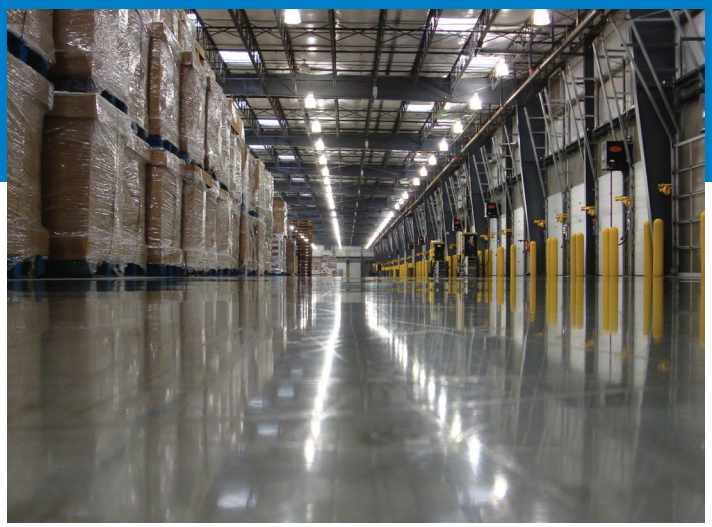
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SYMPOSIUM VOLUME



Shrinkage Compensating Concrete – Past, Present, and Future

SP-307

Editor:
Chris Ramseyer

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First printing, March 2016

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Preface

With the exception of #9, these Papers were presented at:
ACI National Convention, Fall 2012 Toronto, Canada
In the Technical Session
Shrinkage Compensating Concrete – Past, Present, and Future
Part 1 and Part 2

This Publication is
Dedicated to
Edward K. Rice

Ed Rice has been involved in Shrinkage Compensating Concrete from its inception. As co□founder and President of T.Y. Lin and Associates from 1952 through 1970 Ed Rice promoted the novel use of concrete and concrete systems. As early as 1956 T.Y. Lin and Ed Rice provided the necessary funding for fundamental research by Alex Klein on expansive cements. This research led to the development of the Chemically Prestressed Concrete (CPC) co that was primarily in the pipe and roof slab business. In 1965 under Ed Rice's direction as Chairman of CPC, Ed licensed Kaiser to run the first full scale burn at their Cushenberry cement plant and commercially produce the first shrinkage compensating concrete clinker in the world.

In the fifty years since the first production run of shrinkage compensating cement Ed Rice has consistently worked to advance concrete cement technology. He holds 22 US patents in the field of concrete and building technology. For the last forty years Ed Rice has led CTS Cement Manufacturing Co., the largest producer of shrinkage compensating cement in North America. Often Ed Rice worked behind the scenes helping to promote shrinkage compensating concrete and the work of younger engineers. Ed Rice has been a consistent and steady advocate for both increased research on the behavior of shrinkage compensating cements; and increased use of shrinkage compensating concrete to produce stable and durable concrete structures.

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History of Shrinkage Compensating Cement

Edward K. Rice

Synopsis:
This short work details the history of Type K shrinkage compensating cement.

Keywords:
Development, history, Klein, shrinkage compensating cement, type K, SCC, Concrete shrinkage

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Edward K. Rice

Author Biography:

Edward K. Rice, P.E., FACI, FASCE, is the founder and Chairman of CTS Cement Manufacturing Co, a leading manufacturer of specialty cements. He holds 22 patents in concrte and building technology. He is a member of the Post-Tensioning Institute Hall Of Fame, ASTM Honorary Member Committee C1, UC Berkeley Distinguished Engineering Alumnus and UCLA Lifetime Contributing Member

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INVENTION AND EARLY DEVELOPMENT

There are three primary types of expansive cement in ASTM C845: Type K, Type M, and Type S. ACI 223 now also recognizes Type G. My talk will only discuss the history of Type K as I know it. Type K was developed under the supervision of Alexander Klein at the University of California, Berkeley. Alexander Klein joined the Berkeley research team in 1934 and worked on cement for the Hoover Dam.



Figure 1: Alexander Klein (1902 - 1970)

In the early 1950s, Klein began work on expansive cements. Others had developed expansive cements, but Klein's expansive cement was unique in that the expansion was controllable and the expansion stopped in an appropriate time. Many other expansive cements expanded to destruction. Klein's expansive cement was fundamentally based on the formation of C4A3S "Ettringite" crystals during the hydration of the cement. Because he was responsible for some of the earliest developments in this field, C4A3S is often referred to as the Klein compound. Two examples of ettringite crystal growth appear in Figure 2 and Figure 3.



Figure 2: Ettringite Crystal Growth

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Figure 3: Nucleation of Ettringite (also called Bescher balls)

In the early development of Klein's expansive cement, many thought it was the work of a madman to knowingly create a mechanism for ettringite production. This was based on the idea that the crystal would tend to expand without bound, thus compromising the material. However, Klein's ettringite crystals form quickly and the expansion terminates on hydration of C4A3S; the expansion of other types of ettringite crystals may not terminate in other systems.

In the late 1950s, the Berkeley lab did quite a bit of work on the pre- and post-tensioning of concrete and its limitations. It was thought that one could use Klein's expansive cement to chemically pre-stress (Chem Stress) concrete (particularly on thin shells and pressure pipe). Both shells and pressure pipes were successfully constructed in the Berkeley lab, as illustrated in Figure 4 and Figure 5.

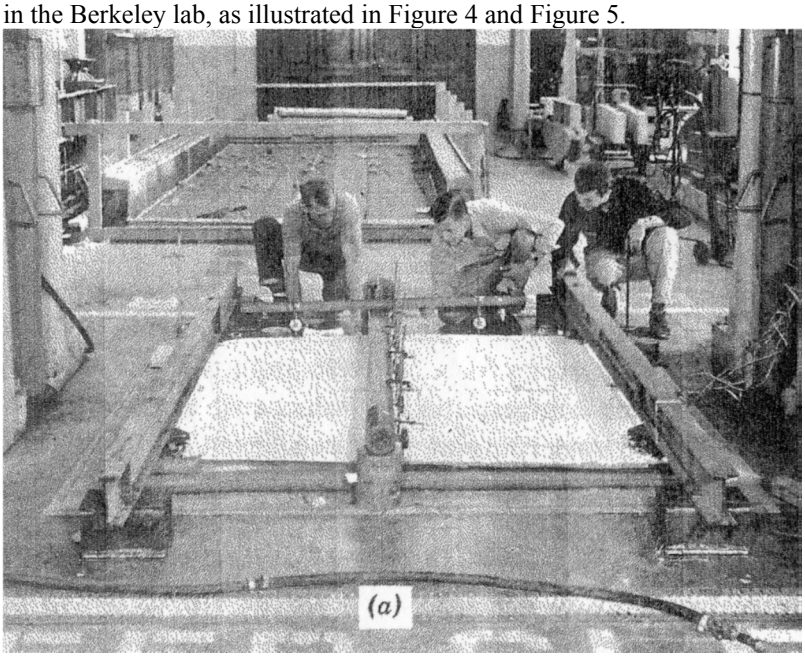


Figure 4: Chemical Pre-Stressing of a Thin Concrete Shell at Berkeley Lab

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Figure 5: Chemical Pre-Stressing of a Concrete Pressure Pipe at Berkeley Lab

CONCEPTS AND FUNCTION

The function of Shrinkage Compensating Concrete (also called SCC) is quite simple. When the concrete is mixed, ettringite crystals begin to form and cause a slight expansion in the concrete. Regular reinforcing steel provides the necessary restraint to place the concrete in compression. This compression in the concrete is necessarily accompanied by tension in the steel during the expansive phase of the concrete. As the concrete dries out, it shrinks. In the case of SCC, the concrete shrinkage is ideally the same as the expansion, and the concrete ultimately returns to its as-cast length. This process is illustrated in Figure 12. The maximum expansion is roughly equivalent to the change in length that would be caused by a 100°F increase in temperature.

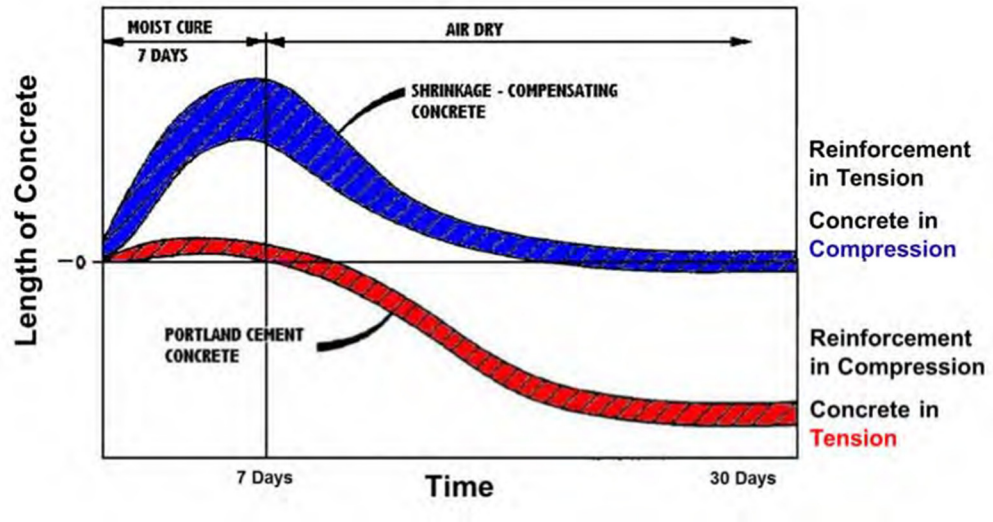


Figure 6: Shrinkage Compensation Compared to Conventional PCC

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With the increased use of SCC over time, appropriate ASTM specifications have been developed for its use and testing. The ASTM specification for testing shrinkage or expansion of Portland cement mortar or concrete is ASTM C157. In this test, length changes are measured at specified times on a bar 10" long. In order to accommodate testing of SCC concrete, the C157 bar is modified to provide the necessary restraint. This longitudinal restraint is provided by a restraining steel rod placed in the center of the bar. The restrained expansion bar test for concrete is ASTM C878, which utilizes a 3"x3"x10" bar. The steel area in the 1/8" diameter restraining rod is equal to 0.15% of the concrete area; this percentage is equal to the code minimum steel requirement for all concrete in the 1960s when this test was developed.

The test for mortar is ASTM C806, which utilizes a 2"x2" bar. The size of the restraining rod in this specimen is of ¼" diameter in order to achieve a mortar expansion similar to that of the C878 concrete test. While the C878 test is used to characterize the expansion of a concrete, the C806 test is used to determine the expected expansion from a particular cement. These restrained bar test were developed by Edward H. Rubin, FACI, and as a result the expansion bars are often referred to as Ruben bars. In addition to the specifications for testing SCC, there is also a standard specification for expansive cement. Properties and performance of expansive cement are dictated by ASTM C845; this standard is similar to ASTM C150 for Portland cement, except that C845 includes an expansion-based performance requirement. The C845 specification requires a mortar bar expansion of 0.04% to 0.1% at 7 days and the 28-day expansion is not allowed to exceed 115% of the 7-day expansion. In developing these expansion limits for shrinkage compensating cement, it was thought that limiting the 28-day expansion would allow direct substitution of SCC for PCC in any structure without making any design changes. Using the ASTM specification, a great number of SCC structures have been constructed without making any special provisions for the expansion of the SCC

Type K expansive cements are generally made by manufacturing an expansive Klein clinker containing C4A3S and either inter-grinding the clinker with Portland cement and gypsum, or mixing ground Klein clinker with Portland cement and gypsum. The combination of ground Klein clinker and gypsum is often referred to as component. The advantage of the component system is that expansion may be adjusted to meet any specific need. The component system also has a major advantage over the inter-ground system in shipping cost, since local Portland cement can be used and only about 15% of the required mix must be shipped.

IMPLEMENTATION

Ultimately, the potential market for chemically pre-stressed concrete was too small to warrant widespread full-scale production in a cement plant. However, a six-story apartment building was later constructed with chemically pre-stressed 2" thick concrete walls and 4.5" thick floors. Fabrication and assembly of this building are illustrated in Figure 6 through Figure 9.

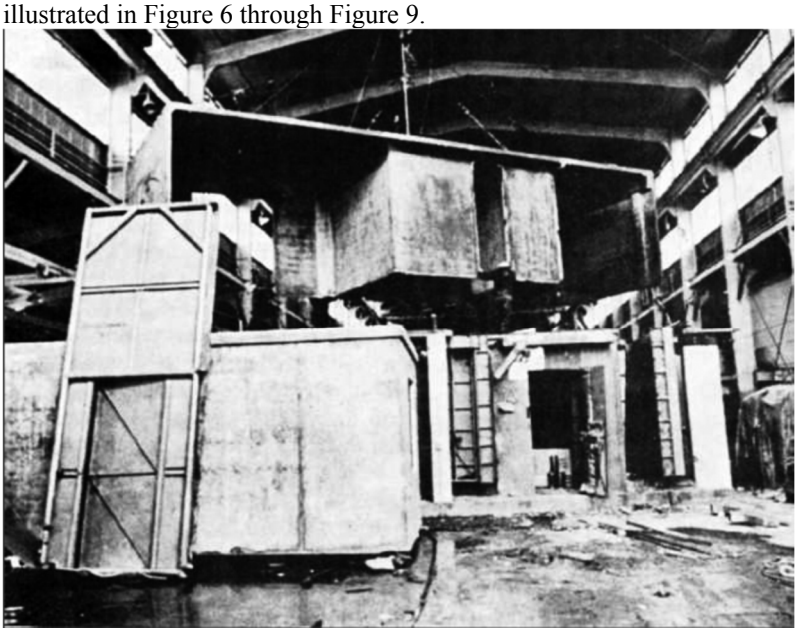


Figure 7: Fabrication of Chemically Pre-Stressed Apartment Building

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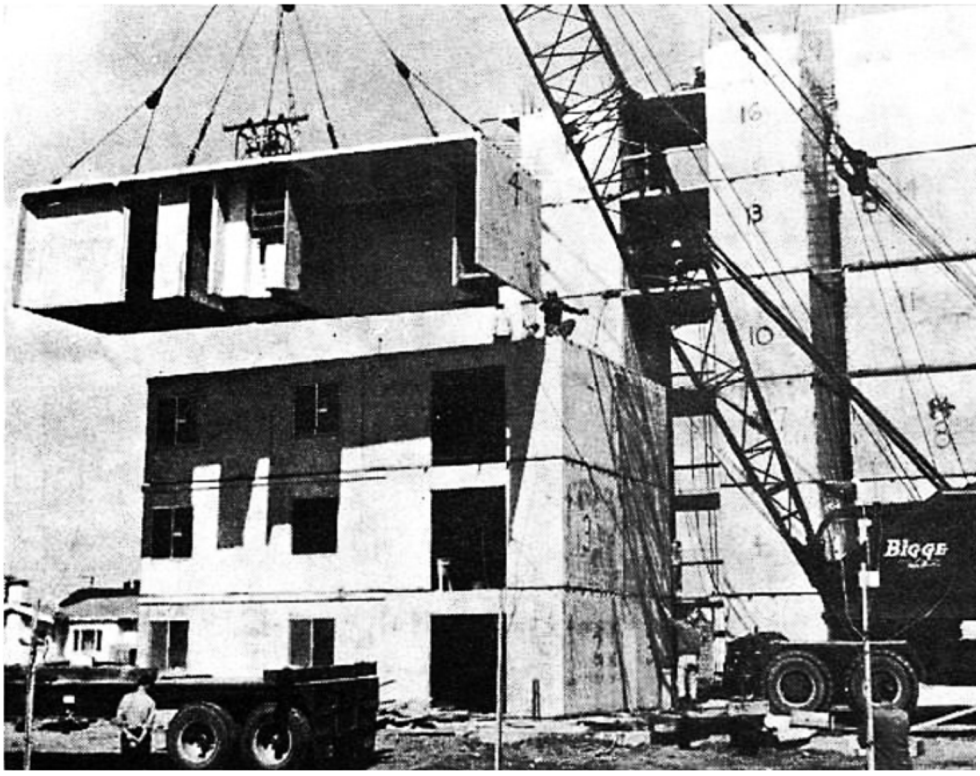


Figure 8: Modular Construction of Apartment Building using chemically Pre-Stressing

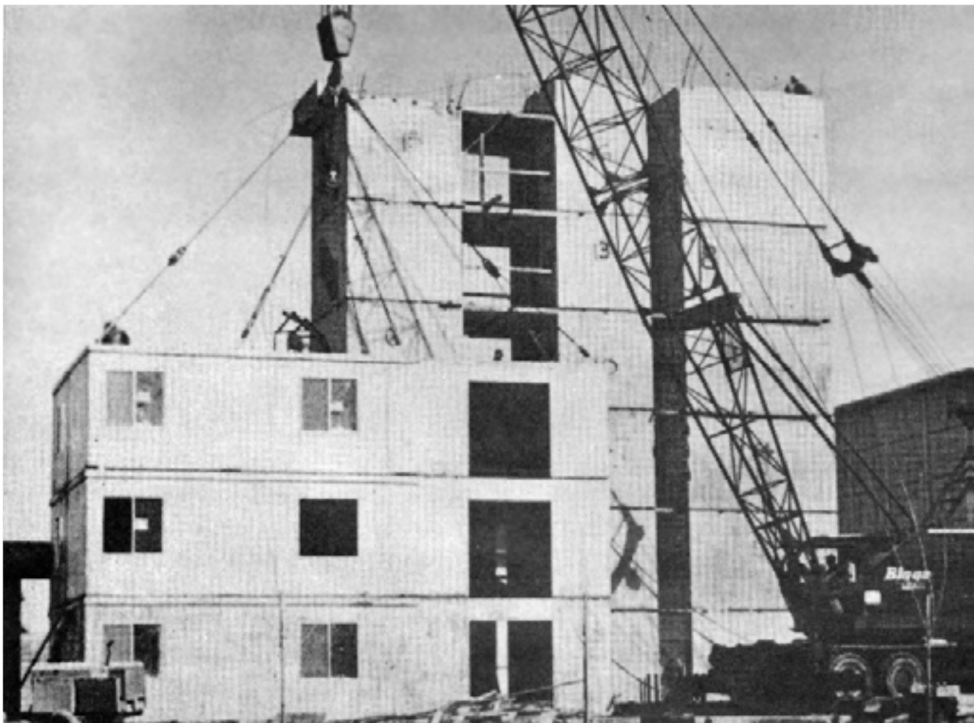


Figure 9: Construction of Apartment Building

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Figure 10: Fully Constructed Chemically Pre-Stressed Apartment Building

During the 1950s, a considerable number of post-tensioned lift slab structures were constructed. As the size of buildings increased, drying shrinkage became a serious structural problem. As the drying shrinkage took place, the floor and roof slabs became shorter and caused significant distress at the shear walls and stair connections. Slip joints were considered as a potential solution, but were not practical. By adding Klein's compound to Portland cement, however, one could compensate for drying shrinkage and the slab stayed the same size as cast. This is referred to as Shrinkage Compensating Cement Concrete, since the amount of shrinkage was balanced or compensated for by the expansion of the Klein compound. The benefit of such a process is readily apparent, and the potential market for making a Klein (Type K) Shrinkage Compensating Cement was large enough to justify commercial production in a full-scale cement plant.

A patent holding partnership named Chemically Prestressed Concrete (CPC) was formed in 1961 to develop and license the Klein cement technology. Klein applied for patents on SCC in 1961 and Kaiser Cement and Gypsum Company of Oakland, California, became the first cement company licensed to make Klein SCC in 1962. The CPC partnership was incorporated in 1963 and three patents were issued over the next several years (one in 1964, one in 1966, and one in 1967). In 1962, Caltrans was keenly interested in finding a solution to shrinkage in concrete pavement, and they let a contract to pour two one-mile sections of pavement. This was a large enough order to warrant production, and the first Type K clinker was made January 4, 1963, at the Kaiser plant in Cushionberry, California. The first one-mile section of pavement was placed on Highway 14 near Lancaster, CA; the second was placed near Lodi, CA. Paving was done using a two-lane wide slip form paver, and expansion joints were placed every 440 feet. After two years, drying shrinkage cracks were measured and found to be spaced approximately double the distance expected with PCC, and these pavements (shown in Figure 11) are still in service today.

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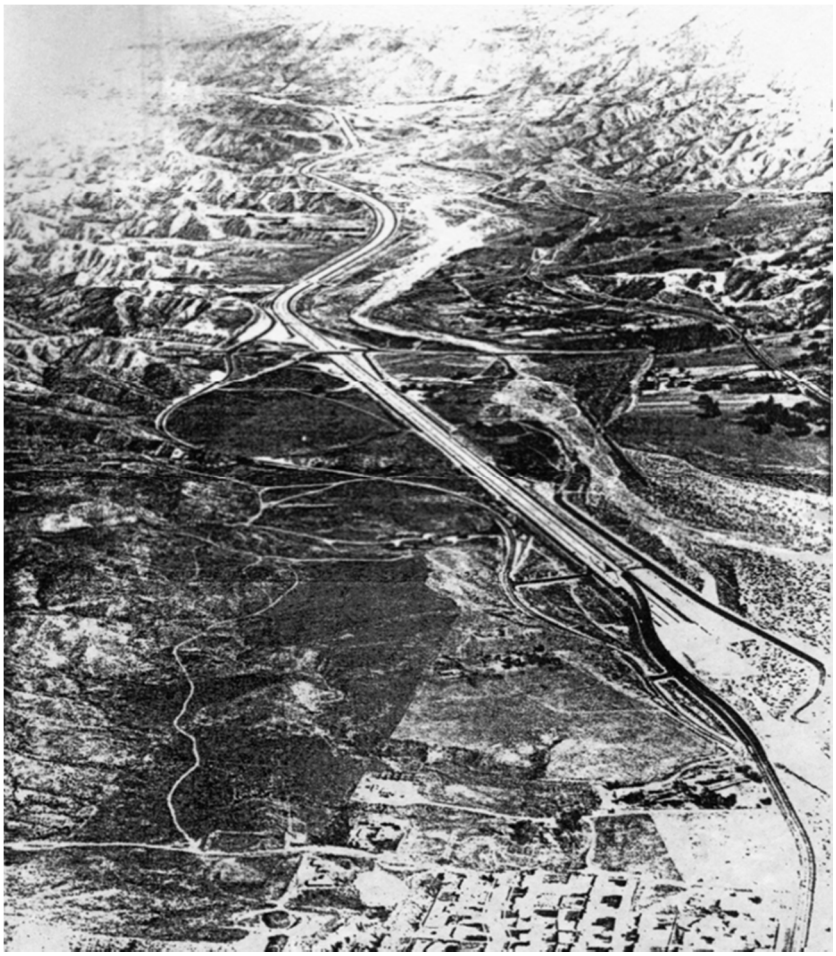


Figure 11: One Mile of SCC Pavement in 1963 near Lancaster, CA (Caltrans)

Several other cement companies including Medusa, TXI, Penn Dixie, and Southwest Portland subsequently obtained licenses to manufacture Type K. These additional licensees provided complete geographical coverage, making Type K available throughout the US. The Dyckerhoff Cement Company in Germany was also a licensee. In 1970, the Uniform Building Code approved the use of Type K cement as a satisfactory substitute for Portland Type I or Type II cement in structural concrete. The ACI Klein Symposium on Expansive Cement Concrete, which was held at the Fall ACI convention in November 1973, was published by ACI as a special publication (SP38). This publication contains 20 papers covering R&D and application of SCC in the US, Japan, and the USSR. The ACI Cedric Wilson Symposium on Expansive Concrete, which was held at eh fall ACI convention in 1977, was also published as a special publication (SP64). This publication contains an additional 15 papers on R&D and applications.

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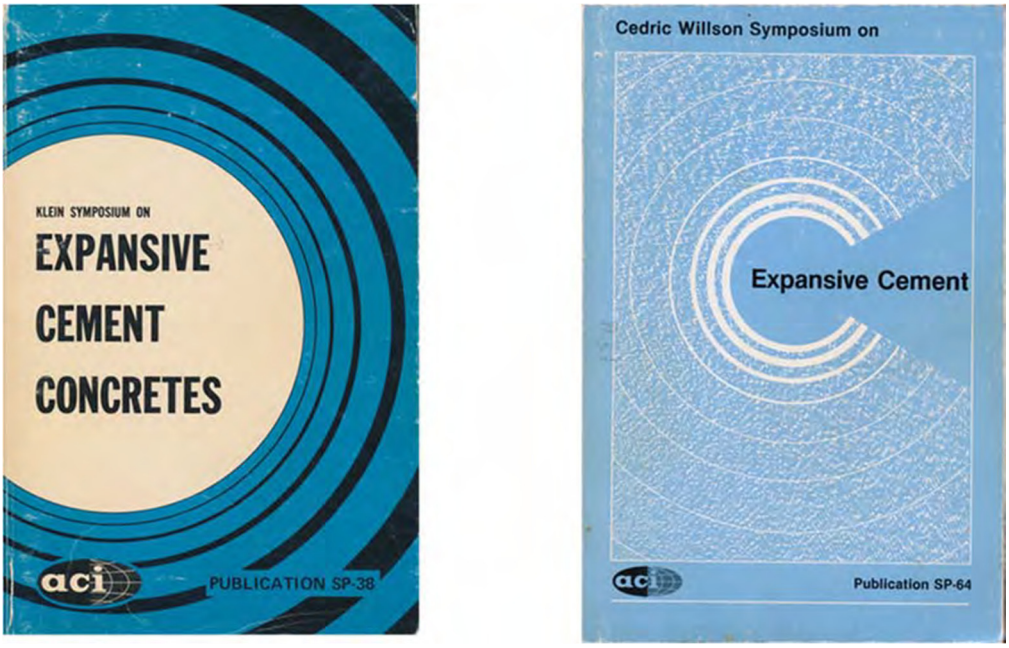


Figure 12: Klein and Wilson Symposium Special Publication Covers

Further examples of both historical and modern projects completed using Type K shrinkage compensating concrete appear in Figure 13 through Figure 21.

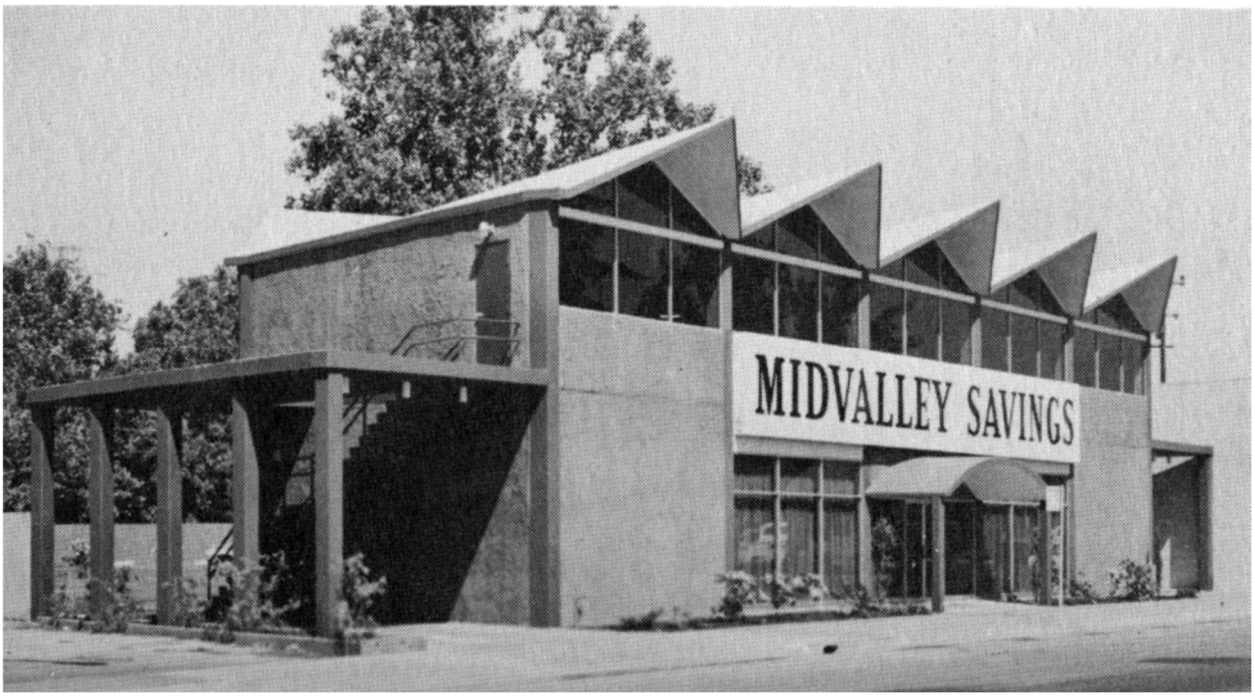


Figure 13: Mid-Valley Bank (Marysville, CA) 1963 -- Folded Plate Roof Without Typical Roofing Material

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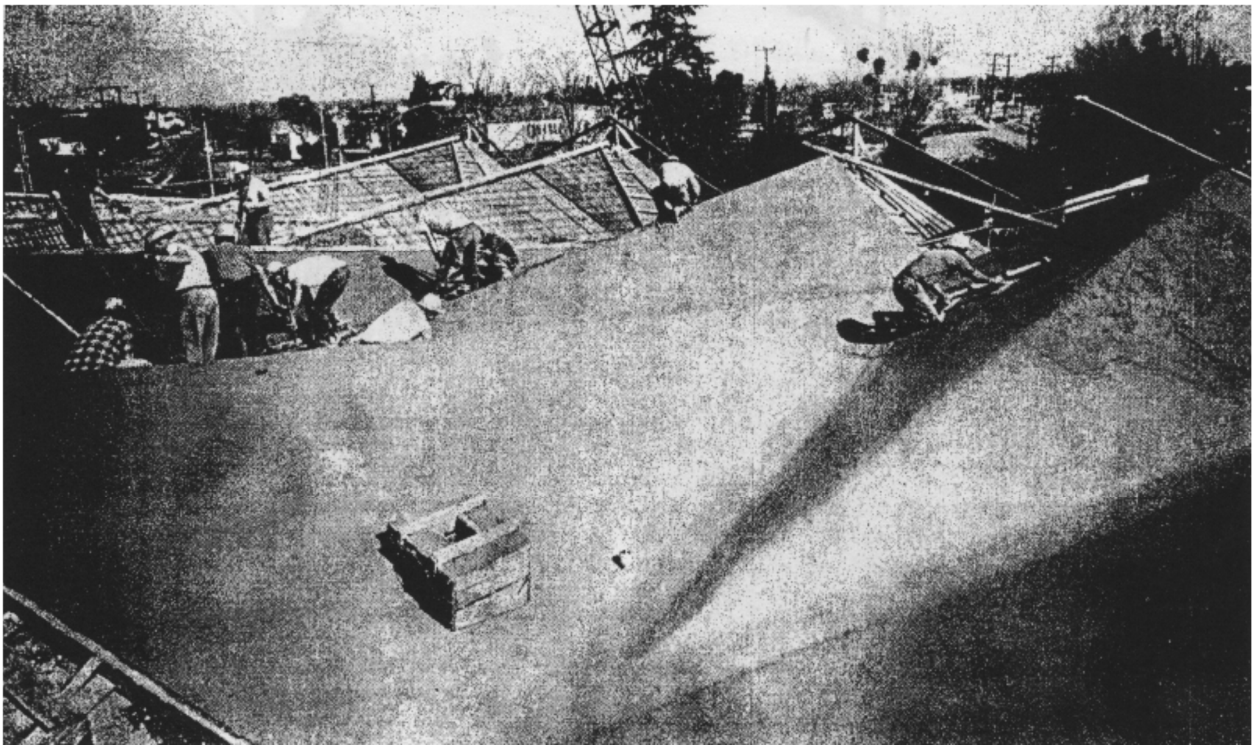


Figure 14: Mid-Valley Bank Roof Under Construction



Figure 15: A House Constructed Completely of Type K (Monolithic Roofs Without Any Roofing Material)

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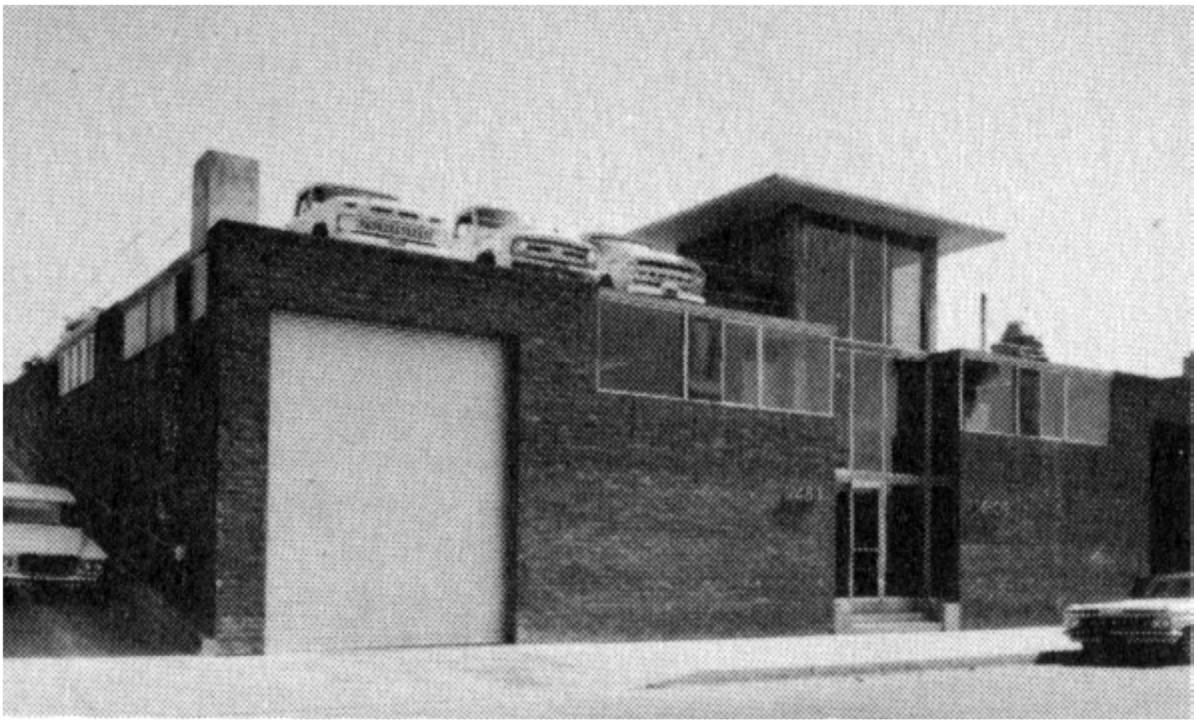


Figure 16: Industrial Building (Los Angeles) 1963 -- Roof Parking Without Typical Roofing Material

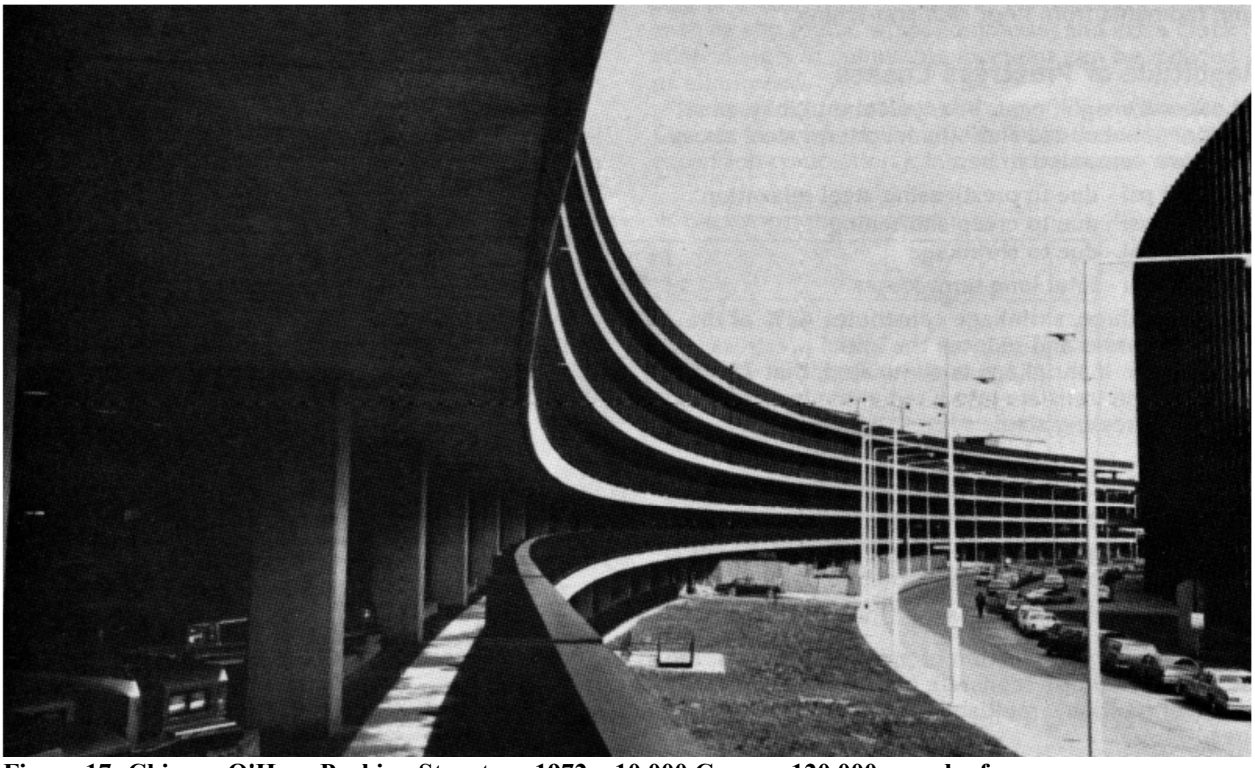


Figure 17: Chicago O'Hare Parking Structure 1972 – 10,000 Cars on 120,000 cu. yd. of SCC

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Figure 18: Rockford Airport Taxiway 1993 – 1,200” x 75” Post Tensioned (7" Thick vs. 15" for PCC)



Figure 19: TRW Office Building 1968 -- Post-Tensioned 439'-Long Without Expansion or Control Joints

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Figure 20: Toyota Warehouse (Ontario, CA) 1995 -- 760,000 sq. ft. Type K Concrete

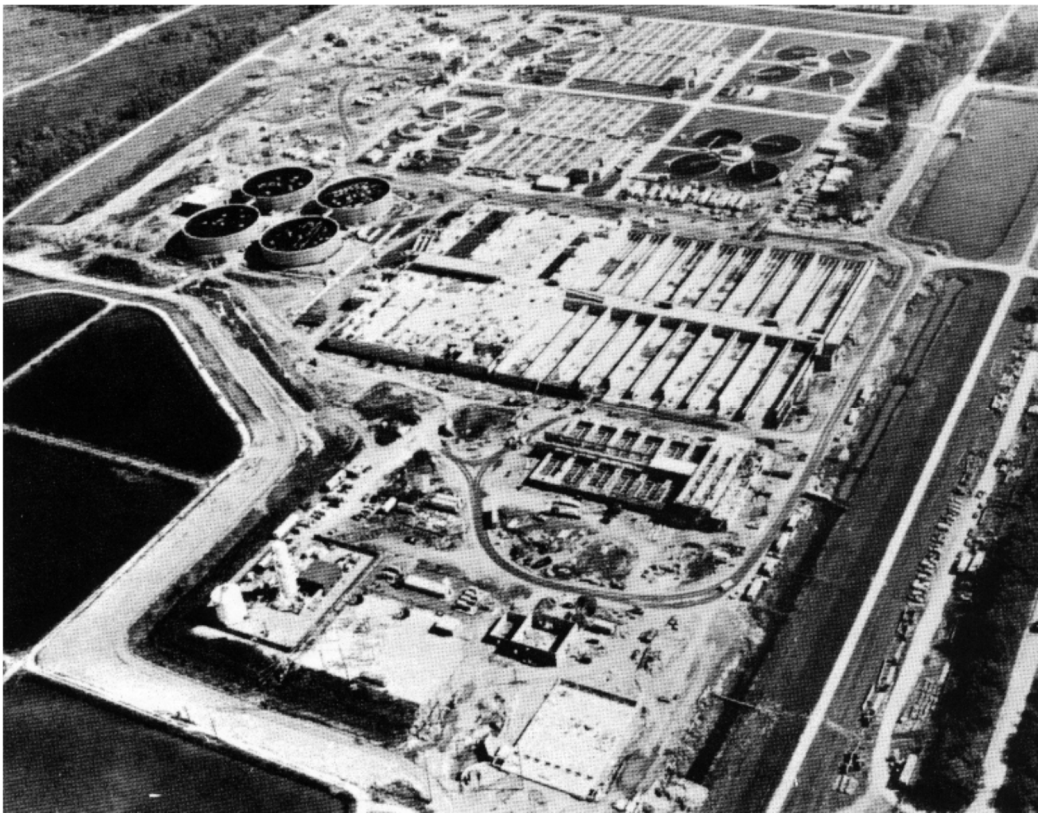


Figure 21: Water Treatment Facility (Indianapolis) 1984 -- 130,000 cu. yd. of Type K Concrete

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A Look Back at 1974 Type K Cements

By George C Hoff

Synopsis: Samples of Type K shrinkage-compensating cement from all 17 mills producing that cement in 1974 were obtained and evaluated for compliance with the specification that was proposed at that time for these types of cements. The cements were also evaluated for specific gravity, fineness, heat of hydration, and expansion and drying shrinkage in mortars. An X-ray diffraction analysis was also made for each cement in an attempt to compare cements to note significant differences in composition or relative amounts of constituents. A standard concrete mixture was also made with all the cements and evaluated for air content, slump, compressive strength, expansion, and drying shrinkage. The results from these evaluations are revisited. The application of the 1974 proposed specification called attention to several short-comings in that specification.

Keywords: Air content, compressive strength, drying shrinkage, restrained expansion, shrinkage compensating cements, slump tests, specifications, Type K expansive cement, X-ray diffraction.

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George C. Hoff

ACI Honorary Member and ACI Past-President Dr. George C. Hoff is a consulting engineer in private practice. He is a member and past secretary of ACI 223, Expansive Cement Concretes, and has served as chairman and secretary of many other ACI technical and Board committees. He has received numerous ACI and International awards and has authored and co-authored over 180 technical papers and 6 books dealing with concrete materials and concrete construction.

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INTRODUCTION

During the early 1970's there was considerable interest by several government agencies in using expansive cements in routine concrete construction as a means of minimizing shrinkage cracking. At that time there was no standard specification, however, for this type of cement by which an agency could insure the reliability and reproducibility of the product. Proposed specifications were being developed in Committee C-1 of the American Society for Testing and Materials (ASTM) but were not formally available for use. As a means of expediting the use of these cements in programs of the U.S. Army Corps of Engineers, an evaluation study was initiated in 1974 at the U.S. Army Engineer Waterways Experiment Station (WES), now known as the Engineering Research and Development Center (ERDC), Vicksburg, Mississippi, to compare all of the Type K expansive cements in production at that time with the proposed ASTM specification for expansive cements which was in a draft form. The chemical and physical requirements of that proposed specification in 1974 became a tentative specification in 1976 as ASTM C 845-76T. The requirements did not change during that period. The requirements of the tentative specification and the requirements of the current specification for Type K cements, ASTM C 845-04, are shown in Table 1. The reader should note that there are some differences in the two specifications.

The purpose of the evaluation was two-fold. First was to test the adequacy and responsiveness of the proposed specification to the needs of the U.S. Army Corps of Engineers. Second, the evaluation would give an indication of the degree of variability that could be expected from the industry and would highlight any special problem areas that might limit the use of these cements.

The contents of this paper are of historical significance with the results being previously presented in a WES report, "A Look at Type K Shrinkage-Compensating Cement Production and Specifications," (Hoff and Mather, 1978) and again in ACI Publication SP-64 (Hoff and Mather, 1981).

Table 1 Type K Cement Chemical and Physical Requirements

	ASTM C 845-76T	ASTM C 845-04
Chemical Requirements		
Magnesium Oxide, (MgO), max. %	5.0	6.0
Insoluble Residue, max., %	1.0	1.0
Loss on Ignition, max., %	4.0	4.0
Total Alkalis**, (Na_2O + 0.658 K_2O), max, %	0.60	0.60**
Physical Requirements		
Air Content, max., %	12.0	12.0
Compressive Strength, min.		
7-day, psi, (MPa)	2100 (14.7)	2100 (14.7)
28-day, psi, (MPa)	3500 (24.5)	3500 (24.5)
Restrained Expansion		
7-day expansion		
min, %	0.04	0.04
max, %	0.10	0.10
28-day expansion, percentage of 7-day expansion, max., %	115	115
Time of Setting, min., minutes	90	75

** Total Alkalis are an optional chemical requirement in both the C 845-76T and C845-04 specifications.

MATERIALS

To make the necessary comparisons, a 100- to 200-lb (45- to 90-kg) sample of Type K shrinkage-compensating cement was obtained from the standard production runs of each of the 17 cement mills which were producing Type K at that time. A list of the cement companies and the mills is contained in Table 2. The samples were obtained over the period of March to December 1974 with most of the samples being obtained in April through August. In two instances, additional samples were obtained from a mill to substantiate the observed performance of

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the first sample. In these instances, there was no way to tell if the two samples came from the same production run. Each sample received was given a WES Research Cement (RC) identification number.

An ASTM C-150, Type II cement was also used for making a control concrete mixture for the concrete part of this evaluation.

Table 2 Sources of Type K Cements Evaluated

Cement Company	Mill
Texas Industries	Midlothian, Texas
Southwestern Portland Cement Company	Odessa, Texas
	Fairborn, Ohio
Penn-Dixie Cement Corporation	Petoskey, Michigan
	Kingsport, Tennessee
	West Winfield, Pennsylvania
	Nazareth, Pennsylvania
	Howes Cave, New York
	West Des Moines, Iowa
Medusa Portland Cement Company	York, Pennsylvania
	Clinchfield, Georgia
	Wampum, Pennsylvania
	Dixon, Illinois
Kaiser Cement and Gypsum Corporation	Permanente, California
	Lucerne Valley, California
	San Antonio, Texas
	Montana City, Montana

TEST PROGRAM

Each cement was evaluated in accordance with the requirements of the tentative Type K specification of Table 1. In addition to these requirements, each cement was also evaluated for its specific gravity, fineness (air permeability), heat of hydration, and restrained drying shrinkage. An X-ray diffraction analysis was also made for each cement in an attempt to compare cements to note significant differences in composition or relative amounts of constituents. A standard concrete mixture was also developed in which each cement was used and evaluated for air content, slump, compressive strength, restrained expansion, and restrained drying shrinkage. The various test procedures used in these evaluations were as follows (The reader should note that these procedures were those in effect in 1974 and may be different in the present day versions of these test methods.):

a) Chemical Analysis – ASTM Method C 114, Chemical Analysis of Hydraulic Cement.
b) Air Content – ASTM Method C 185, Air Content of Hydraulic Cement Mortar, using the actual specific gravity of the cement if it differs from 3.15 by more than 0.05 in calculating the air content.
c) Time of Setting – ASTM Method C 807, Time of Setting of Hydraulic Cement Mortar by Vicat Needle.
d) Compressive Strength (Mortar) – ASTM Method C 109, Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens), except that a water-cement ratio of 0.5 was used, the specimens were covered with glass to prevent loss or gain of moisture at the surface of the specimen during the moist curing period in the molds, and the specimens remained in the molds for 3 days.
e) Restrained Expansion of Mortar – ASTM Method C 806, Restrained Expansion of Expansive Cement Mortar.
f) Specific Gravity – ASTM Method C 188, Specific Gravity of Hydraulic Cement.
g) Fineness – ASTM Method 204, Fineness of Portland Cement by Air Permeability Apparatus.
h) Heat of Hydration – ASTM Method C 186, Heat of Hydration of Hydraulic Cement, determined at 7 and 28 days age.
i) Air Content (Concrete) – ASTM Method C 231, Air Content of Freshly Mixed Concrete by the Pressure Method, using a Type B meter.
j) Slump – ASTM Method C 143, Slump of Portland Cement Concrete.

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k) Compressive Strength (Concrete) – ASTM Method C 39, Compressive Strength of Cylindrical Concrete Specimens, using 6-in. by 12-in. (152-mm by 305-mm) cylinders.
l) Restrained Expansion of Concrete – Proposed Test Method for Restrained Expansion of Shrinkage-Compensating Concrete (1976 Annual Book of ASTM Standards, Part 14, pp 684-688), except that all bars were demolded at 6-1/2 ± ¼ hr with initial bar readings being made 30 minutes after demolding. All aggregate larger than 3/4-in. (19.0-mm) was wet screened from the mixture prior to casting the bars.
m) Drying Shrinkage – ASTM Method C 157, Length Change of Hardened Cement Mortar and Concrete, using both the restrained bars of mortar and concrete and, after 28 days moist curing, storage at 73.4 ± 3°F (23.0 ± 1.7°C) and 50 percent RH for an additional 90 days with length changes being noted to 90 days.

MIXTURE PROPORTIONS

Mortar mixture

The mortar mixture used for all the tests used one part of cement to 2.75 parts of graded Ottawa sand by weight. The water-cement ration was 0.5 by weight. All mixing was done in a table-top paddle mixer. An ASTM Type II Portland cement was also included in the test program for comparison purposes. Two rounds of test specimens were made for each cement.

Concrete mixture

The concrete mixture used with all the expansive cements plus a Type II Portland cement for control was as follows:

Ingredient	Saturated-Surface Dry Batch Weight, lb/yd^3 (kg/m^3)
Cement	550.0 (326.3)
Fine Aggregate	1146.8 (680.4)
Coarse Aggregate	
No. 4 – 3/4-in. (4.75 – 19 mm)	1071.3 (635.6)
3/4 - 1-1/2-in. (19.0 – 38.1 mm)	838.7 (497.6)
Water	291.5 (172.9)

The concrete was air-entrained, and included 4.6 ounces (135 ml) of air-entraining admixture per cubic yard. The coarse aggregate was crushed limestone. The fine aggregate was a manufactured limestone sand. The sand-aggregate ratio was 38 percent by volume. The water-cement ratio was 0.53.

TEST RESULTS FOR SPECIFICATION EVALUATION

The results of the chemical and physical tests of the cement in accordance with the tentative expansive cement specification are contained in Table 3 and 4, respectively.

Chemical analyses

The results of the chemical analysis of 19 samples representing 17 mills (Table 3) show that all the expansive cements meet the requirements for magnesium oxide (Mg0), insoluble residue, and loss on ignition. Two mills (three samples, RC-694, -695, -695(2)) did not meet the optional requirement of 0.60 percent total alkalis with both mills exceeding the maximum allowable. The sulfate content (SO_3) of each cement, although not a specification requirement, is also shown in Table 3 as additional information.

The range of the MgO values obtained was 0.7 to 4.3 with an average value of 2.2 percent. The insoluble residue content varied from 0.10 to 0.82 percent with an average value of 0.38 percent. The loss on ignition ranged from 0.9 to 2.4 percent with an average value of 1.8 percent. The optional requirement for total alkalis varied from 0.14 to 0.77 percent with an average value of 0.47 percent for all samples and ranged from 0.14 to 0.58 percent with an average value of 0.42 percent for those samples which met the specification requirements. The sulfate content ranged from 4.6 to 7.5 percent with an average value of 6.0 percent.

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Table 3 Summary of Expansive Cement Chemical Test Data

Cement	Magnesium Oxide (MgO), %	Insoluble Residue, %	Loss on Ignition, %	Total Alkalis, (Na_2O + 0.658 K_2O)	SO_3, %
Tentative ASTM Spec.	5.0 (Max.)	1.0 (Max.)	4.0 (Max.)	0.60 (max.)	----
Type II Control	1.0	0.12	0.8	0.54	2.0
RC-687	0.7	0.59	1.3	0.43	5.9
RC-689	0.8	0.10	0.9	0.27	4.6
RC-690	3.9	0.45	2.2	0.58	6.8
RC-690 (2)	4.3	0.28	2.0	0.56	5.0
RC-691	3.1	0.22	2.1	0.45	6.0
RC-692	2.9	0.15	1.4	0.57	6.0
RC-693	1.0	0.82	2.1	0.38	6.3
RC-694	2.1	0.33	2.3	0.77	6.4
RC-695	2.2	0.52	2.2	0.75	5.9
RC-695 (2)	2.2	0.39	2.3	0.70	6.1
RC-696	2.8	0.37	2.4	0.43	5.8
RC-697	3.6	0.23	1.6	0.45	5.1
RC-698	2.4	0.60	2.1	0.14	6.3
RC-700	1.1	0.18	1.7	0.46	6.0
RC-702	0.9	0.35	1.1	0.48	6.3
RC-703	1.9	0.54	1.1	0.40	6.5
RC-707	1.1	0.17	1.8	0.26	7.5
RC-709	2.7	0.42	1.6	0.37	6.7
RC-711	2.9	0.48	2.3	0.56	5.2

Air content (mortar)

The air content of the standard mortar mixture (Table 4) ranged from 7.2 to 11.3 percent with an average value of 8.7 percent. Each air content shown in Table 4 represents the average of measurements on two batches.

Compressive strength (mortar cubes)

The compressive strength of the mortar cubes made with a given cement was determined from 2-in. (50-mm) cubes from two individual batches made with that cement. Each strength value shown in Table 4 represents the average of six individual cube tests. For all 19 cement samples, the 7-day cube strengths ranged from 3070 psi (21.2 MPa) (RC-690) to 4730 psi (32.6 MPa) (RC-695) with an average strength of 4145 psi (28.6 MPa). The 28-day cube strengths ranged from 4860 psi (33.5 MPa) (RC-709) to 7010 psi (48.3 MPa) (RC-703 with an average strength of 5750 psi (39.6 MPa).

Restrained expansion (mortar bars)

The restrained expansion values shown in Table 4 represent the average expansion of four bars, two each, from two batches made with each cement. The 7-day restrained expansion ranged from 0.028 (RC-687) to 0.104 percent (RC-690) with an average of 0.052 percent. Seven samples representing 6 mills or approximately 35 percent of the mills did not meet the 7-day expansion requirements. Initially, 5 samples (RC-687, -694, -695, -700, -711) did not meet the minimum expansion requirement of 0.10 percent. Upon evaluating a second sample from two of these mills, one of the mills with a low value (RC-695) achieved satisfactory expansions while the mill with the high value (RC-690) traversed the entire acceptable range of expansions and then failed the minimum expansion requirement (RC-690(2)).

The 28-day expansions were not to exceed the 7-day expansions by more than 15 percent. All but four (RC-690(2), -703, -709, -711) of the samples achieved this. The range of percentages of the 7-day expansions was from 93 to 155 percent with an average of 108 percent.

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Table 4 Summary of Type K Expansive Cement Physical Test Data

Cement	Physical Property**								
	Air Cont, %	Time of Setting, Hr:Min	Compressive Strength, psi (MPa)		Restrained Expansion, %		Specific Gravity	Fineness, Blaine (Air Perm.) cm^2/gm	Heat of Hydration, cal/gm 7-d (28-d)
			7-Day	28-Day	7-Day	28-Day			
Tentative ASTM Spec	12.0, max.	1:30 min.	2100 (14.5) min.	3500 (24.1) min.	0.04 to 0.10	Not more than 115% of 7-d expan	----	----	----
Type II Control	8.1	----	3160 (21.8)	----	0.004	125	3.14	3295	----
RC-687	9.0	3:00	4320 (29.8)	5700 (39.3)	0.028	100	3.09	3550	80 (87)
RC-689	8.8	1:40	4500 (31.0)	5550 (38.3)	0.058	109	3.13	3730	85 (96)
RC-690	8.8	2:00	3070 (21.3)	4940 (34.1)	0.104	102	3.06	4290	72 (89)
RC-690 (2)	8.3	2:00	4190 (28.9)	5470 (37.7)	0.036	125	3.09	4220	78 (88)
RC-691	9.3	3:00	4240 (29.2)	5690 (39.2)	0.058	102	3.06	4210	77 (97)
RC-692	7.2	2:55	4680 (32.3)	6020 (41.5)	0.046	100	3.11	4220	75 (86)
RC-693	7.7	2:40	4320 (29.8)	5970 (41.2)	0.058	96	3.08	4330	72 (92)
RC-694	10.0	2:50	4560 (31.4)	5720 (39.4)	0.034	103	3.05	4510	88 (94)
RC-695	8.6	2:12	4730 (32.6)	6010 (41.4)	0.033	100	3.05	5360	84 (88)
RC-695 (2)	7.6	2:10	4470 (30.8)	---- (----)	0.057	93	3.08	4890	--- (---)
RC-696	10.9	3:10	3880 (26.8)	5080 (32.0)	0.065	98	3.00	4500	79 (84)
RC-697	11.3	3:06	4170 (28.8)	5190 (35.8)	0.040	102	3.12	3600	75 (84)
RC-698	10.1	2:29	4530 (31.2)	6600 (45.5)	0.046	100	3.09	5240	67 (83)
RC-700	7.3	2:40	4230 (29.2)	5740 (39.6)	0.039	108	3.11	4210	71 (84)
RC-702	8.4	4:50	3570 (24.6)	5990 (41.3)	0.055	104	3.16	4520	67 (81)
RC-703	7.7	2:35	3960 (27.3)	6500 (44.8)	0.063	119	3.17	4490	70 (83)
RC-707	7.8	4:27	4320 (29.8)	7010 (48.3)	0.068	107	3.06	4180	73 (94)
RC-709	9.3	4:48	3220 (22.2)	4860 (33.5)	0.062	155	3.12	4270	63 (77)
RC-711	7.8	2:02	3840 (26.5)	5290 (36.5)	0.037	132	3.09	4370	73 (85)

** All values are the average of specimens from two rounds of mortar.

Time of setting

Times of setting were determined on each of the two batches from each cement used to make the strength cubes and expansion bars. The times of setting ranged from 1 hour 40 minutes to 4 hours 50 minutes with an average time of setting of 2 hours 50 minutes.

Other cement data

Although not specifically called for in the tentative expansive-cement specification, additional data on characteristics of the expansive cements were obtained to aid in the overall evaluation of these cements. These characteristics included specific gravity, fineness, and heat of hydration (Table 4).

The specific gravity ranged from 3.00 to 3.17 with an average value of 3.09. The fineness (air permeability) ranged from 3550 to 5360 cm^2/g with an average fineness of 4350 cm^2/g. The heat of hydration at 7-days age ranged from 63 to 88 cal/g with an average value of 75 cal/g, while at 28-days age, the range increased to 77 to 96 cal/g with an average value of 88 cal/g.

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CONCRETE TEST RESULTS

The expansive-cement concrete portion of this study was done to get an indication of any variability effects the cements from across the industry might have on such concrete characteristics as air content, slump, compressive strength, and restrained expansion. The proportions of each batch were the same with only the cement being varied. The results of the physical tests of the concrete are contained in Table 5. Each result represents the average of test specimens from two batches of concrete. The restrained-expansion bars were made from concrete that was wet-sieved over a 3/4-in. (19.0 mm) sieve. This was necessitated by the maximum size of the aggregate (1-1/2-in. (38.1-mm) MSA), the least dimension of the bar (3-in. (76 mm)), and the centrally located restraining rod in the bar.

Air content (concrete)

The air content of the concrete varied for the individual batches from 2.4 percent for RC-694 and RC-698 to 6.0 percent for RC-700. The average air content for concrete made with all 19 cements was 4.1 percent. The Type II control mixture had an average air content of 3.8 percent.

Slump

The slump of the individual batches of concrete varied from a low of 2-1/4 in. (57-mm) for RC-702 to a high of 4-1/2 in. (117-mm) for mixtures RC-687, RC-689, and RC-709. The average slump for all the expansive cement concrete rounded to the nearest 1/8-in. (3.2-mm) was 3-1/4 in. (83-mm). The average slump of the Type II control concrete was 3-7/8-in. (98-mm).

Table 5 Summary of Type K Expansive Cement Concrete Test Results

Cement	Physical Property**						
	Slump, in. (mm)	Air Content %	Unit Weight, pcf (kg/m^3)	Compressive Strength, psi (MPa)		Restrained Expansion, %	
				7-day	28-day	7-day	28-day
Type II Control	3-7/8 (98)	3.8	147.1 (2356)	3335 (24.9)	4645 (32.0)	-0.002	0.002
RC-687	4-1/8 (105)	4.8	144.3 (2311)	3605 (24.9)	4665 (32.2)	0.024	0.027
RC-689	4-1/8 (105)	4.6	146.7 (2350)	3595 (24.8)	4910 (33.9)	0.065	0.070
RC-690	2-7/8 (73)	3.4	147.0 (2354)	3535 (24.4)	4665 (32.2)	0.130	0.133
RC-690 (2)	2-1/2 (64)	4.0	147.9 (2369)	3970 (27.4)	5015 (34.6)	0.039	0.040
RC-691	3 (75)	3.6	147.1 (2356)	4000 (27.6)	5205 (35.9)	0.047	0.046
RC-692	3 (75)	2.4	148.7 (2382)	4185 (28.8)	5565 (38.4)	0.034	0.033
RC-693	3 (75)	3.3	147.5 (2363)	3860 (26.6)	5080 (35.0)	0.028	0.030
RC-694	3-1/4 (82)	3.9	145.8 (2335)	4205 (29.0)	5180 (35.7)	0.030	0.030
RC-695	3 (75)	2.6	148.1 (2372)	4145 (28.6)	5465 (37.7)	0.050	0.051
RC-695 (2)	2-3/4 (70)	3.4	149.6 (2396)	4085 (28.2)	5865 (40.4)	0.044	0.050
RC-696	2-1/2 (64)	2.9	148.2 (2374)	4455 (30.7)	5820 (40.1)	0.037	0.041
RC-697	3-1/2 (89)	5.3	144.6 (2316)	3560 (24.5)	4470 (30.8)	0.028	0.030
RC-698	2-3/8 (60)	2.4	148.4 (2377)	4080 (28.1)	5845 (40.3)	0.032	0.032
RC-700	3-3/4 (95)	6.0	145.6 (2332)	3630 (25.0)	4580 (31.6)	0.025	0.028
RC-702	4-1/2(114)	5.2	146.2 (2342)	3355 (23.1)	5135 (35.4)	0.044	0.044
RC-703	3-1/2 (89)	5.5	146.2 (2342)	3405 (23.5)	5160 (35.6)	0.052	0.052
RC-707	4 (100)	4.2	148.4 (2377)	4560 (31.4)	5720 (39.4)	0.036	0.036
RC-709	4-1/8 (105)	5.2	147.1 (2356)	3135 (21.6)	4495 (31.0)	0.038	0.048
RC-711	3-3/8 (86)	4.8	144.2 (2310)	3465 (23.9)	4710 (32.5)	0.029	0.030

** All values are the average of specimens from two rounds of concrete

Compressive strength (concrete cylinders)

The compressive strength of the concrete was determined from testing 6-in. by 12-in. (152-mm by 305-mm) cylinders. Each batch of concrete had two cylinders evaluated at both 7 days and 28 days age. The values shown in Table 5 represent the average of two batches for each cement or a total of 4 cylinders at each age.

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The 7-day compressive strengths of the individual batches varied from 3135 psi (21.6MPa) for RC-709 to 4560 psi (31.4 MPa) for RC-707. The average 7-day strength for all 19 cements was 3830 psi (26.4 MPa). The Type II control strength at the same age was 3335 psi (24.9 MPa). The 28-day strengths varied from 4495 psi (31.0 MPa) for RC-709 to 5865 psi (40.4 MPa) for RC-696(2). The average 28-day strength for all 19 cements was 5130 psi (35.4 MPa). The Type II control strength at the same age was 4700 psi (32.4 MPa).

Restrained expansion (concrete bars)

The restrained-expansion values shown in Table 5 represent the average expansion of four bars, two each from two batches made with each cement. The 7-day restrained expansions ranged from 0.024 percent for RC-687 to 0.130 percent for RC-690 with an average restrained expansion for all 19 cements of 0.044 percent. The 28-day restrained expansion ranged from 0.027 percent for RC-687 to 0.133 percent for RC-690. It should be noted that both these cements also established the range limits for the 7-day expansions. The average 28-day restrained expansion for all 19 cements was 0.045 percent which was significantly different than the average expansion at 7 days.

The average restrained expansions for the Type II control mixture at 7 and 28 days were -0.002 percent and +0.002 percent, respectively.

DRYING SHRINKAGE TEST RESULTS

Drying shrinkage of cement paste, mortar, and concrete is usually measured on unrestrained prisms of the material. Restraint is the mechanism by which the expansive cements effectively use their expansions, however, this restraint should also then be present when the expansive cements lose their effectiveness through drying. The data contained in Table 6 represent the restrained drying shrinkage of the same restrained expansion prisms used in this study for the mortars and concretes, respectively. Although the prisms are allowed to dry for 90- days, most of the length change had occurred after 60 days of drying. The shrinkage values reported in Table 6 for both mortar bars and concrete bars are referenced to the length of each bar after 28-days expansion.

Restrained mortar bar shrinkage

The length changes of the restrained mortar bars after 90 days of curing at 73°F (22.8°C) and 50 percent relative humidity, shown in Table 6, varied from a low value of 0.065 percent for RC-695(2) to a high value of 0.103 percent for RC-709. The average shrinkage for all 19 cements was 0.080 percent, which was slightly more than the 0.063 percent shrinkage experienced by the Type II control cement.

When these shrinkage values are combined with the observed expansions which preceded the shrinkage, the net change in bar lengths was observed to vary from a net increase of 0.014 percent for RC-690 to a net decrease of 0.051 percent for RC-687. The average net length change for all cements was a shrinkage of 0.024 percent as compared to a net shrinkage of 0.058 percent for the Type II control cement.

Restrained concrete bar shrinkage

The length changes of the restrained concrete bars after 90 days of curing at 73°F (22.8°C) and 50 percent relative humidity, shown in Table 6, varied from a low value of 0.033 percent (RC-707) to a high value of 0.052 percent (RC-687, -691). The difference in the high and low values for the concrete was 0.019 percent, which was only 60 percent of the difference (0.032) for the mortars with the same cements. The average concrete shrinkage for all 19 cement samples was 0.044 percent which was not significantly different than the 0.045 percent shrinkage observed for the Type II Portland cement control bars.

Combining these shrinkage values with the observed expansions at 28-days age which preceded the shrinkage, the net change in bar lengths varied from a net increase of 0.082 percent (RC-690) to a net decrease of -0.025 percent (RC-687). The range of these length changes was approximately 60 percent greater than the range observed for the mortar bars. The average net length change for all 19 cements was 0 percent as compared to a net shrinkage of 0.043 for the Type II Portland cement control bars.

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Table 6 Summary of Length Change Measurements of Restrained Bars

Cement Designation	Mortar Bars				Concrete Bars		
	Total 28-Day Expansion, %	Total 90-Day Shrinkage, %	Change From Initial Length, %		Total 28-Day Expansion, %	Total 90-Day Shrinkage, %	Change From Initial Length, %
Type II Control	0.005	0.063	-0.058		0.002	0.045	-0.043
RC-687	0.028	0.079	-0.051		0.027	0.052	-0.025
RC-689	0.063	0.090	-0.027		0.070	0.050	+0.020
RC-690	0.106	0.092	+0.014		0.133	0.051	+0.082
RC-690 (2)	0.045	0.071	-0.026		0.040	0.037	+0.003
RC-691	0.059	0.094	-0.035		0.046	0.052	-0.006
RC-692	0.046	0.083	-0.037		0.033	0.045	-0.012
RC-693	0.056	0.085	-0.029		0.030	0.047	-0.017
RC-694	0.035	0.083	-0.048		0.030	0.049	-0.019
RC-695	0.033	0.077	-0.044		0.051	0.047	+0.004
RC-695 (2)	0.053	0.065	-0.012		0.049	0.044	+0.006
RC-696	0.064	0.097	-0.033		0.041	0.048	-0.007
RC-697	0.041	0.071	-0.030		0.030	0.040	-0.010
RC-698	0.046	0.086	-0.040		0.032	0.043	-0.011
RC-700	0.042	0.073	-0.031		0.028	0.041	-0.013
RC-702	0.057	0.073	-0.016		0.044	0.041	+0.003
RC-703	0.075	0.084	-0.009		0.052	0.035	+0.017
RC-707	0.073	0.066	+0.007		0.036	0.033	+0.003
RC-709	0.096	0.103	-0.007		0.048	0.043	+0.005
RC-711	0.049	0.072	-0.023		0.030	0.047	-0.017

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X-Ray diffraction test procedures

Each cement was examined in the as-received condition, front loaded and tight packed in a sample holder giving a sample surface approximately 2-3/4 in. (70 mm) long. All examinations were made in a static nitrogen atmosphere. Another sample of each cement, weighing 0.176 ounces (5.0000 grams) was treated with maleic acid in absolute methanol to remove the calcium silicates and leave calcium aluminoferrites, tricalcium aluminate (C_3A), calcium sulfates, tetracalcium trialuminate sulfate ($C_4A_3\hat{S}$), and magnesia (MgO) in the insoluble residue. The residue was weighed after drying to a free-flowing condition and was examined on the diffractometer. A few of the residues insoluble in maleic acid were treated with 10 percent ammonium chloride (NH_4Cl) solution to remove calcium sulfates and were then examined on the diffractometer.

The diffractometer was standardized using an external quartz standard before each examination. Although the X-ray diffraction work covered a period of 10 months, the diffraction charts are regarded as comparable because of the standardization and adjustment of the ratemeter, kilovoltage (kv), and milliamperage (ma) to comparable intensity levels at low-power and high-power settings. Low power was used from 5 to 20° two theta, with 27 kilovolts constant potential (kvcp) and 41 ma, using a 1° beam slit, 3° beam slit as a soller slit, and a 0.2° detector slit. The chart range was approximately logarithmic from 10 to 4000 counts for full-scale deflection. High-power settings were used for the range from 20° two theta to 65°, at 50 kvcp and 21 ma, using a 3° beam slit and the same scale, with the rest of the X-ray collimation for low power. All of the X-ray diffractometer charts were compared and intensities in chart units were measured on the charts of as-received cements and of maleic acid-insoluble residues, after a background had been drawn to bisect the background level from 20° to 65° two theta and sketched from 5° to 20° two theta on the diffraction charts. Table 7 show the most easily measured intensities of alite (substituted tricalcium silicate), belite (substituted dicalcium silicate), the strongest line of ($C_4A_3\hat{S}$), two tricalcium

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aluminate lines, the strongest line of magnesia (MgO), and an aluminoferrite line of fairly high intensity that is not interfered with.

It is possible that some of the maleic acid used to remove silicates may have contained other materials that also affected other constituents, because some of the maleic acid was not satisfactory in determining cement in hardened concrete.

Identification of constituents

Calcium sulfate was found in these cements as $CaSO_4$ (anhydrite), $CaSO_4 \cdot 0.5H_2O$ (plaster of paris), and $CaSO_4 \cdot 2\ H_2O$ (gypsum). In 10 of the 19 cements, gypsum was shown clearly to be present and made a considerable contribution to the total calcium sulfate. In 4 of the cements, it was barely detectable, and in the remaining 5 cements, it was not detected at all by X-ray diffraction of the as-received samples. All 19 cements contained $CaSO_4$ (anhydrite). All of the cements contained $CaSO_4 \cdot 0.5H_2O$ after treatment with maleic acid. However, it was not surely identified although it was suspected in the diffraction charts of several of the as-received cements. Because of the uncertainty in identifying $CaSO_4 \cdot 0.5H_2O$ in the as-received cements, the distribution of calcium sulfate in two or three compounds in most of the cements, and since each sulfate differs from the others in absorption coefficient and thus somewhat in diffracting ability, there was no satisfactory measurement of total calcium sulfate by X-ray diffraction. Table 7 shows SO_3 by chemical analysis as a measure of calcium sulfate. Tricalcium aluminate (C_3A) was identified in 17 of the 19 cements.

Table 7 X-Ray Diffraction Intensities in Chart Units, SO_3, and Amount Insoluble in Maleic Acid in Percent

Cement Designation	As Received		SO_3 %	Insoluble in Maleic Acid, % (by weight)	Constituents Insoluble in Maleic Acid			MgO[c] 2.10A	Alumino-ferrites[c] 7.2-7.3A
					$C_4\bar{A}_3S$[c]	C_3A[d]			
	Alite 1.76A[a]	Belite 2.88A[b]			3.76A	1.90A	1.558A		
RC-687	43	11	5.9	28.07	21.7	27	23	2.5	36
RC-689	41	10	4.6	22.48	25.2	12	12	2	12
RC-690	29	14	6.8	27.03	27.5	20	15	31	16
RC-690 (2)	34	8	5.0	27.45	22.5	15	15	35	12
RC-691	39	11	6.0	26.06	26	26	19	18	12
RC-692	31	13	6.0	28.01	24.5	22	16	12	14
RC-693	35	11	6.3	26.50	23.5	18	11	6	18
RC-694	29	7	6.4	31.78	23	29	23	20	12
RC-695	27	9	5.9	30.70	18	20	14	19	13
RC-695 (2)	30	17	6.1	24.92	29.7	16	11	16	16
RC-696	39.5	6	5.8	27.09	29	22	18	21	12
RC-697	23	10	5.1	28.10	19	11	6	21	15
RC-698	36	14	6.3	23.39	27.9	19	15	4	16
RC-700	29	8	6.0	28.48	20.6	nd[e]	nd	3	21
RC-702	30.5	8	6.3	25.79	28.9	8	nd	5	16
RC-703	33.3	6	6.5	24.94	30.2	tr[f]	nd	12	16
RC-707	36.8	11	7.5	29.82	20.8	33	24	5	12
RC-709	30.5	8	6.7	26.61	25	nd	nd	14	16
RC-711	26.8	8	5.2	27.25	21.1	4	nd	16	17

a. Strongest uninterfered with line of substituted C_3S.
b. Only measurable line of substituted C_2S.
c. Strongest line.
d. Lines of second and third intensity in C_3A
e. nd = not detected.
f. tr = trace.

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Effects of composition

Although C_3A as well as $C_4A_3\hat{S}$ can participate in forming ettringite, and although C_3A was as or more abundant than $C_4A_3\hat{S}$ in several of the cements, it appears that the C_3A did not affect the restrained expansion significantly with the possible exception of RC-707, which contained more C_3A than any of the other cements. The restrained expansion at 7 days was significantly higher than in several other cements with similar intensity of $C_4A_3\hat{S}$ but RC-707 also contained more SO_3 than any of the others. It seems reasonable to postulate that $C_4A_3\hat{S}$ blended with Portland cement is more easily accessible to hydration and formation of ettringite than C_3A which may be protected in part from hydration by other cement constituents and thus hydrate more slowly to, or convert to, monosulfate ($C_4A\hat{S}H_{12}$) rather than forming and persisting as ettringite. The apparent absence of effect of C_3A in these shrinkage-compensating cements was somewhat surprising.

Aluminoferrite is recorded in Table 7 but no effect on the behavior of the shrinkage-compensating cements was expected from it nor was any effect found.

The influences on retrained expansion that appear to be most active include the amount of $C_4A_3\hat{S}$ (as indicated by the height of the line at 3.76 A chart intensity), the fineness of the cement, the amount of alite, and the total amount of sulfate. Strength at early ages is also significant along with extremes of fineness. Examples are given in the following discussion.

RC-687 had the lowest fineness recorded (3550 cm^2/gm), low $C_4A_3\hat{S}$, high alite, and an above average 7-day compressive strength (4320 psi (29.8 MPa)), all of which suggests that there was too little $C_4A_3\hat{S}$ to form enough ettringite to expand the fairly strong framework developed in the first few days of strength gain. Six of the 19 cements failed to meet the proposed ASTM specification requirement of 0.040 percent at 7 days (RC-687, -690(2), -694, -695, -700, -711). These six cements had $C_4A_3\hat{S}$ chart intensities below 24, alite ranging from 27 to 43, SO_3 from 5.2 to 6.4 percent, fineness ranging from 3550 to 5360 cm^2/gm (the highest recorded), and 7-day strengths from 3840 to 4730 psi (26.5 to 32.6 MPa), the latter being the highest 7-day strength in the group. However, two cements (RC-697, -707) with $C_4A_3\hat{S}$ chart intensities of 19 and 21, respectively, met the 7-day expansion requirement. RC-697 had 0.040 % restrained expansion which barely met the expansion requirement and had low total sulfate (5.1 %) and low alite (23 chart intensity). RC-707, with a 7-day restrained expansion of 0.68% had the highest sulfate (7.5%) of any of the cements and moderately high alite (36.8 chart intensity). RC-690, which had the highest expansion at 7 days (0.104%) had rather low alite (29 chart intensity) and the lowest 7-day strength (3070 psi (21.3 MPa) of the 19 cements. Four cements (RC-690(2, -701, -709, -711) had expanded more than the allowed 115 percent of the 7-day expansion. RC-703 had the highest $C_4A_3\hat{S}$ at 30.2 chart intensity and an alite (33.3 chart intensity) closer to the average. The other three cements had average $C_4A_3\hat{S}$ values and average or below alite chart intensities.

$C_4A_3\hat{S}$ chart intensities from 23.5 to 29 with alite chart intensities ranging from 30 to 41 and associated with finenesses from 3730 to 5240 cm^2/g produced cements that met the requirements of the proposed ASTM specification. The sulfate contents in the group of acceptable cements ranged from 4.6 to 7.5 percent.

A regression analysis equation between the amount of $C_4A_3\hat{S}$ (on the x-axis) and the 28-day restrained expansion (on the y-axis) was derived and found to be a straight line function in the form

$$Y = -0.0214 + 0.0032X \quad (1)$$

The correlation coefficient is R = +0.56. For n – 2 = 17, this correlation would occur by chance less than 2 times in 100. Considering that the behavior in restrained expansion of these cements must be affected by compressive and tensile strength of the specimens, which depends on fineness, cement composition, and sulfate available to provide early strength, it is somewhat surprising to find a significant relation between these two variables. The correlation of SO_3 and restrained expansion at 7 days was calculated but was just below significant at the 5 percent level.

A regression equation was calculated between MgO determined chemically (on the X-axis) and MgO in X-ray diffraction chart units (on the Y-axis) and was best represented by a simple power function of the form

$$Y = 4.4X^{1.37} \quad (2)$$

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With a correlation coefficient of +0.94 which, for n – 2 = 17, has substantially less than one chance in 100 of the relation occurring by chance.

CaO (free lime), a significant constituent of self-stressing cements, was not certainly identified in any of the 19 cements. While it may have been present in some of the cements in small amounts, it appears that the Ca needed to combine with $C_4A_3\hat{S}$ and $CaSO_4$ to form ettringite was obtained as $Ca(OH)_2$ from the hydration of alite.

The averages, standard deviations, and variances of several variables in the cements are shown in Table 8.

Table 8 Averages, Standard Deviations, and Variances

Item	No. of Samples	Average	Standard Deviation	Variance
Material insoluble in maleic acid, %	19	27.007	2.2973	5.27771
$C_4A_3\hat{S}$ (chart units at 3.76A)	19	24.426	3.732	13.924
Calcium Sulfate (anhydrite) (chart units at 3.495A)**	19	30.068	14.943	223.30
C_3A (chart units at 1.904A)	16	18.875	7.085	60.917
Alite (chart units at 1.76A)	19	32.837	5.393	28.780
Belite (chart units at 2.88A)	19	10	2.944	8.667
Aluminoferrite (chart units at 7.2 - 7.4A)	19	15.894	5.476	29.888
Fineness, cm^2/g	19	4352	466	216662
Restrained Expansion, %				
7-days	19	0.052	0.0177	0.0003
28-days	19	0.056	0.0203	0.0004
Compressive Strength, psi (MPa)				
7-days	19	4147 (28.6)	461 (3.2)	212809 (9.98)
28-days	18	5740 (39.4)	577 (4.2)	333253 (17.88)
SO_3, %	19	6.02	0.688	0.474

** Individual readings for $CaSO_4$ (anhydrite) in each cement are not shown in this report.

From the examinations by X-ray diffraction, it seems probable that five of the shrinkage-compensating Type K cements have their Portland cement portion sufficiently low in C_3A, so as to have this portion regarded as ASTM Type V Portland cement. In these five cements, no C_3A line was detected at 1.558A. Possibly the Portland cement portion of a few others had ASTM Type II compositions. Several apparently contained ASTM Type I Portland cements. Factors upon which the behavior of the Type K shrinkage compensating cements in this study are dependent appear to be more difficult to assess than was the case with 15 self-stressing cements that had been examined previously (Mather 1977).

DISCUSSION OF RESULTS

Specification compliance

All of the 19 Type K cements met the mandatory chemical requirements of the proposed specification although cements from two mills (RC-695, RC-695(2) and RC-697) did not meet the optional maximum requirements for total alkalis.

None of the cements appeared to have a problem meeting the physical requirements of air content, compressive strength, and time of setting. However, there was a problem with the principal feature for which these cements were produced, that is expansion, with several cements not meeting the requirements for 7-day expansion. Of the initial sampling, five cements (RC-687, -694, -695, -700, -711) having values of 0.028, 0.034, 0.033, 0.039 and 0.037 percent, respectively. A review of these values, together with the 0.036 percent value obtained from the second sample from one mill (RC-690(2)), points out a feature of the specification which warrants further discussion.

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Restrained expansion

The length change of the restrained bars is measured in a comparator to the nearest 0.0001 in. (0.0025 mm). The standard method for this measurement is ASTM C 806, "Standard Test Method for Restrained Expansion of Expansive Cement Mortar" which was first approved in 1975, at a time when these 19 cements were being evaluated. Expressed as a percentage of length change, measurements are made and reported to the nearest 0.001 percent in accordance with ASTM C 806, which is a number of three significant figures. The minimum and maximum expansion of the proposed specification (and the current 2004 version) are 0.04 percent and 0.10 percent), respectively, which are numbers to two significant figures. Having made measurements to three significant figures, they are then rounded to two significant figures for compliance with to the specification. The result of the rounding is that three of the six cements that failed the minimum expansion requirement (RC-690(2), -700, -711) and the one cement that failed the maximum requirement (RC-690) at three significant figures, now meet the specification at two significant figures. On this point, the intent of the proposed specification (and the current specification) is not clear. To eliminate this dilemma and insure that the cements with adequate and safe expansive potentials are being used, the limits in the proposed specification (and the current specification) should be expressed to three significant figures as 0.040 and 0.100 percent for minimum and maximum limits, respectively.

The problem of two versus three significant figures also carries over into the requirement that the 28-day expansions be not more than 115 percent of the 7-day expansions. Using the three significant figures obtained in the actual length change measurements in accordance with ASTM C 806, four cements (RC-690(2), -703, -709, and -711) failed this requirement. If the numbers had been rounded to two significant figures prior to determining the increase, RC-690(2) would have met the specification requirement, but the other still would have failed. The proposed specification should contain more explicit language as to how this increase in percentage is to be determined.

The allowable later expansions, expressed as a 115 percent increase, should also be reviewed from the standpoint of the actual expansions that occur. Under this requirement, cements expanding to the minimum level of 0.04 percent or 0.004 in. (0.102 mm) for a 10-in (254-mm) restrained bar, would be allowed to increase in length by an additional 0.0006 in. (0.0152 mm). At the maximum allowable level of 0.10 percent, or 0.010 in. (0.254 mm) for a 10-in (254-mm) restrained bar, the acceptable increase could be 0.0015 in. (0.0381 mm) or 2-1/2 times the increase of the bar at the minimum level. For two concretes of identical proportions, all other things being equal except for the expansive potential of the cement, a concrete having a large initial expansion (0.010-in. (0.0254-mm)) will probably not tolerate an additional expansion of 0.00115-in. (0.0381-mm) as well as would a concrete having a low initial expansion (0.0004-in. (0.102-mm)). This is not to say that an additional expansion of 0.0015-in. (0.102-mm) would be harmful to a concrete expanding 0.10 percent. This fact is not known to the author but, if in fact it is not harmful, that amount of additional increase could also be safely tolerated by a concrete expanding 0.04 percent at 7 days age. This suggests that the additional expansion requirement should perhaps be stated as a fixed amount over the entire range rather than as a percent increase. The amount of this fixed value would have to be defined and substantiated by additional testing.

X-Ray diffraction analysis

The X-ray diffraction analysis indicates that the performance of the cement with regard to expansion is affected by the amounts and types of constituents not identified in the chemical requirements. This suggests that the chemical requirements might be expanded to include other chemical requirements that may provide a more rapid indication of the expansive potential of the cements. These additional requirements might include upper and lower limits on SO_3 and Al_2O_3.

Expansive potential requirements

The principal reason for using expansive cements in concrete is to provide an overall combination of expansion and drying shrinkage such that the resulting dimensions of the element made with the concrete will not cause tensile stresses of such magnitude that they will cause cracking to occur within the element. The data in Table 6 for the mortar bars indicate that after 90 days restrained drying shrinkage, all of the cements but two (RC-690 and RC-707) had shrunk to less than the original length of the specimens before expansion had occurred. The average change from initial length was a shrinkage value of 0.025%. With additional time in the same curing environment, even more shrinkage will occur. Even the concrete specimens (Table 6) that had less cement per unit volume to contribute to shrinkage and that also had its shrinkage restrained by the presence of aggregate, 10 of the 19 cements exhibited more shrinkage than expansion. Although not measured, the shrinkage trends indicated that by 120 days age in the same drying environment, 16 of the 19 cements would have had more shrinkage than expansion.

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It is not known whether these values of shrinkage (Table 6) for either the mortar or concrete would induce shrinkage cracking in a concrete element because of the many factors that can influence shrinkage in concrete. These shrinkage values do suggest, however, that if volume stability (zero length change after expansion and shrinkage) will insure the elimination or significant reduction in drying shrinkage cracking, the minimum specification limit of 0.04 percent may not be adequate and perhaps should be increased. The amount of this increase would have to be determined through additional testing.

Other cement characteristics

The specific gravities of the 19 expansive cements (Table 4) were generally less than those normally associated with Type I and II Portland cements although a few exceptions occurred. This presents no problem for their use except that this fact should be called to the attention of the cement user so that they will make the necessary determinations of this value before beginning mixture proportioning.

The fineness of the expansive cements is generally higher than that of Type I and II Portland cements and is comparable to those normally associated with Type III Portland cements. These higher fineness values (Table 4) may be the result of the increased amount of gypsum in these cements. The gypsum, being softer than the cement clinker, will reduce more readily during grinding and thus increase the apparent fineness of the cement.

The heats of hydration of the 19 Type K cements (Table 4) were not significantly different from the usual Portland cements and thus could be used in larger concrete sections without increasing thermal problems.

The fact that the air contents in concrete (Table 5) varied from 2.4 to 6.0 percent for the same amount of a given brand of air-entraining admixture in each concrete batch and varied from 7.2 to 11.3 percent in mortar (Table 4) suggests that there is a compatibility requirement for air-entraining admixtures and Type k expansive cements that may warrant further study.

The slumps of the concrete made with Type K expansive cements have historically been reported as always being ***less*** than comparably proportioned Type I and II Portland-cement mixtures. This has been attributed to both increased cement fineness and the need for additional water in the formation of ettringite. In general, most of the Type K cements did not produce a lower slump than the Type II cement control mixture, however some exceptions were noted (Table 5)

As with slumps, compressive strengths of Type K expansive cements have historically been reported as being ***more*** than those achieved with comparable proportioned mixtures made with Type I and II Portland cements. This has usually been attributed to the increased fineness of the Type K cements, the reduction of free water in the concrete as more of the batch water is used for the development of hydration products, and also the densification of the paste caused by the formation of larger amounts of ettringite. In general, the 19 Type K cements evaluated exhibited this behavior, but again, there were some exceptions.

CONCLUSIONS

In assessing the significance of the data reported herein, it must be appreciated that the cements evaluated were from production in 1974 and were evaluated with test methods and procedures that were in effect at that time and do not necessarily reflect the condition of the Type K expansive cement industry and associated test methods and procedures at the time this paper was published. What the data do indicate, however, are some apparent shortcomings in the proposed specification at that time for these cements. The proposed specification, as it existed in 1974, and the current ASTM C 845-04 may satisfy most user, however, there are a number of aspects in the specification that could be revised to form a much stronger and responsive specification. These include the following:

1) Use of additional chemical requirements to assess expansive potential more quickly.
2) A restatement of expansion requirements to three significant figures.
3) An upgrading of the minimum expansion requirement of the specifications.
4) The revision of the later age expansion requirement to a constant value requirement rather than a percentage requirement.

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When moist cured, Type K expansive cements do in fact expand substantially more than normal Portland cements. When they undergo drying shrinkage, the amount of that drying shrinkage is comparable to that of normal Portland cement. The combined expansion and shrinkage produce less total shrinkage in test prisms than occurs with normal Portland cements.

The other characteristics of the Type K expansive cements such as specific gravity, fineness, and heats of hydration present no special problems for their use in a wide variety of different applications. When used in concrete they tend to reduce slumps and slightly increase compressive strengths at 28-day ages over those of comparably proportioned Type I and Type II Portland cement concretes. There may be some slight compatibility problems between individual cements and air-entraining agents, but these should be evaluated on an individual basis.

The tests described and the resulting data presented in this paper were obtained from research conducted under the Civil Works Research Program of the United States Army Corps of Engineers by the U. S. Army Engineer Waterways Experiment Station (now the Engineering Research and Development Center (ERDC)). Permission was granted by the Chief of Engineers in 1975 to publish this information which puts this information in the public domain.

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Behavior of Type K Shrinkage Compensating Concrete Under Various Forms of Mechanical Restraint

Chris Ramseyer
Seth Roswurm

Synopsis:

Shrinkage compensating concrete is one of the most common products currently used to mitigate the influence of drying shrinkage cracking in slabs, beams and other structural components. Type K expansive concretes have proved effective for prevention of structural and aesthetic damage due to tensile cracking in many modern applications. However, the ACI 223R-10 technical guide still indicates that a shrinkage compensating slab cannot expand adequately if it is surrounded on all sides by mature reinforced concrete. The objective of this project was to investigate whether the presence of a stiff external restraint condition, which may be provided by adjoining concrete, prevents a Type K expansive concrete slab from compensating for shrinkage.

To investigate this behavior, the field condition of a slab-to-slab interaction was simulated using a steel restraint system with varying degrees of stiffness and amounts of Type K expansive cement component. Test frames were instrumented to evaluate the force and displacement responses of the Type K expansive concrete to the different boundary conditions provided by varying the steel restraint system. The results of this investigation support a conclusion contrary to that currently found in the ACI 223R-10 guiding document. This study concludes that a Type K expansive cement concrete does not suffer a severe reduction in shrinkage compensation in the presence of a very stiff boundary condition.

Keywords:

Shrinkage compensating concrete, restrained expansion, Type K concrete, ettringite, expansive concrete, vibrating wire strain gage

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Author Biographies:

Chris Ramseyer, PhD., P.E., is an Associate Professor and the Director of Donald G. Fears Structural Engineering Laboratory at the University of Oklahoma in Norman, OK. He is the secretary of the ACI 223 Committee on Shrinkage Compensating Concrete and a member of S802, Teaching Methods and Educational Materials. His research interests include concrete shrinkage and creep, concrete repair – rehabilitation, specialty concretes, and in-situ testing of structures.

Seth Roswurm, M.S., E.I., is a structural engineer in training at Frankfurt-Short-Bruza Associates, P.C. and a Research Associate at the Donald G. Fears Structural Engineering Laboratory at the University of Oklahoma in Norman, OK. He is an ACI national member and is active in his local chapter as well, currently serving as the Vice President of ACI Oklahoma. He received his BS, and MS in civil engineering from the University of Oklahoma in 2012, and 2013, respectively. His research interests include behavior and applications of Type K shrinkage compensating concrete, performance of high early strength concrete, and large-scale structural testing.

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INTRODUCTION

The total volumetric change of a concrete specimen represents an aggregation of several material behaviors, including plastic shrinkage, carbonation shrinkage, autogenous shrinkage, drying shrinkage, and thermal effects. Of these behaviors, drying shrinkage is generally considered to constitute a majority of the total shrinkage volume change. Beginning at early age and continuing throughout the lifespan of a concrete structure, the magnitude of drying shrinkage significantly exceeds that of the other effects (Aly and Sanjayan, 2009). Fundamentally, drying shrinkage refers to an overall volume reduction that occurs as moisture evaporates from the concrete. Contingent upon the severity of this drying shrinkage effect, the integrity of the concrete may be significantly compromised. As drying shrinkage increases, the volume reduction induces internal tensile stresses within a restrained or partially restrained concrete member. Even in an unrestrained member, internal stress may be produced by differential shrinkage effects between the surface and center of the element (Moon and Weiss, 2006). These tensile stresses can cause tensile cracking, damaging the aesthetics, the structural capacity, and the long-term durability of the concrete.

The potential for internal stresses due to shrinkage is particularly problematic at an early age, since the ability of a concrete to resist cracking is directly dependent upon strength and stiffness. At an early age tensile stress capacity is limited, making shrinkage even more hazardous to the concrete. The two mechanical properties of strength and stiffness (along with relaxation due to creep in the material) are collectively referred to as "extensibility" by Neville (1981). The balance of extensibility with shrinkage behavior is illustrated in Figure 1. During early age, a concrete specimen will have a very low extensibility. This will cause it to be significantly more vulnerable to shrinkage cracking.

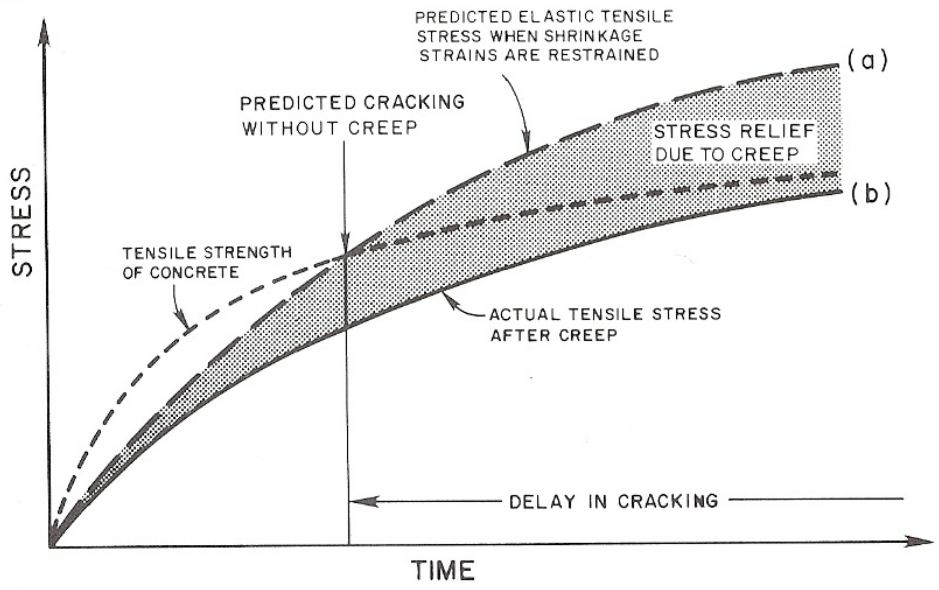


Figure 1 -- Influence of Shrinkage and Creep on Cracking (Mehta, 1986)

In modern concrete construction, one of the simplest and most effective methods for solving the problem illustrated in Figure 1 is the use of shrinkage compensating concrete. The addition of various non-portland cements (principally Type K or Type G cement) to induce a volumetric expansion of concrete during early age curing serves to not only delay, but also possibly even prevent the development of tensile stresses within a concrete element. Since the shrinkage in a shrinkage-compensated member begins after a positive length change has occurred, the specimen will begin by receding towards zero rather than immediately crossing into a negative length change which produces a tensile regime if the shrinkage is restrained in any manner. Based upon these properties, shrinkage compensation has been used successfully for a broad range of projects and applications (ACI 223R-10).

The purpose of the investigation described in this paper is to evaluate the performance of shrinkage compensating concrete under a specific set of restraint conditions. Since the fundamental purpose of a shrinkage compensating concrete is to grow during early age, it is important to consider the influence of boundary conditions

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on the ability of an expansive concrete to compensate for shrinkage. Such considerations are of particular concern when a shrinkage compensated concrete is to be used in a retrofit application within an existing structure or slab. The same may be said of new construction that is carried out in phases such that new concrete will be placed against a more mature, hardened concrete. Under both of these conditions, the newly cast expansive concrete is necessarily restrained to varying degrees, whether by existing framing in an existing structure or by surrounding concrete and subgrade friction in a slab-on-grade. These scenarios may cause potential users of shrinkage compensating concrete to question whether a structural restraint may prevent compensation from occurring. The objective of this investigation is to develop a laboratory test that imitates varying degrees of external restraint stiffness that would have the same stiffness as a more mature, hardened concrete and evaluate the response of the concrete. In particular, the goal is to determine whether a Type K expansive concrete element subject to increasingly stiff boundary conditions would necessarily suffer a reduction in shrinkage compensation.

BACKGROUND

The primary work referenced in industry today as the benchmark for proper use of shrinkage compensation is the ACI 223R-10 Guide for Use of Shrinkage Compensating Concrete. In addition to providing guidance for the proper use of shrinkage compensating concrete, the document also contains some general handling of mechanical behavior under restraint. This document indicates that for a structural member the amount of initial expansion is inherently related to the degree of restraint. It goes a step further to state that for a reinforced member with no external restraint, the expansion is inversely proportional to the percentage of steel. These guiding statements are fundamentally based on work by Russell (1973). Russell's work forms the basis for the reinforcement design recommendations found in the ACI 223R-10 (Figure 2). As is demonstrated by Figure 2, the concept that drives the ACI 223R-10 guide is that the amounts of internal and external restraint in a slab or other element are the determining factors in achieving shrinkage compensating performance. The document also indicates that the shrinkage compensation after accounting for this restraint needs to be equivalent to the long-term shrinkage of an unrestrained concrete sample.

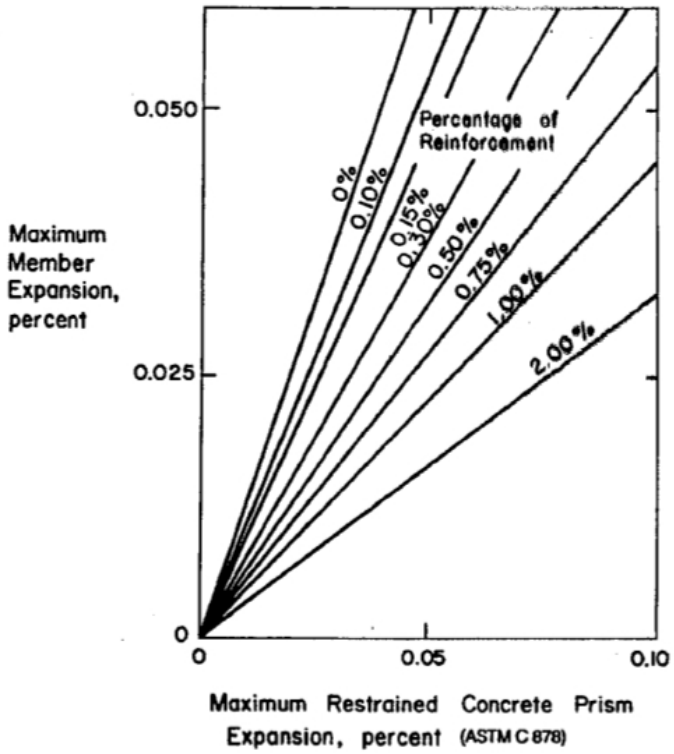


Figure 2 -- ACI 223 Sample Slab Design Curve

Russell's work dealt with mechanical restraint of shrinkage compensating slabs. In his investigation, all three typical classes of shrinkage compensating cement at that time (S, K, and M) were tested, and compared with

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Type I portland cement. Although the control batch used ordinary Type I portland cement, none of the other batches were documented to require any blending. This would suggest that rather than using the percent replacement method (also called the expansive component system, which may not have been available at the time) all expansive batches appear to have been mixed using only bagged expansive cement. Please note that ACI 223R-10 in Chapter 4 finds the use of an expansive component system to achieve a Type K cement to be equivalent to a bagged Type K cement, as defined in Chapter 2. The testing was performed on slab specimens that measured 2 ft. (610 mm) wide and 4 ft. (1.2 m) long. Each slab had a thickness of 3 in. (76 mm), 6 in. (150 mm), or 9 in. (230 mm). These slabs were placed in a vertical orientation to eliminate any frictional interaction that might influence the test. This vertical orientation of Russell's unrestrained slab specimens is illustrated in Figure 3 (A). Each slab in the test was assembled with either complete external restraint or no external restraint. With respect to internal restraint, each slab fell into one of three categories: unrestrained, symmetrically restrained, or asymmetrically restrained. An example of the jacking head of the external restraint frame is shown in Figure 3 (B). As with most other previous studies including Hanson et al., (1973), external restraint on the specimens was achieved with a jacking system that prevented any axial displacement.

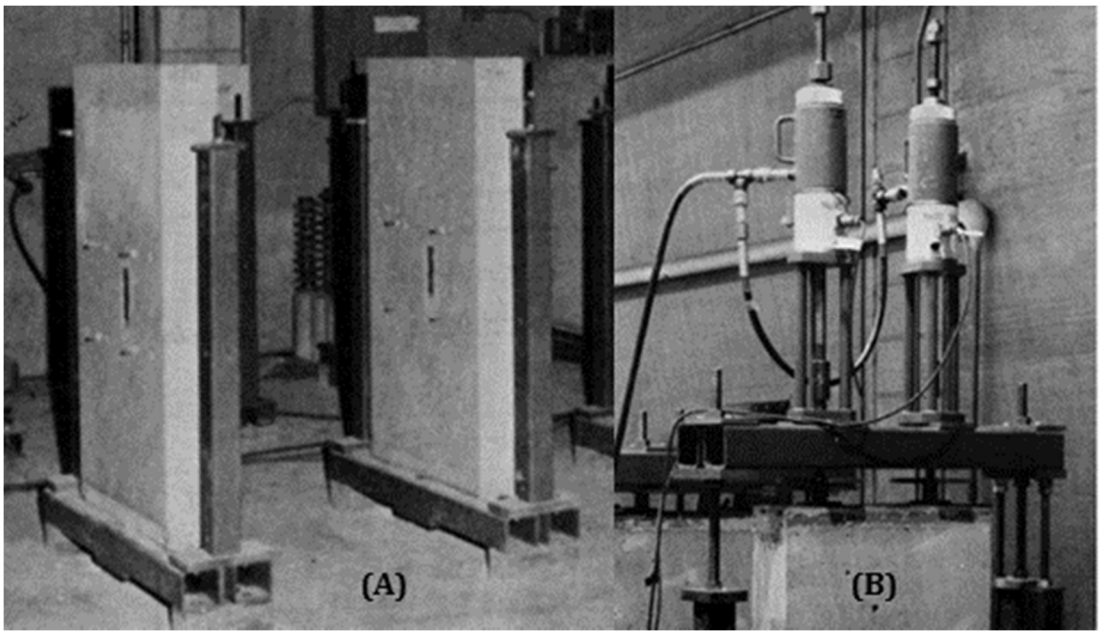


Figure 3 – (A) Vertical Unrestrained Slabs and (B) Slab Jacking Head (Russell, 1973)

It should be noted, however, that the authors could not locate any literature showing a modern reprisal or updates of the testing programs outlined above. As a result, the performance of current shrinkage compensating concrete materials under mechanical restraint (either internal or external) is not well documented. In addition to a general lack of modern laboratory studies on the topic, true field data from a shrinkage compensating structure is also extremely rare (Richardson et al., 2010). Despite the lack of testing data, however, field case studies continue to confirm the success of restrained shrinkage compensating concrete in the field. As Bondy (2010) observed, Type K shrinkage compensating concrete has now been applied in elevated post-tensioned slabs for approximately 40 years with overwhelming success. In addition to successful use in building structures, there are also over 600 Type K shrinkage compensated bridge decks in the U.S. that are essentially crack-free, as noted by Rubin (2006). The objective of this project was to characterize restrained Type K shrinkage compensating concrete behavior using modern materials, modern instrumentation, and a unique testing apparatus to impose various boundary conditions.

As a result of the desire to understand restrained expansion of Type K shrinkage compensated concrete, this study involved developing a new test capable of replicating restrained field conditions. Based on a desire to truly capture the internal behavior of the material, the testing in this experiment uses an embedded vibrating wire strain gauge (VWSG). According to Hornby and Noltingk (1974) the concept of VWSG measurement dates back as far as 1928. In their 1974 article, Hornby and Noltingk gave a thorough description of the principles and design of a VWSG to detect strain in a concrete element. As the use of VWSG instrumentation has become more prolific, other

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works have examined the theory and application of the method for accurately detecting small strains in a concrete specimen. Neild et al. (2005) revisited the basic stress-frequency relationship for a tensioned wire, described a simple laboratory-built VSWG for concrete, and described the underlying concepts that allow compensation for temperature changes. Sreeshylam et al. (2008) examined practical methods for field installation of VWSGs and demonstrated that they could be used to estimate pre-stress losses in concrete. The great advantage of VWSGs is that because they are embedded within the material, they not only measure the true in-situ behavior of the specimen, but also exhibit longevity and durability far superior to other forms of instrumentation (Lee et al., 2010). In this testing program, a set of parallel tests were carried out using both VWSG measurement and ASTM-based length comparator testing.

The set of ASTM tests selected for this experiment are motivated by the need to: 1.) fully characterize the behavior of the material and 2.) demonstrate reliable convergence with the vibrating wire strain gauge (VWSG) instrumentation used throughout the testing program. These tests include ASTM C39 compression testing to evaluate strength as well as ASTM C157 and ASTM C878 to evaluate length change behavior. It is important to note that the ASTM C157 test was not developed for evaluating expansive behavior; the intent of the test is to measure shrinkage. However, the test has been applied in this program in order to determine the unrestrained expansion of each shrinkage compensating mix. This unrestrained expansion may then be compared not only to the restrained behavior from ASTM C878 but also to the unrestrained behavior as measured by the new VWSG cylinder test described in Section 3.0. In a similar manner, restrained behavior captured using ASTM C878 prism tests is then compared to the restrained length change observed via VWSG in a cylinder specimen that has been restrained with an identical reinforcement ratio.

This parallel testing with alternate means of instrumentation forms the basis for two important discussions about the testing program. First, it provides compelling evidence concerning the validity and reliability of VWSG data, as will be further discussed. Secondly, it facilitates a direct comparison between the length change behavior of two specimens having the same concrete mix and the same restraint conditions, but having different geometric properties. For example, consider the comparison of an ASTM C157 prism length change with that of a 6x12 (150 mm x 300 mm) cylinder. The two specimens are characterized by drastically different volumes and exposed surface areas. Due to the body of VWSG data developed in this test, the subtle impacts of varying specimen geometry may be observed and are discussed. Once the material had been characterized by ASTM testing and the VWSG data had been validated, the final phase of this project was to replicate the field condition of a trapped slab and observe the material response. This was achieved using a steel frame to impose external restraint on a round column specimen.

RESEARCH METHODS

This investigation included 4 mix designs and a variety of different tests. The mix designs used in this project were based on a process of "percent replacement" by which the content of portland cement was reduced and replaced with an expansive component system to achieve a Type K cement. These mix designs are summarized in Table 1, and are ordered in terms of increasing expansive cement content from left to right. The first three percentages of replacement were determined based on recommendations by the expansive component cement supplier and are based on industry standards for shrinkage compensation. The highest replacement mix was added as an extreme condition to evaluate behavior at a level that vastly exceeds a "typical" dosage. All materials weights in these mix designs are expressed in lb. per cubic yard, with the SI conversion shown.

Table 1 -- Mix Design Summary (1 lb./yd^3 = 0.5933 kg/m^3)

	15%	17%	19%	30%
PC Type I	493	481	470	406
Expansive component - Type K Cement	87	99	110	174
Total Cementitious	580	580	580	580
Rock	1780	1786	1776	1776
Sand	1369	1392	1383	1377
Water	287	256	275	275
W/Cm Ratio	0.5	0.5	0.5	0.5

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The two parameters that are highlighted in Table 1 indicate mix design variables that were not allowed to vary from one batch to the next. All batching of concrete and casting of test specimens were performed in general accordance with the procedures of ASTM C192.

Test specimens from ASTM

The testing performed in this project included both standard ASTM tests and several original tests developed specifically for this investigation. Unless otherwise stated, all specimens were cured in an environmental chamber that maintained constant temperature and relative humidity at 73.4 ºF (23 ºC) and 50% RH, respectively. The specimens dictated by ASTM standards are as follows:

- ASTM C39 Compression Cylinders: 4" x 8" (100 mm x 200 mm)
- ASTM C157 Unrestrained Shrinkage Prisms
- ASTM C878 Restrained Expansion Prisms

The C39 cylinders were used for material characterization on the basis of compressive strength for every batch in this project. For every batch in this experiment, compressive cylinders were cast in sufficient quantity to accommodate testing at ages of 1 day, 7 days, 14 days, and 28 days. This testing made it possible to evaluate strength development, final 28-day strength, and any potential influence by expansive cement content.

The C157 prisms were used to indicate the unrestrained expansive potential of each mix design based upon daily length comparator readings. Three prisms were cast for each batch. These specimens were read once daily for 14 days followed by one reading on day 21 and one on day 28. This measurement schedule generated a total of 16 data points for evaluating the material behavior and making comparisons to other forms of instrumentation that are described later in this paper. The length comparator is shown both with and without a specimen in Figure 4.



Figure 4 -- Length Comparator

All C157 prisms were cured in lime water saturation for the first 7 days. After water curing was terminated, the prisms cured for the remaining 21 days in the ambient conditions within the environmental chamber. The prism wet curing condition (in a galvanized steel tub) is illustrated in Figure 5.

The C878 prisms were used to indicate the restrained expansion behavior of each mix design based upon daily length comparator readings. As with the unrestrained evaluation, three C878 prisms were cast for each batch. These specimens were read once daily for 14 days followed by one reading on day 21 and one on day 28. The same measurement schedule as that for the C157 tests was used in order to facilitate comparison of restrained and unrestrained expansion behavior. In order to ensure uniform behavior across the various types of expansion specimens, the C878 prisms were subject to the same curing process as the C157 specimens. The use of the C157 and C878 tests provided the data needed to demonstrate convergence between existing ASTM test methods and the new test methods described.

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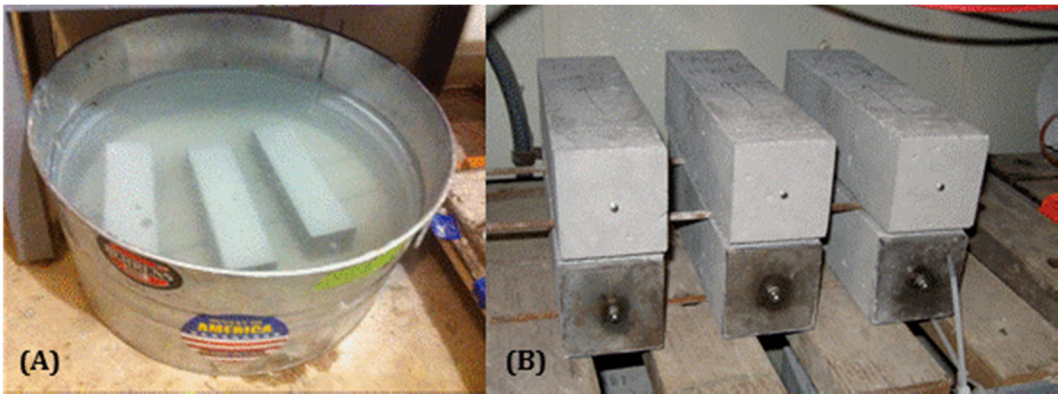


Figure 5 -- ASTM Length Change Prisms (A) Wet Cure Condition and (B) Dry Cure Condition

Test specimens from new tests

In addition to the ASTM-standardized tests that have been discussed thus far, three new tests were developed to aid in the investigation:

- Unrestrained 6" x 12" (150 mm x 300 mm) cylinders with VWSG
- Restrained 6" x 12" (150 mm x 300 mm) cylinders with VWSG
- Restrained 4" x 48" (100 mm x 1.2 m) columns with VWSG

Rather than relying on hand readings taken by an experimenter, the behavior of each of these three new tests was measured with Vibrating Wire Strain Gauge (VWSG) instrumentation. One VWSG unit was embedded in the center of each specimen in order to measure both shrinkage and expansion length-change throughout the 28-day testing period. Each strain gauge was connected to a separate channel in the data logger and readings were taken electronically at an interval of 15 minutes.

The unrestrained cylinder test (accurate to 1 microstrain) was developed as a more accurate equivalent of the unrestrained ASTM C157 prism test (accurate to 10 microstrain). The apparatus was assembled by modifying a standard 6" x 12" (150 mm x 300 mm) cylinder mold. The mold was outfitted with zip-ties in order to secure a VWSG in the center (mid-height and diametrically centered) of the specimen. The result is a VWSG with 3 inches of cover in all directions. This apparatus is illustrated in Figure 6.

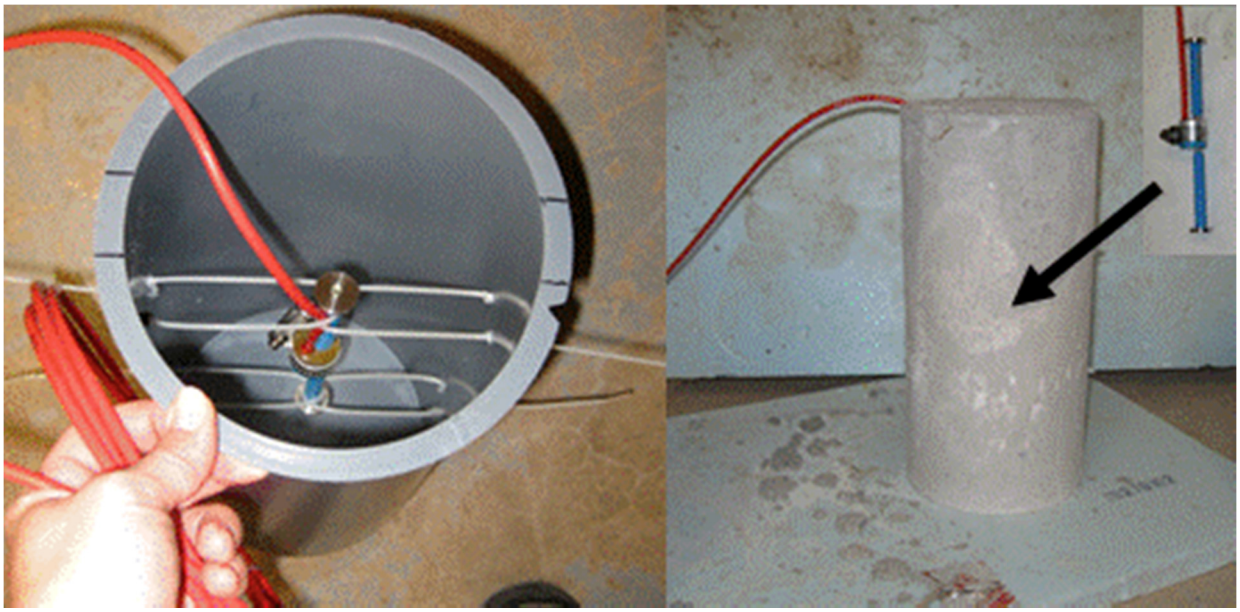


Figure 6 -- Unrestrained VWSG Cylinder Specimen

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The unrestrained cylinder specimens were subjected to the same curing process as the ASTM length-change prisms. The cylinders were submerged in lime water within an hour after casting. At an age of 8 hours, the plastic molds were stripped away, and the cylinder remained in in the lime water until the age of 7 days. At an age of 7 days, wet curing was terminated and the cylinders were cured in the environmental chamber for the remaining 21 days of the testing period.

The restrained cylinder test was developed as an automated equivalent to the restrained ASTM C878 prism test. As with the unrestrained test, this specimen was assembled using a modified 6 “x 12” (150 mm x 300 mm) plastic cylinder mold. The mold was equipped with holes so that the VWSG could be secured with zip-ties. In addition, the bottom of the plastic mold was removed and replaced with a steel plate measuring 6 in. x 6 in. x ¼ in. (150 mm x 150 mm x 6.4 mm). An identical plate rested on the top of the cylinder. A steel rod with a major diameter of 5/16 in. (7.9 mm) was placed the center of the cylinder to join the two plates and provide a degree of restraint against axial displacement. This rod was sized in order to give the cylinders the same reinforcement ratio as that of the ASTM C878 restrained prism. The assembly procedure and appearance of the restrained cylinders are similar to those for the unrestrained cylinders, as illustrated in Figure 7, though the VWSG is slightly off-center due to the restraining rod. These restrained specimens were subjected to the exact same curing and testing procedure as the unrestrained cylinders.

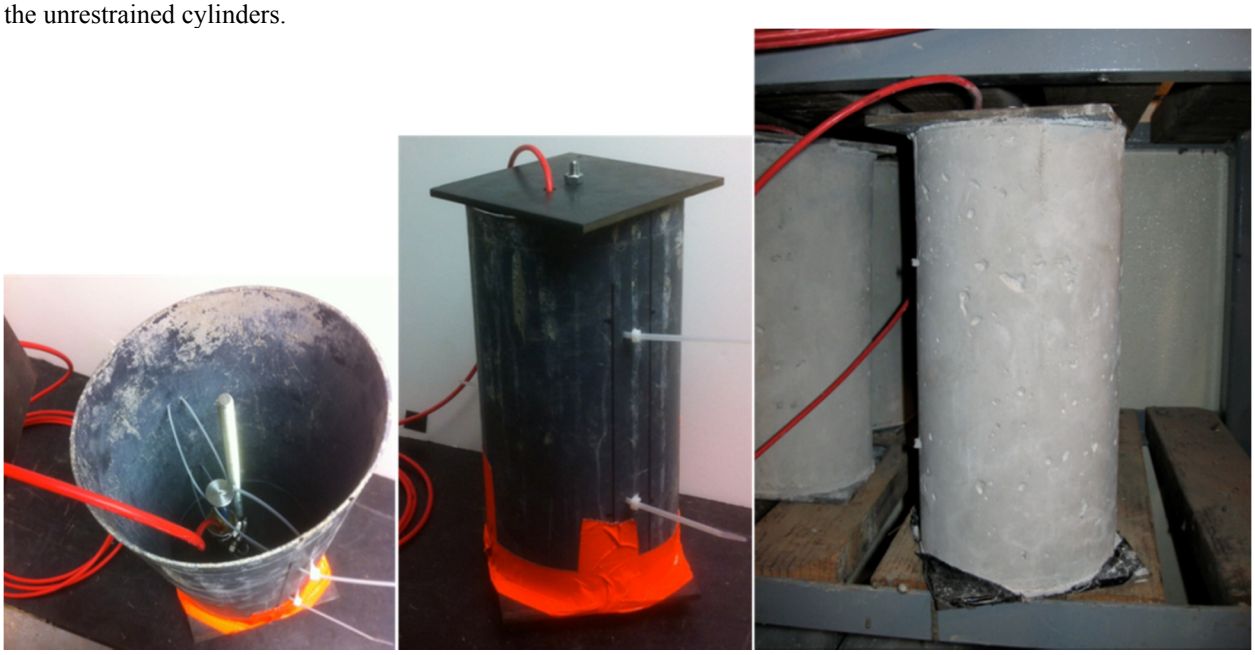


Figure 7 -- Restrained VWSG Cylinder Specimen

The third and final new test developed for this investigation was the 4 in. x 48 in. (100 mm x 1.2 m) restrained columns. While the previous two tests were developed only to characterize the testing material, the restrained column test was designed to explicitly test the sensitivity of Type K shrinkage compensating concrete behavior and response to variations in boundary condition stiffness. This response was evaluated on the basis of two forms of instrumentation; every column was outfitted with both a VWSG to determine length change cast at mid height and a load cell at the top surface to determine compressive force developed during the test. The general setup used for this test is summarized in Figure 8.

In the experimental setup illustrated in Figure 8, an expansive slab has been modeled as a column with a diameter of 4 in. (100 mm) and a height of 48 in. (1.2 m). The mature properties of the confining slabs have been modeled as a set of steel restraining rods. According to the principles of elementary solid mechanics, it is possible to simulate a concrete boundary condition if a smaller area of steel is used to supply an equivalent axial stiffness (defined as k = AE/L). Calculations indicated that the axial stiffness of four 5/8 in. (16 mm) restraint rods had an axial stiffness equivalent to that of a mature 4 in. (100 mm) diameter column. As a result, the frame assembled with 5/8 in. (16 mm) rods is theoretically equivalent to the stiffness of a mature concrete boundary condition. In order to evaluate the concrete response to change in boundary condition, frames were then assembled with ½ in. (13 mm) rods and ¾ in. (19 mm) rods. These larger and smaller restraint rods correspond to a stiffness increase of 44% and a

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stiffness reduction of 36%, respectively. This was done to investigate the sensitivity of the results due to a change in the boundary conditions. The column specimen was cast with a round cross section in order to facilitate the forming and wet-curing process.

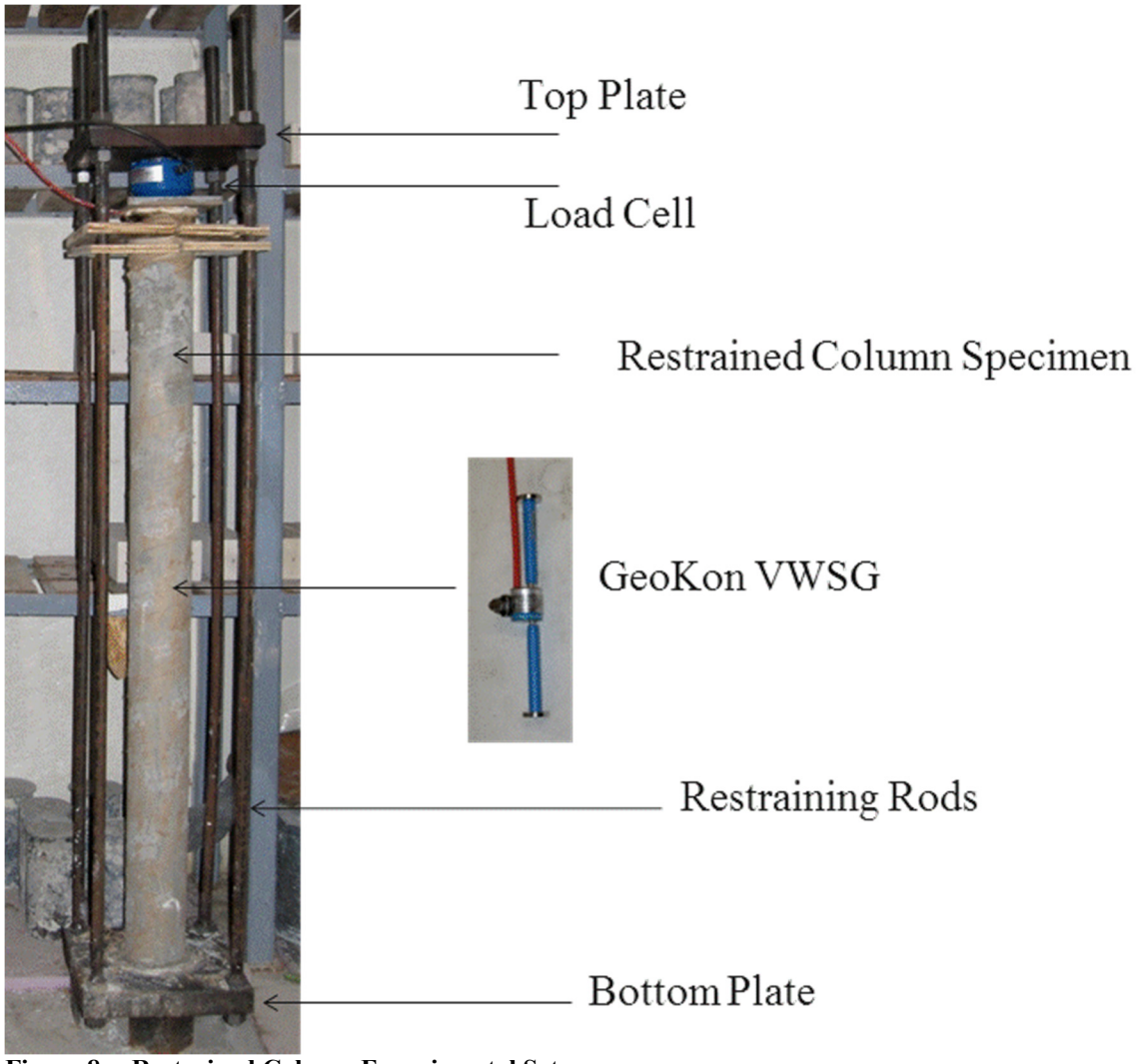


Figure 8 -- Restrained Column Experimental Setup

During the casting procedure, the columns were formed using a cardboard tube sealed at the base. Surrounding the cardboard form was a 6 in (150 mm) diameter PVC pipe also sealed to the base of the testing frame. Forms were filled in four lifts and were consolidated by rodding with a ½ in. (13 mm) rod. It was noted at the conclusion of the experiment that none of the specimens exhibited bug holes or other signs of poor consolidation. When the column form was half full (at the conclusion of two lifts), the VWSG was inserted at the mid-height of the tube. Concentric alignment of the tube was ensured by stiff wires wrapped around the body of the gauge to function in a manner similar to plastic rebar spacer wheels in drilled shafts or pipe centering devices in wells. At the conclusion of the casting procedure, the space outside the cardboard tube form but within the PVC tube was filled with water to provide a wet cure. As indicated in Figure 8, the test head on each restrained column consisted of the top plate, the load cell, and the steel bearing plate beneath the load cell. This test head assembly was placed on the column when the concrete reached an age of 8 hours. Once the head had been placed on the column, it was tightened with nuts on the threaded rods in order to ensure that the column and bearing plate would maintain contact throughout the life of the test. The most noteworthy aspect of this tightening process is that it left each column with a unique "pre-compression" force induced at the very beginning of the test. The potential influence of this pre-compression force over experimental results is examined and discussed.

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RESULTS AND DISCUSSION

As discussed in the previous section, every mix was subjected to a series of basic characterization tests in order to establish the fundamental behavior of the material. Among these tests were the ASTM C878 and C157 length change protocols. The results of these tests for each of the 4 mix designs are summarized in Figure 9, (A) and (B).

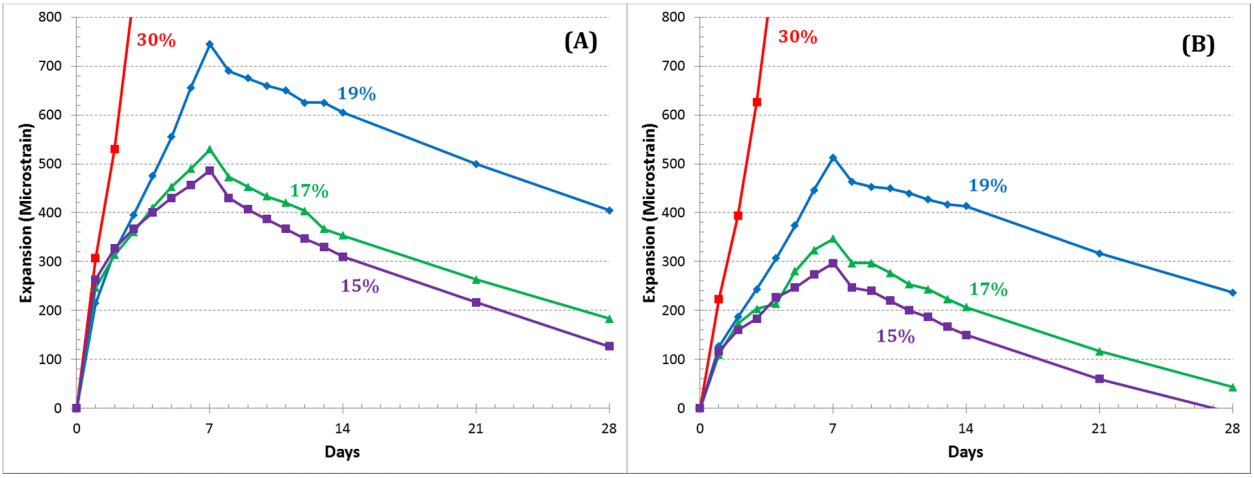


Figure 9 -- Expansion Curves According to ASTM Tests C157 (A) and C878 (B)

The curves seen in Figure 9 provide a general sense of the material behavior exhibited by shrinkage compensating concrete. The variation of the expansions seen in Figure 9 indicates that an increase in expansive cement content corresponds directly to an increase in expansive length change. This relationship is shown to hold true for both unrestrained C157 expansion and restrained C878 expansion. Figure 9 also illustrates the impact of restraint in the prisms; for a given replacement percentage, the unrestrained C157 prisms (A) exhibit a larger expansion than the restrained C878 prisms (B).

Figure 10 shows the comparison between ASTM and VWSG results in order of increasing expansive cement content (clockwise from bottom right). Overall, these comparisons demonstrate that the VWSG 6 in. x 12 in. (150 mm x 300 mm) specimens consistently agree closely with the results generated by a traditional ASTM length comparator test. Both forms of measurement show the maximum expansion occurring at an age of 7 days. On most comparisons, the two methods also give identical maximum expansion values. In cases where the values did not match identically, the gap between maximums never exceeded 75 microstrain. The two forms of instrumentation even converge almost flawlessly during the most demanding expansion condition with 30% replacement. In this case, the VWSG gave consistent data to an expansion of roughly 9000 microstrain. The only divergence between the two types of testing is observed during the shrinkage after the termination of wet curing. In each case, Figure 10 shows a more severe trend of shrinkage for ASTM prisms than for VWSG cylinders.

This difference in behavior is most likely due to a fundamental difference between the physical properties of the specimens. Since the rate of drying shrinkage is inherently dependent upon the process of moisture loss, then, it is postulated that the ASTM prisms are subject to far more rapid desiccation than are the cylinders. This contention is supported by a comparison of the volume and surface area-to-volume (SA/V) ratio for the two specimens, as shown in Table 2.

Table 2 -- Comparison of Specimen Physical Properties

	Volume	Surface Area/Volume
Units:	**in^3 (m^3)**	**1/in (1/mm)**
ASTM - 3" x 3" Prism	90 (0.001475)	1.533 (0.061)
VWSG - 6" x 12" Cylinder	339.3 (0.005560)	0.667 (0.026)

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