceedings, ACI, Vol. 58, 1961, pp. 59-81.
5. Mikhailov, V. V., "Stressing Cement and the Mechanism of Self-Stressing Concrete Regulation", Proceedings, Fourth International Symposium on Chemistry of Cement, Washington, D.C., Vol. 11, 1960, pp. 927-955.
6. Mikhailov, V. V., "Stressing Cement and Self-Stressed Structures in the USSR", Publication SP-38, pp. 415-482.
7. Lafuma, H. "Expansive Cements", Proceedings of the Third International Symposium on the Chemistry of Cement, London, 1962, pp. 581-597.
8. Mikhailov, V. V. "New Developments in Self-Stressed Concrete", Proceedings, World Conference on Prestressed Concrete. (San Francisco), University of California, Berkeley, July 1957.
9. Klein, A., and Troxell, G. E. "Studies of Calcium Sulfoaluminate Admixture for Expansive Cements", Proceedings, ASTM, V. 58, 1958, pp. 986-1008.
10. Polivka, M., "Self-Stressing Concrete", Publication SP-38, pp. 483-487.

11. Mikhailov, V. V., and Litver, S. L. "Expansive and Stressing Cements and Self-Stressed Reinforced-Concrete Elements of Construction", 1974, 312 pages.
12. Mikhailov, V. V., Litver, L. S., Karasev, A. K., Budagyants, L. I., and Titov, Yu. N., "Stressing-Cement Concrete in Cast-in-Place and Precast Construction", 1975, 52 pages.
13. Klein, A., and Bertero, V. V., "Effects of Curing Temperature and Creep Characteristics of Expansive Concretes", Proceedings, ASTM, V. 63, 1963, pp. 1009-1025.
14. Bertero, V. V. "Effects of Size of Cross-Section Upon the Expansion History and Mechanical Behavior of Expansive-Cement Concrete", Report No. SESM 66-25, Department of Civil Engineering, University of California, Berkeley, December 1966.
15. Polivka, M., and Bertero, V. V. "Factors Affecting Properties of Expansive Cement Concrete", Proceedings, International Conference of the Structure of Concrete (London, 1965), pp. 479-492.
16. Bertero, V. V. "Effects of Type of Restraint Upon Mechanical Behavior of Expansive-Cement Concrete", Report No. SESM 66-26, Department of Civil Engineering, University of California, Berkeley, December 1966.
17. Lin, T. Y., and Klein, A. "Chemical Prestressing of Concrete Elements Using Expanding Cements", ACI Journal, Proceedings, V. 60, No. 9, Sept. 1963, pp. 1187-1216.
18. Tso, S. "Testing and Analysis of Self-Stressed Concrete Elements", Graduate Student Research Report SESM 23, Department of Civil Engineering, University of California, Berkeley, 1961.
19. Monji, T., and Inoue, I. "On the Mechanical Properties of Reinforced Concrete Beams Using Expansive Cement", Nihon Cement Co., Ltd., Tokyo.
20. Iida, H., and Monji, T. "Study on the Optimum restraint of Self-Stressed Concrete Pipe", Publication SP-38, pp. 69-88.
21. Bertero, V. V., and Irigorry Montero, C. J. "Precast Chemically Prestressed Concrete Frame", Report No. SESM 63-4, Department of Civil Engineering, University of California, Berkeley, October 1963.

22. McKee, D. C. "The Properties of an Expansive Cement Concrete Reinforced with Steel Wire Fibers", Ph.D. Thesis, University of Illinois, Urbana, 1968.
23. Monfore, G. E. "Properties of Expansive Cement Made with Portland Cement, Gypsum and Calcium Aluminate Cement", Journal, P C A Research and Development Laboratories, Vol. 6, No. 2, May 1964, pp. 2-9.
24. Wong, J. S. "Study of the Mechanical Behaviors of Chemically Prestressed Concrete Structural Elements", Graduate Student Research Report, S E S M 156, Department of Civil Engineering, University of California, Berkeley, 1964.
25. "Design and Control of Concrete Mixtures", PCA, July 1968.
26. Mehta, P. K., and Polivka, M. "Expansive Cements", Proceedings, Sixth International Symposium of Chemistry of Cement, Moscow, 1975.
27. "Expansive Cement Concretes - Present State of Knowledge" ACI Journal Proceedings, V. 67, No. 8, August 1970, pp. 583-610.
28. Bertero, V. V., and Bresler, B. "The Behavior of Expansive-Cement Concrete under Load", Proceedings, International Conference on the Structure of Concrete (London, 1965), pp. 493-498.
29. Aroni, S., Polivka, M., and Bresler, B. "Expansive Cements and Expanding Concrete", SESM Division, University of California, Berkeley, Report No. 66-7, July 1966.
30. Brito, J., and Bertero, V. V. "Behavior of Expansive Cement Concrete-Filled Steel Tube Columns", Report No. 66-10, Department of Civil Engineering, University of California, Berkeley, September 1966.
31. Benuska, K. L., Bertero, V. V., and Polivka, M. "Self-Stressed Concrete for Precast Building Units", Jour. Prestressed Concrete Institute, V. 16, No. 2, pp. 72-84, (March-April 1971).
32. Aylward, T. J. "Studies of Volume Change in Expansive Cements", Thesis for M.S.C.E., Purdue University, Lafayette, Indiana.

NOTICE

The following Appendices listed in the Table of Contents of this Report have not been included in this copy of the Report.

<u>Appendix No.</u>	<u>Title</u>	<u>Pages</u>
I	Stress-Strain Relationship of Different Steels	102-106
II	Free Expansion of Mortar Specimens	107-108
III	Crack Patterns of 3 x 3 x 11 in. Beams	109-112
IV	Stress-Strain Relationship of Compression Test Cylinders	113-118
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A recipient of the Report may secure a copy of the Appendix or Appendices desired upon request to:

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