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Shrinkage-Compensating Concrete—Guide

Reported by ACI Committee 223

ACI PRC-223-21



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Shrinkage-Compensating Concrete—Guide

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Shrinkage-Compensating Concrete—Guide

Reported by ACI Committee 223

Karl J. Bakke, Chair

Chris C. Ramseyer, Secretary

Jason Barnes
Benoit Bissonnette
Craig M. Dahlgren
C. Rick Felder

Barry E. Foreman
Greg K. Fricks
Terry J. Fricks
Todd R. Hawkinson

Jerry A. Holland
Federico Lopez Flores
Kevin A. MacDonald
Alma L. Reyes

John W. Rohrer
Edward D. Russell
Henry G. Russell
Lawrence J. Valentine

Consulting Member

Roy H. Reiterman

The committee would like to thank the following people for their contributions to this report: Charles Alt, Eric Beshar, Ken Bondy, Juan Roberto Pombo, Edward K. Rice, and Ken Vallens.

Shrinkage-compensating concrete is used in construction to minimize drying-shrinkage cracking. Its characteristics are similar to those of portland-cement concrete. The materials, proportions, placement, and curing should ensure that expansion compensates for subsequent drying shrinkage.

This guide sets forth criteria and practices to ensure the development of expansive strain in concrete. In addition to a discussion of basic principles, methods and details are given covering structural design details and applications, concrete mixture proportioning, placement, finishing, and curing.

The materials, processes, quality control measures, and inspections described in this document should be tested, monitored, or performed as applicable only by individuals holding the appropriate ACI certifications or equivalent.

Keywords: calcium cement; drying shrinkage; expansion cement; mixture proportions; restraints; shrinkage-compensating concrete; shrinkage cracking; slab-on-ground; structural design.

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ACI PRC-223-21 supersedes ACI 223R-10, was adopted June 3, 2021, and was printed November 2021.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Shrinkage-compensating concrete is made with an expansive cement or expansive component system in which initial expansion, if properly restrained, offsets strains caused by drying shrinkage. Since the mid-1960s, shrinkage-compensating concrete has been used in many applications. These applications include highway and airport pavements (McLean et al. 2016; Ramseyer and Roswurm 2019), bridge decks (Gruner and Plain 1993; Ramey et al. 1999; Gagné et al. 2008), hydraulic structures (Ramseyer et al. 2016), wastewater treatment plants, containment structures (Valentine 1994), post-tensioned structures (Hoffman 1980; Eskildsen et al. 2009), parking structures (Bondy 2010, 2011), and slabs-on-ground (Keith et al. 1996, 2006; Bailey et al. 2001; Shadravan et al. 2016; Ramseyer and Roswurm 2016).

Shrinkage-compensating concrete is used to minimize cracking and structural movement caused by drying shrinkage in concrete. Drying shrinkage is the contraction in the concrete caused by moisture loss from drying concrete. It does not include plastic volume changes that occur before setting when surface evaporation exceeds concrete bleeding rate or length and volume changes induced by temperature, structural loads, or chemical reactions.

The amount of drying shrinkage that occurs in concrete structures depends on the constituent materials, mixture proportions, curing, drying environment, and restraint. Tensile stresses caused by restraint to drying shrinkage can occur before concrete tensile strength is fully developed. When concrete is restrained by reinforcement, subgrade friction, or other means, drying shrinkage causes tensile

stresses to develop. When drying shrinkage stresses exceed the tensile strength of the concrete, it cracks. The spacing and size of cracks that develop in structures depend on the amount of shrinkage, degree of restraint, and amount of reinforcement.

Shrinkage-compensating concrete is proportioned so concrete volume increases after setting and during early-age hardening. When restrained by reinforcement, concrete expansion results in tension in reinforcement and compression in concrete. Upon drying, the shrinkage, instead of causing tensile stress that results in cracking, relieves compressive stresses caused by initial expansion of the shrinkage-compensating concrete.

1.2—Scope

Recommendations of this guide include proportioning, mixing, placing, finishing, curing, and testing. Shrinkage-compensating concrete is produced using expansive cements or expansive component systems.

There have been significant changes and advances in the use of shrinkage-compensating concrete since it was first introduced into the market but, in some areas, the original practices remain the best current practice. Although many references used in this guide are over 10 years old, they remain a valid reference to today's practice.

CHAPTER 2—DEFINITIONS

2.1—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

expansive component system—combination of portland cement and expansive component that, when mixed with water, forms a paste that, after setting, increases in volume to a significantly greater degree than portland cement paste.

1. expansive component Type K—blend of calcium sulfoaluminate and calcium sulfate that produces ettringite when mixed with portland cement and water.
2. expansive component Type M—blend of calcium-aluminate cement and calcium sulfate that produces ettringite when mixed with portland cement and water.
3. expansive component Type S—blend of tricalcium aluminate (C_3A) cement and calcium sulfate that produces ettringite when mixed with portland cement and water.
4. expansive component Type G—blend of calcium oxide (CaO) (SiO_2 and Al_2O_3) that produces calcium hydroxide platelet crystals when mixed with portland cement and water.

CHAPTER 3—GENERAL CONSIDERATIONS

Drying shrinkage of concrete is affected mainly by water content, aggregate composition and size, drying environment, mixture proportions, paste content, and binder characteristics. Lower water content, aggregate with a higher modulus of elasticity, larger aggregate size, longer curing, and leaner mixtures reduce drying shrinkage.

Concrete drying shrinkage at 28 days typically ranges from 0.03 to 0.11% depending on local material supplies (Lee and Hewlett 2018; Mindness 2003). Drying shrinkage of a concrete mixture is determined by using **ASTM C157/C157M**. Laboratory tests give results that are typically higher than the shrinkage of concrete placed in the field due to differences in size, restraining conditions, and exposure conditions.

Beyond the expansive cement or expansive component added to the cement, the materials used to produce shrinkage-compensating concrete are the same as those required to produce portland-cement concrete. The ability of shrinkage-compensating concrete to minimize cracking depends on water curing for 7 days, among other factors. This moist curing is required to properly develop the ettringite or calcium hydroxide crystal structure that offsets drying shrinkage.

It is essential that water curing and protection of the concrete is provided as discussed in **ACI 301** or **ACI 308.1**. Mixture proportions should ensure initial expansion to offset subsequent drying shrinkage. Physical characteristics and durability of cured shrinkage-compensating concrete are similar to those of portland-cement concrete.

3.1—Preconstruction meeting

The owner's representative, in cooperation with the designer and general contractor, should conduct a preconstruction meeting after all mixture designs are approved. This should occur at least one week before the first placement of concrete. Parties review, discuss, and agree to procedures for placing, finishing, and curing the concrete to meet specifications under anticipated field conditions. Responsible representatives of all contractors and material suppliers, including the manufacturer of the shrinkage-compensating cement or component, the ready mixed concrete producer, and concrete testing laboratory, should participate in this meeting.

Be aware that additional time for testing may be necessary when using an expansive component to produce shrinkage-compensating concrete. Proportions may need to be adjusted

or materials sources changed during the testing process to achieve the strength and expansive properties specified.

CHAPTER 4—MATERIALS

4.1—Expansive cement and expansive component systems

The expansion characteristics of expansive cements and expansive component systems (as defined in 2.1) are determined by the constituents that create the expansion mechanisms (refer to Table 4.1). The difference between expansive cements and expansive component systems is limited to expansive cements being a single product while the expansive component systems require the addition of portland cement. Expansion produced in a mortar by each system is determined by the **ASTM C806** test method. This test measures the expansive potential of the cementitious materials and component systems and is used to evaluate performance of mortar compared with expansion requirements of mortar in **ASTM C845/C845M**.

When using ASTM C806 with a component system, the test amount of cement required in the mortar should consist of the portland cement and component in the same proportions that will be used in the concrete.

4.2—Aggregates

Both normal weight and lightweight aggregates can be used to produce shrinkage-compensating concrete. The aggregates used should meet **ASTM C33/C33M** or **ASTM C330/C330M**. Aggregates containing gypsum or other sulfates may increase expansions or cause delayed expansion or subsequent disruption of the concrete. Significant amounts of chlorides in aggregates, such as found in beach sand, tend to decrease expansion and increase drying shrinkage. For these reasons, use job aggregates in the laboratory trial batch proportioning test.

Table 4.1—Types of expansive cements or expansive component systems and their constituents

Designation	Type of expansive system	Main constituent(s)	Reactants involved in expansive compound formation
Expansive cements			
Type K*	ettringite-based	a) Portland cement b) Calcium sulfate c) Portland-like cement containing $C_4A_3\bar{S}$	$C_4A_3\bar{S}$
Type M*	ettringite-based	a) Portland cement b) Calcium sulfate c) Calcium-aluminate cement (CA and/or $C_{12}A_7$)	CA and/or $C_{12}A_7$
Type S*	ettringite-based	a) Portland cement high in C_3A b) Calcium sulfate	C_3A
Expansive components			
Type K†	ettringite-based	a) Portland-like cement containing $C_4A_3\bar{S}$ b) Calcium sulfate	$C_4A_3\bar{S}$
Type M†	ettringite-based	a) Calcium aluminate cement (CA and $C_{12}A_7$) b) Calcium sulfate	CA and/or $C_{12}A_7$
Type G†	calcium hydroxide-based	a) Calcium oxide b) Pozzolan (SiO_2 and Al_2O_3)	CaO

*ASTM C845/C845M designation.

†ACI PRC-223 designation.



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4.3—Water

Mixing water should be of the same quality used in portland-cement concrete (Kosmatka et al. 2002). If mixer wash water or water containing sulfates or chlorides is used, trial batches to disclose possible adverse effects on the desired strength and expansion levels of shrinkage-compensating concrete are recommended (Wendy et al. 2019). The use of reclaimed water should be avoided.

4.4—Admixtures

Air-entraining admixtures, water-reducing admixtures, retarding admixtures, and accelerating admixtures may increase, decrease, or have no effect on the amount of expansion. The same is true for a specific type or brand of expansive cement or expansive component system. Consult the cement, component, and admixture producers regarding compatibility issues.

Admixtures should be tested in trial batches with job materials and mixture proportions. Such tests should evaluate:

- a) The admixture's influence on expansion
- b) Water requirements
- c) Air content
- d) Consistency
- e) Rate of slump loss
- f) Bleeding
- g) Rate of hardening
- h) Strength development over time
- i) Drying shrinkage
- j) Segregation

Air-entraining admixtures are as effective with shrinkage-compensating concrete as with portland-cement concrete in improving freezing-and-thawing resistance and scaling resistance. Admixtures containing triethanolamine (TEA) have been known to interfere with expansion of shrinkage-compensating concrete (Erkin and Hime 2009). Shrinkage-compensating concretes containing TEA can be successfully used provided sufficient expansion can be demonstrated in trial batches at the lowest concrete and ambient temperatures expected the day of concrete placement.

4.5—Concrete

4.5.1 Strength—After expansion, the tensile, flexural, and compressive strength developments of shrinkage-compensating concrete is similar to that of portland-cement concrete under moist- and steam-curing conditions.

The water requirement for shrinkage-compensating concrete is greater than that of portland-cement concrete for a given consistency. Compressive strengths, however, are comparable to portland-cement concretes with lower water-cementitious material ratios (w/cm) if the cement is manufactured from the same clinker, and the concrete has identical cement content and aggregate proportions.

As with those of portland-cement concrete, the lower the w/cm , the greater the compressive strength (refer to 4.2.5 of ACI Committee 223 [1970]).

Compressive strength concrete test cylinders should be thoroughly protected from the environment and carefully transported in accord with ASTM C31/C31M. Note that

unrestrained expansion in moist rooms may decrease the rate of strength gain. Fifty-six-day cylinders are recommended as an additional set of test cylinders in case the 28-day strengths are lower than specified. It is good practice to mold and cure additional compressive strength cylinders in their mold in the field for 7 days for comparative purposes.

4.5.2 General physical properties—The modulus of elasticity, creep, Poisson's ratio, and coefficient of thermal expansion of shrinkage-compensating concrete are similar to portland-cement concrete made with similar materials.

4.5.2.1 Modulus of elasticity—Static and dynamic determinations of the modulus of elasticity of Type K, S, and M cement concretes have been made using both natural and lightweight aggregated, and the results were comparable to portland cement concretes (Gustaferro et al. 1966).

4.5.2.2 Creep—Available data on the creep characteristics of shrinkage-compensating concrete indicate that creep coefficients are within the same range as those of portland cement concrete of comparable quality.

4.5.2.3 Poisson's ratio—Limited and preliminary data indicate little, if any, difference in Poisson's ratio between portland cement concrete and shrinkage-compensating concrete.

4.5.2.4 Coefficient of thermal expansion—Type K cement concrete has been tested between 40 and 158°F (4 and 70°C) and at four intermediate points using 517 lb of cement per cubic yard of concrete (307 kg/m³). The coefficient determined in this experiment was 5×10^{-6} in. per in. per °F (9×10^{-6} cm/cm/°C) (U.S. Bureau of Reclamation 1963). This is consistent with the coefficient of thermal expansion for corresponding portland cement concrete.

4.5.3 Volume change—Volume change with shrinkage compensating concrete is related to the percentage of expansive component in the mixture design. During the moist cure, shrinkage-compensating concrete typically has a restrained expansion of between 0.03 and 0.1%, with expansion at 28 days to not exceed 0.15%. Actual values will vary depending on the expansive system being used and the mixture design. After expansion, the drying-shrinkage characteristics of a shrinkage-compensating concrete tested in a controlled laboratory environment are similar to those of portland-cement concrete (Ramseyer and Roswurm 2016; Ramseyer et al. 2016; Ramseyer and Roswurm 2019).

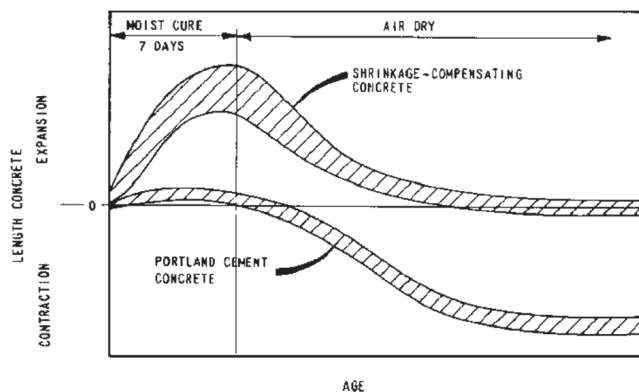


Fig. 4.5.3—Typical length change characteristics of shrinkage-compensating concrete and portland-cement concrete

Figure 4.5.3 illustrates the typical length change behavior of shrinkage-compensating and portland-cement concrete tested in accordance with ASTM C878/C878M.

4.5.4 Freezing-and-thawing resistance—When properly designed per ACI 211.1 and adequately cured per ACI 308.1, shrinkage-compensating concrete made with expansive cements K, S, or M is equally resistant to freezing and thawing and scaling in the presence of deicer chemicals as portland-cement concrete of the same water-cement ratio (w/c). The effects of air content and aggregates are essentially the same (Jabbari and Vallens 2014; Polivka et al. 1975; Gustafsson et al. 1966; Klieger and Greening 1969).

4.5.5 Sulfate resistance—Sulfate resistance of shrinkage-compensating concrete is inversely proportional to the amount of C_3A in the portland cement portion. When portland cement is used with an expansive component, the resulting concrete has greater sulfate resistance per unit mass of cement than the concrete made with portland cement alone. Nevertheless, shrinkage-compensating cement made with Type I portland cement may be undersulfated with respect to the aluminate available and susceptible to further expansion and disruption after hardening when exposed to an external source of additional sulfates. Shrinkage-compensating cements made with Type I, Type II, or Type V portland cement clinker, and adequately sulfated, produce concrete having sulfate resistance equal to or greater than portland cement made of the same type of clinker (Mehta and Polivka 1975; Ramseyer et al. 2011; Bescher et al. 2016).

4.5.6 Testing—Compressive and flexural strengths are determined in the same manner and using the same ASTM methods as for portland-cement concrete. The design of shrinkage-compensating concrete should treat the desired amount of expansion as significantly as strength. Mixtures that expand too little or too much are likely to induce undesirable cracking or warping in slabs. The performance of a shrinkage-compensating concrete should be tested in accordance with ASTM C878/C878M to determine the quantity of expansive cement or expansive component required to achieve the desired concrete expansion. For moderate exposure conditions, a specified strength of 3000 psi (21 MPa) should be attained. Before severe exposure to extended freezing, the concrete should attain a specified compressive strength of 4000 psi (28 MPa). A period of drying following curing is advisable before exposure to freezing temperatures.

4.5.7 Abrasion resistance—Shrinkage-compensating concrete, when properly designed per ACI 211.1 and adequately cured per ACI 308.1, has an abrasion resistance 30 to 40 percent higher than portland-cement concrete of comparable mixture proportions for Type K, M, and S shrinkage-compensating systems (Rubin 2006; ACI Committee 223 1970; Nagataki and Yoneyama 1973; Klieger and Greening 1969).

4.5.8 Thermal stability—Type K shrinkage-compensating concrete can form crystals and is thermally stable for a temperature range from 38 to 212°F (3 to 100°C), similar to portland cement concrete (Zhou and Glasser 2001).

CHAPTER 5—STRUCTURAL DESIGN DETAILS AND APPLICATIONS

5.1—Behavior of shrinkage-compensating concrete

Properly proportioned, placed, and cured shrinkage-compensating concrete behaves similarly to portland cement concrete with the exception that it expands for a short period of time after placement during wet curing. After the initial expansion, at the termination of wet curing, normal drying shrinkage begins and the expansion strains decrease with time, approaching zero as the magnitude of the shrinkage approaches the initial dimensional state of the element. This behavior is the opposite of members constructed with typical portland cement concrete (not shrinkage-compensated) where shrinkage strains increase with time. Because net long-term volume change caused by shrinkage can be designed to approach zero (Rubin 2006; Eskildsen et al. 2009; Ramseyer et al. 2016; Bissonnette et al. 2016; Ramseyer and Roswurm 2016), drying shrinkage cracking in members made with shrinkage-compensating concrete, is minimized.

The expansion, which usually occurs during wet curing in the first 7 days after placement, is generally restrained to some degree by one or more factors, which can include bonded reinforcement internal to the member, connected members (such as columns and walls) if the member is in an elevated floor or roof system, or sub-grade friction if the member is cast on ground. In the latter case, the importance of the restraint may vary significantly, depending on the nature of the sub grade material. Restraint to the initial expansion produces compression in the shrinkage-compensated member, which is also beneficial in resisting cracks.

In typical portland cement concrete, the potential for internal stresses due to shrinkage is particularly problematic at an early age because the ability of a concrete to resist cracking is directly dependent on strength and stiffness that, at an early age, is just starting to develop. Another way to state this is that at an early age, the tensile stress capacity is limited, making shrinkage strains and the tensile stresses that develop from them even more impactful to the concrete. The two mechanical properties of strength and stiffness (along with relaxation due to creep in the material) collectively define extensibility as described by Neville (1981) and Ramseyer et al. (2016). Early evolution of the internal stress balance in a concrete member undergoing restrained shrinkage is illustrated in Fig. 5.1a. This balance depends on the degree of restraint, the magnitude of shrinkage, the modulus of elasticity, and the creep/relaxation characteristics, which altogether determine the state of stress inside the member, and ultimately on the tensile strength of the material. Although creep can play a highly beneficial role in relaxing shrinkage-induced stresses, the total extensibility of concrete is typically overcome by the ultimate drying shrinkage strain, causing it to be vulnerable to shrinkage cracking.

In modern concrete construction, one of the simplest and most effective methods for solving the problem illustrated in Fig. 5.1a is the use of shrinkage-compensating concrete. Shrinkage-compensating concrete expands for

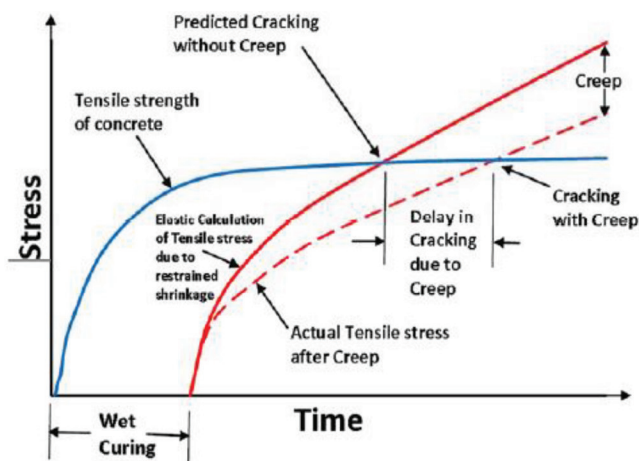


Fig. 5.1a—Stress balance in a concrete element undergoing restrained shrinkage (Ramseyer et al. 2016).

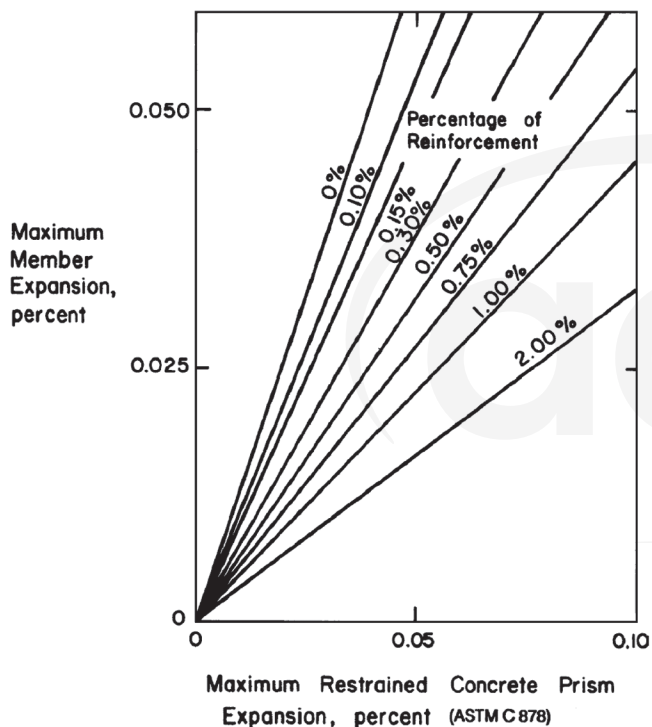


Fig. 5.1b—Estimation of member expansion of ettringite-based system from ASTM C878/C878M prism expansion (based on Russell 1973).

a short period of time after placement. The expansion, which usually occurs in the first 7 days after placement during wet curing, is generally restrained to some degree by one or more factors, which can include bonded reinforcement internal to the member, connected members (such as columns and walls) if the member is in an elevated floor or roof system, or subgrade friction if the member is cast on ground. Restraint to the initial expansion produces compression in the shrinkage-compensating member, which is beneficial in resisting cracks. Welded-wire reinforcement or steel deformed bars should meet the requirements of ACI 318.

In building construction, particularly with post-tensioned concrete floor systems, the use of shrinkage-compensating

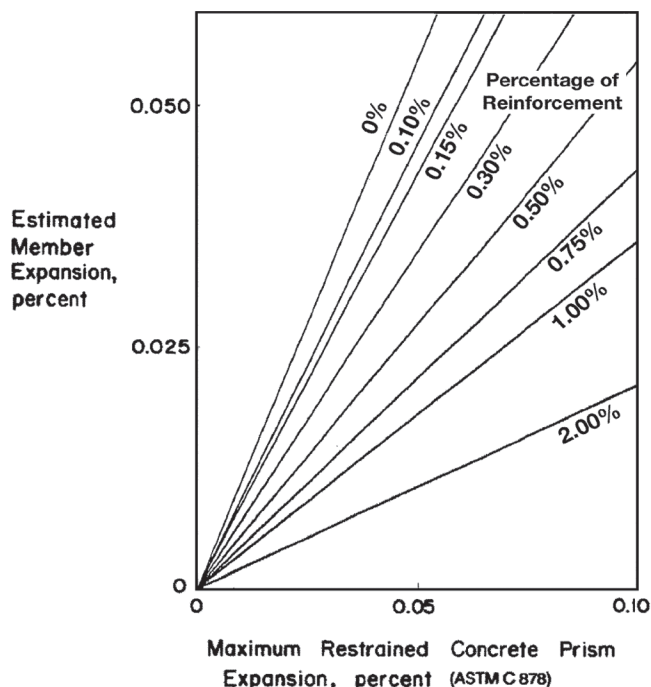


Fig. 5.1c—Estimation of member expansion of calcium hydroxide platelet-based system from ASTM C878/C878M prism expansion (Russell et al. 2002).

concrete can permit much longer lengths between expansion joints (up to 500 ft [150 m]), and the elimination of costly separation details such as closure strips (Eskildsen et al. 2009).

For reinforced shrinkage-compensating concrete, as the amount of reinforcement is increased, the concrete member initial expansion strains are reduced, and the induced initial compressive stress in the concrete is increased.

In the absence of external restraint, the amount of initial expansion in shrinkage-compensating concrete may be estimated as a function of the reinforcement ratio from Fig. 5.1b for an ettringite crystal system or Fig. 5.1c for a calcium hydroxide platelet crystal system (Russell 1973; Russell et al. 2002). The figures are based on correlations established between strain measurements performed on concrete slab specimens containing different percentages of steel reinforcement and the expansion data determined in accordance with ASTM C878/C878M. Based on the test results, the length changes for shrinkage-compensating concrete are comparable to those caused by temperature change.

Design example: A slab to be designed for shrinkage compensation has a steel reinforcement percentage of 0.30 percent for structural reasons. Based on the experience of the local area, shrinkage for the concrete selected for this slab is estimated to be 0.04%. Determine the required restrained expansion as determined by ASTM C878/C878M for complete shrinkage compensation.

Solution: The necessary expansion in the member to completely offset concrete drying shrinkage is 0.04%. Using this value for the estimated member expansion for an ettringite-based system in Fig. 5.1d and considering a reinforcement ratio of 0.30%, the required ASTM C878/C878M

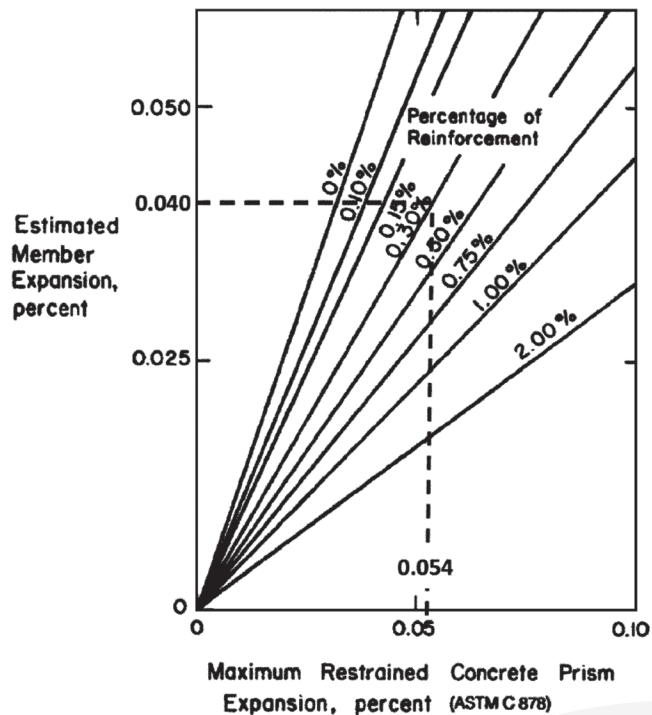


Fig. 5.1d—Design example for ettringite-based system.

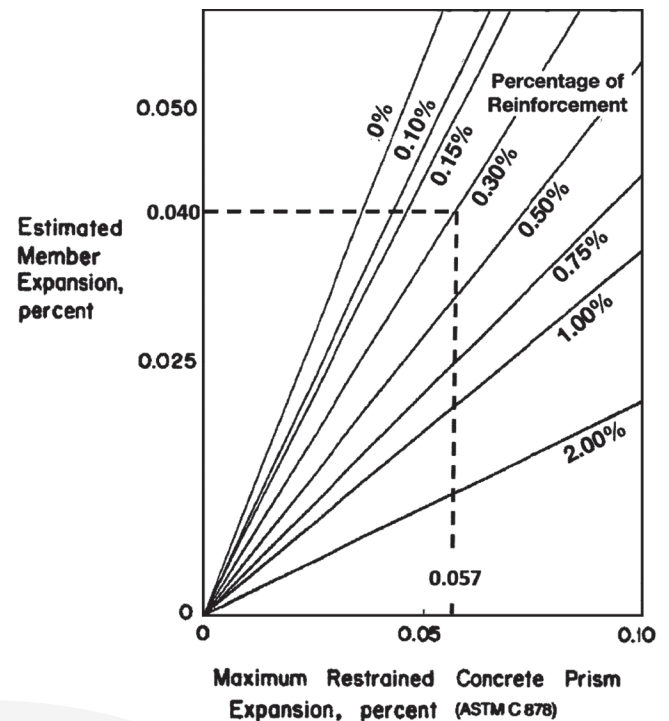


Fig. 5.1e—Design example for calcium hydroxide platelet-based system.

Table 5.1—Mixture design summary

	Percentage replacement			
	15	17	19	21
Portland cement, lb/yd ³	493	481	470	458
Expansive cement, lb/yd ³	87	99	110	122
Total cementitious material, lb/yd ³	580	580	580	580
Coarse aggregate, lb/yd ³	1772.6	1772.6	1772.6	1772.6
Fine aggregate, lb/yd ³	1349.2	1348.2	1347.4	1346.4
Water, lb/yd ³	290	290	290	290
w/cm	0.5	0.5	0.5	0.5

Note: (1 lb/yd³ = 0.5933 kg/m³).

maximum prism expansion is 0.054%. A member expansion in excess of the shrinkage will increase the likelihood that complete shrinkage compensation will be obtained.

Similarly, for a calcium platelet system, and using the same process, the required **ASTM C878/C878M** expansion is 0.057%, as shown in Fig. 5.1e. These are the minimum expansions needed to offset the subsequent shrinkage.

Ramseyer and Roswurm (2019), building upon the work of **Ramseyer and Roswurm (2016)** investigated four shrinkage-compensating mixture designs using expansive component Type K under varying degrees of external restraint stiffness and varying amounts of expansive cement component. The mixture 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. These mixture designs are summarized in Table 5.1 and are ordered in terms of increasing expansive cement content from left to right.

The expansion test results obtained for each of the four mixture designs are summarized in Fig. 5.1f(a), (b), (c), and (d). These samples were moist-cured for 7 days followed by dry curing. Expansion in graphs in 5.1f(a) and (b) were measured using a standard comparator with a resolution of 10 microstrains with data recorded once a day for the first 14 days and then weekly, whereas Fig. 5.1f(c) and (d) were measured using vibrating wire strain gauges with a resolution of 1 microstrain with data generally recorded every 15 minutes.

The variation of the expansions seen in Fig. 5.1f indicates that an increase in expansive component content corresponds directly to an increase in expansive length change, but that the relationship may not be linear. This behavior is shown to hold true for both unrestrained **ASTM C157/C157M** modified by measuring expansion instead of shrinkage and restrained **ASTM C878/C878M** expansion. Figure 5.1f also illustrates the impact of restraint in the prisms. For a given replacement percentage, the unrestrained **ASTM C157/C157M** expansion is generally higher than the restrained **ASTM C878/C878M** expansion.

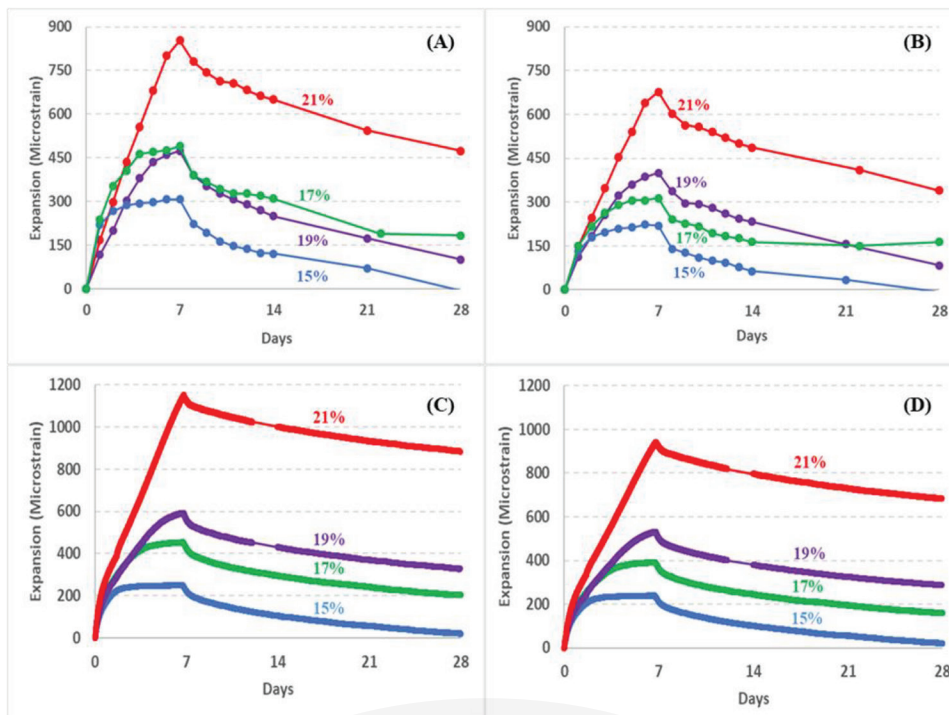


Fig. 5.1f—Expansion curves determined in accordance with: (a) ASTM C157/C157M modified by measuring unrestrained expansion instead of unrestrained shrinkage; (b) ASTM C878/C878M restrained expansion; (c) 6 x 12 in. (152 x 305 mm) unrestrained expansion cylinders; and (d) 6 x 12 in. (152 x 305 mm) restrained expansion cylinders. (Ramseyer and Roswurm 2019). Note: percent values next to the curves indicate the rate of addition of the expansive component.

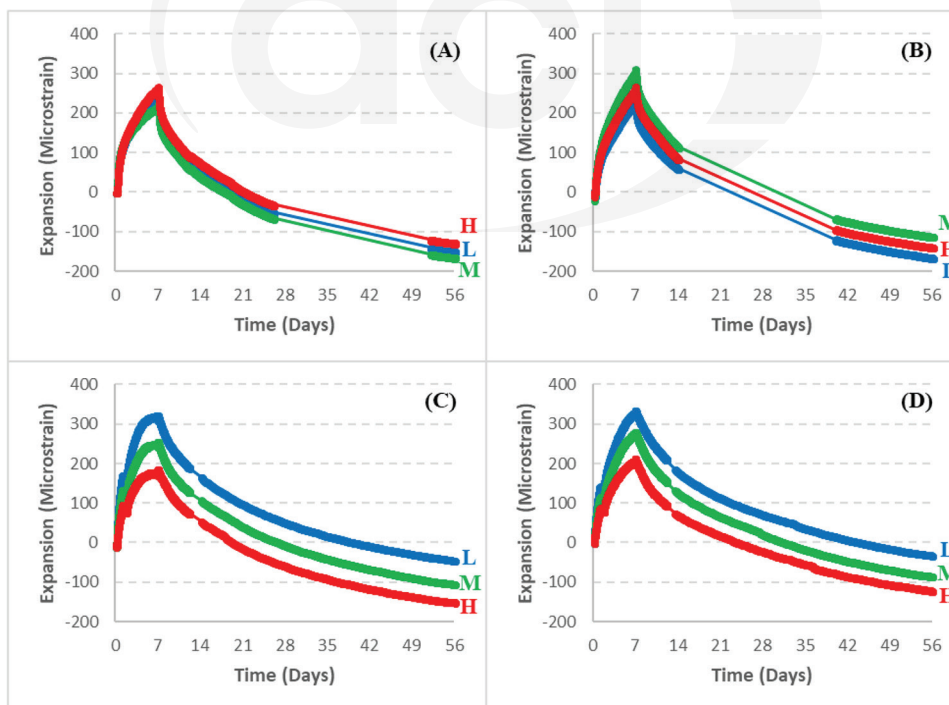


Fig. 5.1g—Expansion results from restrained columns for: (a) 15%; (b) 17%; (c) 19%; and (d) 21% ettringite-based additive cement. Note: L, M, and H next to the curves indicate low, medium, and high test-frame stiffness, respectively (Ramseyer and Roswurm 2019). (50 lb [220 N] = initial load; 1 lbf = 0.004448 kN)

C157M prisms (a) and 6 x 12 in. (152 x 305 mm) unrestrained expansion cylinders (c) exhibit a larger expansion than the restrained ASTM C878/C878M prisms (b) and 6 x 12 in. (152 x 305 mm) restrained expansion cylinders (d).

Ramseyer and Roswurm (2019) investigated the behavior of shrinkage-compensating concrete when cast against various elastic boundary conditions. Test frames with varying stiffness (low = L, medium = M, and high = H) were used to provide

boundary conditions. Calculations indicated that the axial stiffness of the M frame was theoretically equivalent to the stiffness of a mature concrete boundary condition, whereas the stiffness of the H test frame was 44% stiffer, and the stiffness of the L test frame was 36% less stiff. The test specimen where 4 ft (1219.2 mm) tall cylindrical columns with a 4 in. (101.6 mm) diameter. They were cast in PVC split forms and were wet cured immediately upon release from the forms at 8 hours. A vibrating wire strain gauge was cast in the test specimen to measure the strains and the top of the specimen was in contact with a load cell to measure load. The initial load of approximately 50 lb (220 N) was applied at 8 hours and wet curing was terminated at 7 days and then dry cured.

Figure 5.1g shows the results of these tests. A comparison of the four graphs shown in Fig. 5.1g shows a trend similar to that seen in Fig. 5.1f. Despite the presence of restraint, the column expansion increases as the expansive component content increases.

Testing of a variety of mixture designs with varying proportions by [Ramseyer and Roswurm \(2019\)](#) indicated that higher expansive component content corresponds directly to a higher, more rapid expansion with less aggressive shrinkage during the drying phase. An increase in the test frame stiffness of the external restraint by 44%, corresponding to the H restraint frame, led to a very slight reduction in maximum expansion and slightly more aggressive shrinkage during the drying phase. Conversely, a decrease in the test frame stiffness by 36%, corresponding to the L restraint frame, resulted in a slight increase in maximum expansion and higher residual expansion at test termination. In general, differences in performance from one stiffness to the next were subtle, indicating that a significant change in the boundary condition stiffness from an increase of 44% to a decrease of 36% does not cause correspondingly large changes in maximum expansive potential or shrinkage-compensation in the concrete. As a result, it may be concluded that the presence of a very stiff boundary condition will not prevent shrinkage-compensation in the concrete.

5.2—Member types

Shrinkage-compensating concrete has been successfully used for over 50 years in a variety of applications, notably:

- a) Post-tensioned slabs and beams (5.3)
- b) Slabs-on-ground (5.4)
- c) Overlays and topping slabs (5.5)
- d) Bridge decks (5.6)
- e) Airport pavements (5.7)
- f) Tanks (5.8)

5.3—Post-tensioned slabs and beams

Different case studies have shown that shrinkage-compensating concrete is a highly desirable option for post-tensioned slabs and beams because of the negligible restraint to shortening and the ability to eliminate closure strips from the construction process. [Bondy \(2010, 2011\)](#) provided a series of four case studies using expansive component Type K that demonstrate the ability of shrinkage-compensating concrete to perform well in such applications.

The primary focus of the article is on the concept of restraint to shortening (RTS). RTS is of interest to designers of post-tensioned concrete structures because of the length change that is induced by the process of tensioning. The effect of this tensioning is to move the two ends of a beam or slab closer together, thus causing a reaction force due to restraint by walls or columns where the member terminates. In his article, Bondy (2010, 2011) indicates that the use of shrinkage-compensating concrete can reduce or eliminate cracking due to RTS by inducing an expansion during early age.

This expansion does not induce severe stresses because the stiffness of the restraining members is not yet fully developed. As the concrete ages, the natural shortening of the post-tensioned structure causes member lengths to move back towards a neutral position, rather than shrinking into the tensile regime where one would expect to find cracks occurring at critical connection points. Bondy (2010) documents an investigation of four different buildings of varying ages in which shrinkage-compensating concrete was successfully used to mitigate or eliminate RTS cracking.

The first of these four buildings is the Santa Monica Parking Structure #2. The first four floors of this building were constructed in 1968 and each floor was framed with monolithic cast-in-place post-tensioned beams using shrinkage-compensating concrete. The floors were instrumented with pins so that strains in the floor could be measured before, during, and after post-tensioning, and at 5-year intervals following construction. After 5 years of service, measurements indicated a total shortening of 0.00034 in./in. (0.00034 mm/mm), which is roughly 30% of the 0.00112 in./in. (0.00112 mm/mm) observed in a similar nearby structure built with Type II portland cement. Figure 5.3a shows the interior of Level 4.

According to Bondy, a 2010 investigation of the structure revealed only 80 linear feet of cracks in the roughly 120,000 ft² (11,000 m²) of the first four floors. All of these cracks were concentrated in the first elevated slab, near the elevator/stair shaft on one end and the basement wall on the other end. On the next three floors where local end restraints were not present, no cracking was observed in structural members of any kind. In contrast, however, the upper four floors (four through eight), which were added on in 1980



Fig. 5.3a—Parking Structure #2 (Level 4 interior) (Bondy 2011).