Guide for the Use of Shrinkage-Compensating Concrete

Reported by ACI Committee 223

American Concrete Institute®

First Printing
December 2010

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Guide for the Use of Shrinkage-Compensating Concrete

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ISBN 978-0-87031-404-9

Guide for the Use of Shrinkage-Compensating Concrete

Reported by ACI Committee 223

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

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ACI 223R-10 supesedes 223-98 and was adopted and published December 2010.

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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, bridge decks (Gruner and Plain 1993; Ramey et al. 1999), hydraulic structures, wastewater treatment plants, containment structures (Valentine 1994), post-tensioned structures (Hoffman 1980; Eskildsen et al. 2009), parking structures, and slabs-on-ground (Keith et al. 1996, 2006; Bailey et al. 2001).

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—NOTATION AND DEFINITIONS

2.1—Notation

c = bar diameter/2 = $d_b/2$
d_b = bar diameter
E = modulus of elasticity of the bar
f_y = stress in reinforcing bar
I = moment of inertia of bar
L = length
ℓ = total length of wall between free ends
M = moment in reinforcing bar
T = tolerance allowance
Δ = anticipated wall movement relative to footing
ε = expansion of wall

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org. Definitions provided herein complement that resource.

concrete, shrinkage-compensating—a concrete made with an expansive cement or component system in which the expansion, if properly restrained, induces compressive stresses that approximately offset tensile stresses caused by shrinkage.

cement, expansive—a cement that, when mixed with water, produces a paste that, after setting, increases in volume to a significantly greater degree than does portland cement paste; used to compensate for volume decrease due to shrinkage or to induce tensile stress in reinforcement.

1. **cement, expansive, Type K**—a mixture of portland cement, anhydrous tetracalcium trialuminate sulfate ($C_4A_3\overline{S}$), calcium sulfate ($CaSO_4$), and lime (CaO); the $C_4A_3\overline{S}$ is a constituent of a separately burned clinker that is interground with portland cement or alternately, it may be formed simultaneously with the portland-cement clinker compounds during the burning process.
2. **cement, expansive, Type M**—interground or blended mixtures of portland cement, calcium-aluminate cement, and calcium sulfate suitably proportioned.
3. **cement, expansive, Type S**—a portland cement containing a high computed tricalcium aluminate

(C_3A) content and an amount of calcium sulfate above the usual amount found in portland cement.

expansive component system (general)—a 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**—a blend of calcium sulfoaluminate and calcium sulfate that produces ettringite when mixed with portland cement and water.
2. **expansive component Type M**—a blend of calcium-aluminate cement and calcium sulfate that produces ettringite when mixed with portland cement and water.
3. **expansive component Type S**—a 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**—a blend of calcium dioxide and aluminum dioxide 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, and paste content. Lower water content, aggregate with a higher modulus of elasticity, larger aggregate size, longer moist curing, and leaner mixtures reduce drying shrinkage.

Concrete drying shrinkage typically ranges from 0.03% to 0.06%. Drying shrinkage of a concrete mixture is determined by using ASTM C157/C157M. ASTM C157/C157M laboratory tests give results that are typically higher than the shrinkage of concrete placed in the field.

Beyond the shrinkage-compensating component, the materials used to produce shrinkage-compensating concrete are the same as those required to produce portland-cement concrete. Shrinkage-compensating concrete's ability to minimize cracking depends on water curing for 7 days. 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 1 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 material 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 are determined by the constituents that create the expansion mechanisms (refer to Table 4.1). Expansion produced 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 compared with expansion requirements of mortar in ASTM C845.

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 normalweight and lightweight aggregates can be used to produce shrinkage-compensating concrete. The aggregates used should meet ASTM C33/C33M or 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 tests.

4.3—Water

Mixing water should be of the same quality as 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 expansion levels of shrinkage-compensating concrete are recommended.

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 in regard to compatibility issues.

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

- The admixture's influence on expansion;
- Water requirement;
- Air content;
- Consistency;
- Rate of slump loss;
- Bleeding;
- Rate of hardening;
- Strength; and
- Drying shrinkage.

Table 4.1—Types of shrinkage-compensating cements and their constituents

Expansive type*	Principal constituents	Reactive aluminates available for ettringite formation
K	(a) Portland cement (b) Calcium sulfate (c) Portland-like cement containing $C_4A_3\overline{S}$	$C_4A_3\overline{S}$
M	(a) Portland cement (b) Calcium sulfate (c) Calcium-aluminate cement (CA and $C_{12}A_7$)	CA and $C_{12}A_7$
S	(a) Portland cement high in C_3A (b) Calcium sulfate	C_3A
G	(a) Portland cement high in CaO (b) Calcined pozzolan (SiO_2 and $A1_2O_3$)	$CA(OH)_2$, CaO, and $A1_2O_3$

*Three types of shrinkage-compensating cements described in ASTM C845 are designated K, M, and S.

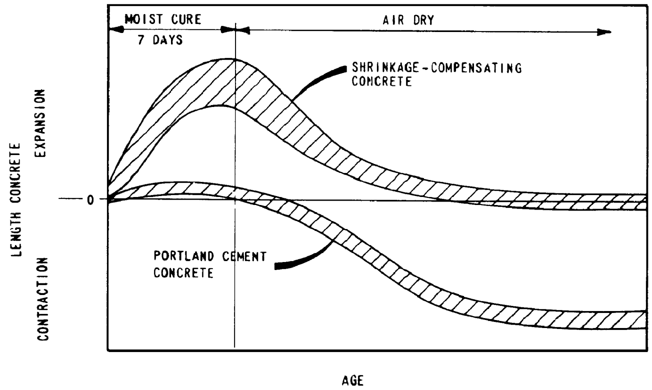


Fig. 4.1—Typical length change characteristics of shrinkage-compensating concrete and portland-cement concretes (ACI 223-98).

Air-entraining admixtures are as effective with shrinkage-compensating concrete as with portland-cement concrete in improving freezing-and-thawing resistance and scaling resistance.

4.5—Concrete

4.5.1 *Strength*—After expansion, the tensile, flexural, and compressive strength development 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 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 water-cementitious material ratio (*w/cm*), the greater the compressive strength (refer to Section 4.2.5 of ACI Committee 223 [1970]).

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. (For modulus of elasticity, refer to Section 4.2.7 of ACI Committee 223 [1970]. For creep, refer to Section 2.5.4 of ACI 223-98. For Poisson's ratio, refer to Section 4.2.14 of ACI Committee 223 [1970]. For coefficient of thermal expansion, refer to Section 4.2.9 of ACI Committee 223 [1970].)

4.5.3 *Volume change*—After expansion, the drying-shrinkage characteristics of a shrinkage-compensating concrete are similar to those of portland-cement concrete. Figure 4.1 illustrates the typical length change characteristics of shrinkage-compensating and portland-cement concrete tested in accordance with ASTM C878/C878M. (Refer to Fig. 4.2.6 of ACI Committee 223 [1970] and Section 2.5.3 of ACI 233-98.)

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. The effects of air content and aggregates are essentially the same. For further details, refer to ACI 201.2R and Sections 4.2.10 and 4.2.11 of ACI Committee 223 (1970).

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. Shrinkage-compensating cement made with a 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 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 clinker (Mehta and Polivka 1975).

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. Before severe exposure to extended freezing, the concrete should attain a specified compressive strength of 4000 psi (27.6 MPa). For moderate exposure conditions, a specified strength of 3000 psi (20.7 MPa) should be attained. 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% higher than portland-cement concrete of comparable mixture proportions (ACI Committee 223 1970; Nagataki and Yoneyama 1973; Klieger and Greening, 1969).

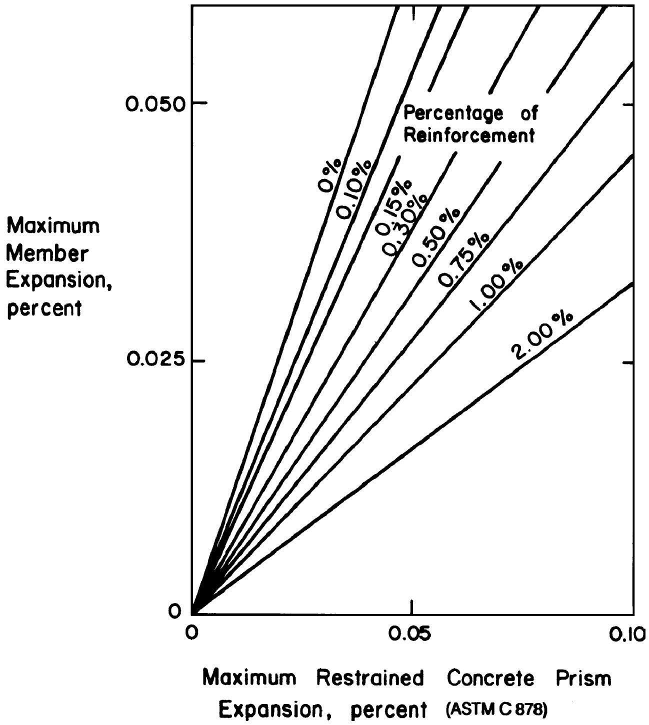


Fig. 5.1—Estimation of member expansion of ettringite-based system from prism expansion (based on Russell [1973]).

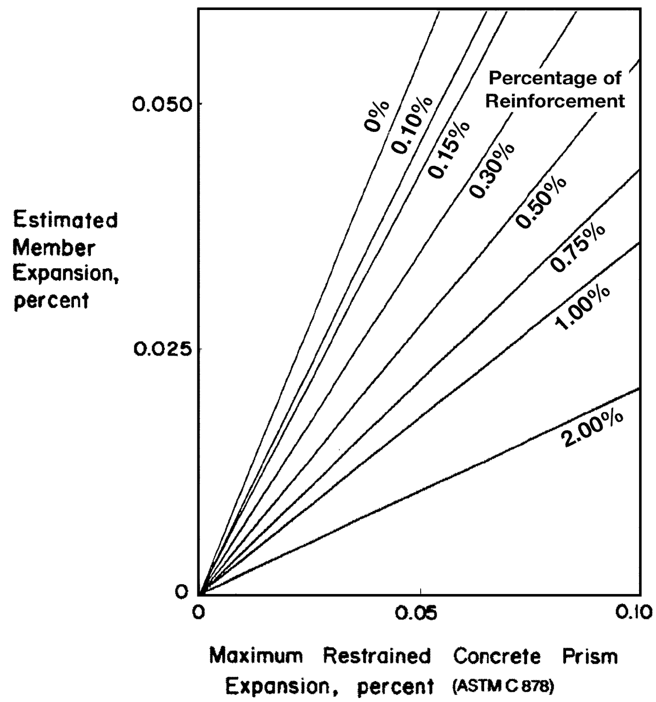


Fig. 5.2—Estimation of member expansion of calcium hydroxide platelet-based system from prism expansion (Russell et al. 2002).

CHAPTER 5—STRUCTURAL DESIGN CONSIDERATIONS

5.1—General

The design of reinforced concrete structural elements using shrinkage-compensating concrete should conform to the requirements of applicable ACI standards, building codes, and bridge specifications. Design the concrete mixture such that the expansion is adequate to overcome the stresses that will be induced by subsequent drying shrinkage. Because the intended final net result of expansion and shrinkage is generally zero, structural consideration need not be given to the stresses developed in the concrete during this process. The internal concrete stresses that develop due to expansion are less than those due to shrinkage as the expansion occurs when the stiffness and modulus of elasticity of the concrete are not fully developed and creep is high. Thus the internal concrete stresses are relatively small during the initial expansion phase and then tend to reduce, not increase, with time after full expansion has occurred.

In a structural member, the amount of initial expansion is proportional to the amount of restraint. In a reinforced concrete member with no external restraint, the amount of expansion is inversely proportional to the percentage of reinforcing steel. Refer to Fig. 5.1 for Type K (ettringite) systems or Fig. 5.2 for Type G (calcium hydroxide platelet) systems.

The length changes are small and similar to those caused by temperature change.

In the case of slabs-on-ground, if the slab is surrounded by existing slabs (infinite restraint), there can be no movement, but the expansive energy within the concrete causes compressive stress in the concrete. As drying shrinkage takes place in this part of the slab, the concrete loses compression. Where the expansion coefficient is higher than that of shrinkage, the slab will not crack due to drying shrinkage stresses. High restraint will induce a high compressive stress in concrete, but may provide little shrinkage compensation.

An analogy to infinite restraint is the heating and subsequent cooling of a steel bar with ends against rigid restraints. As the bar is heated, it presses against the restraint and the bar goes into compression. This is similar to the expansive phase of shrinkage-compensating concrete. If the bar is cooled to its original temperature (drying shrinkage), it returns to its original length and the stress in the bar is zero. If the bar retains some heat, the bar has a slight compression. If the bar is cooled below the original temperature and the bar ends are restrained, the bar is in tension.

Subgrade friction at the edge of the slab can be insufficient to restrain the expansion. Slab reinforcement provides the necessary restraint and there is a slight movement of the edge of the slab, placing reinforcement in tension and the concrete into compression. As the concrete dries, the slab shortens and the tension in the reinforcement decreases. This may result in an opening of the joint between adjacent slabs.

In the case of post-tensioned concrete, the post-tensioning compresses the concrete. The shrinkage-compensating expansion adds to the post-tensioning compression. As drying shrinkage takes place, the compression due to shrinkage compensation diminishes, but most of the post-tensioning compression remains.

5.1.1 *Design example*—A slab to be designed for shrinkage compensation has a steel reinforcement percentage

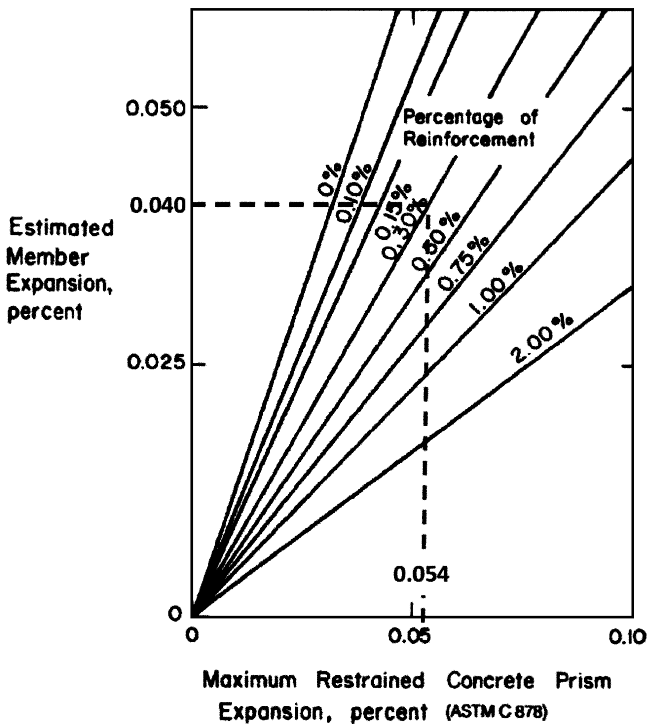


Fig. 5.3—Design example for ettringite-based system.

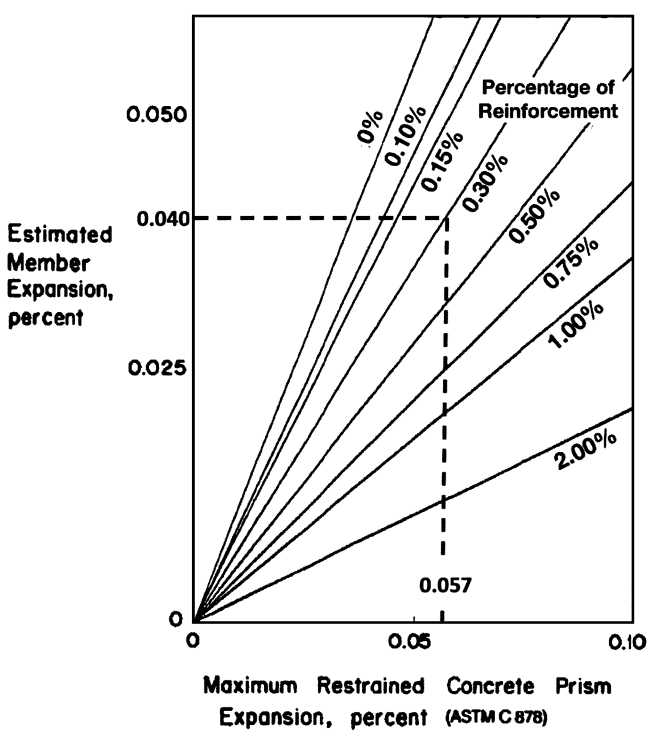


Fig. 5.4—Design example for calcium hydroxide platelet-based system.

of 0.30% for structural reasons. Determine the required restrained expansion as determined by ASTM C878/C878M for complete shrinkage compensation.

Solution: Based on the experience of the local area, the anticipated shrinkage of the concrete is 0.04%. The actual shrinkage will be less due to restraint from the subgrade. For complete shrinkage compensation, the amount of expansion must be at least equal to the anticipated shrinkage.

For an ettringite system, refer to Fig. 5.3. Entering the graph at an estimated expansion of 0.04 and turning on the line labeled 0.30% reinforcement results in a required ASTM C878/C878M expansion of 0.054%.

Similarly, for a calcium platelet system, and using the same process, the required ASTM C878/C878M expansion is 0.057%, as shown in Fig. 5.4. These are the minimum expansions needed to offset the subsequent shrinkage.

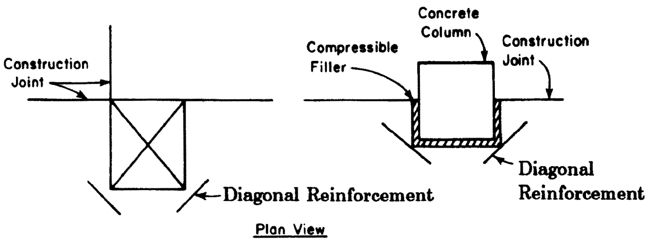
5.2—Restraint

5.2.1 *Types of restraint*—An elastic restraint, such as that provided by internal reinforcement, is used to develop compression within the concrete. Other types of restraint, such as adjacent structural elements, integral abutments, and subgrade friction also provide restraint and produce compression in the concrete. Subgrade frictional coefficients range from 1.0 to 0.5. Values of the coefficient of friction for different bases and subbases are given in ACI 360R.

5.2.2 *Reinforcement details*—Engineering analysis and design practices for structural elements will normally provide a sufficient amount of steel for restraint. A minimum ratio of reinforcement area to gross concrete area of 0.0015 is desired. This minimum is similar to recommendations of ACI 318 for temperature and shrinkage stresses. Reinforcement should be welded wire reinforcement or steel deformed bars meeting the requirements of ACI 318.

In structural members, the reinforcement location is determined from design requirements. Structural considerations may require a higher reinforcement ratio. This may result in a concentration of reinforcement in one section. Experience shows that warping caused by concentrated reinforcement is not a problem in typical structures. In slabs-on-ground, where most of the drying occurs in the top portion, the reinforcement should be placed in the upper half of the slab (preferably 1/3 of the depth from the top), while still allowing for adequate cover. Reinforcing steel should be placed and supported in such a manner that it will maintain its positioning during concrete placement and provide restraint during the curing process. To ensure accurate positioning, use deformed bars or welded wire reinforcement placed on chairs or tied to other fixed rods, concrete supports, or portions of the structure. Where wire reinforcement is used in place of deformed bars, it should be in flat sheets or mats rather than rolls. The use of rolled welded wire reinforcement is not recommended. Hooking or pulling the reinforcement off the form or subgrade should not be permitted.

5.2.3 *Estimation of maximum expansions*—When structural design considerations result in a reinforcement ratio greater than the recommended minimum, such as in bridge decks, or when it is desired to use less than the minimum reinforcement of Section 5.2.2, the level of expansion in structural members is estimated from Fig. 5.1 for an ettringite crystal system or Fig. 5.2 for a calcium hydroxide platelet crystal system. These graphs show the relationship between a reinforced concrete member with no external restraint, concrete prism expansion, and percentage reinforcement



(1) Eliminate corner if possible by locating construction joint. (2) If construction joint is not feasible, reinforce corner with diagonal reinforcement to keep re-entrant corner crack from opening excessively.

Fig. 5.5—Re-entrant corners (pits, trenches, floor layout, and truck dock) (ACI 223-98).

(Russell 1973; Russell et al. 2002). The prism expansion test is defined in ASTM C878/C878M.

Concrete member expansion is reduced as the amount of reinforcement is increased but the amount of compressive stress in the concrete will be increased.

5.3—Reinforced structural slabs

5.3.1 *Structural design*—Base the design on the strength design provisions of ACI 318 or ACI 350. The designer should specify the minimum level of expansion desired for each project based on the estimated shrinkage under anticipated environmental conditions. The required level of expansion, as measured using ASTM C878/C878M at 7 days or earlier under laboratory conditions, is then determined using Fig. 5.1 or Fig. 5.2. ASTM C878/C878M 7-day expansions in water generally range from 0.03% to 0.06%.

5.3.2 *Deflection*—Deflection analysis should be made in the same manner as for portland-cement concrete.

5.3.3 *Cracking moment*—The use of shrinkage-compensating concrete does not affect the flexural strength of reinforced concrete members. It does, however, influence the load at which flexural cracking occurs. Cracking moments in shrinkage-compensating concrete are higher than in portland-cement concrete. (Pfeifer 1973; Cusick and Kesler 1976).

5.4—Reinforced slabs-on-ground

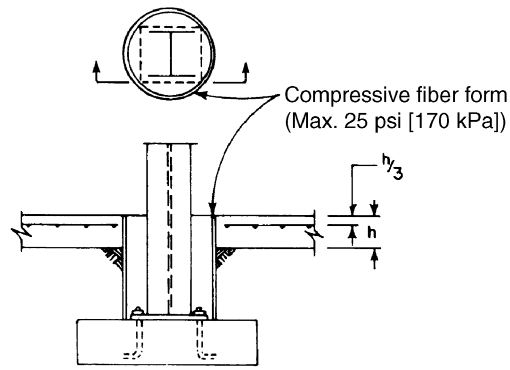
Shrinkage-compensating concrete expands shortly after setting, placing the concrete into compression at a time when the concrete has little tensile strength to resist tensile stresses due to temperature drops and construction loads.

5.4.1 *Warping*—In shrinkage-compensating concrete, when properly designed, the warping of slabs-on-ground is generally prevented. This is due to the lack of net shrinkage in adequately designed and installed members (Keeton 1979).

5.4.2 *Isolation joints*—Joints used to accommodate vertical movement or horizontal movement should be provided at junctions with walls, columns, machine bases, footings, or other points of external restraint. Details of isolation joints are shown in Fig. 5.5 through 5.11. The isolation joint material should allow for sufficient movement at the joint caused by expansion of the concrete.

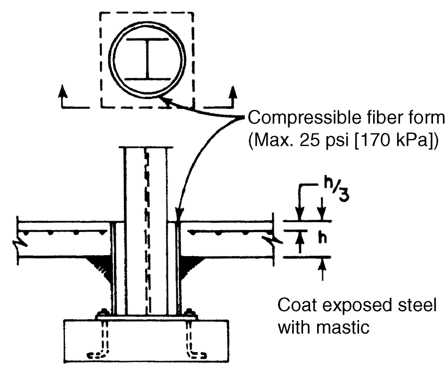
5.4.3 *Joints*—With the use of shrinkage-compensating concrete, larger areas can be placed without contraction joints. Slabs have been placed in areas from approximately 10,000 to 20,000 ft^2 (930 to 1850 m^2) without joints.

Whenever possible, place slabs-on-ground as square as possible, preferably with a length-to-width ratio not greater than 3:1. When properly designed, exceptions to this ratio have been used successfully on pavements and long, narrow



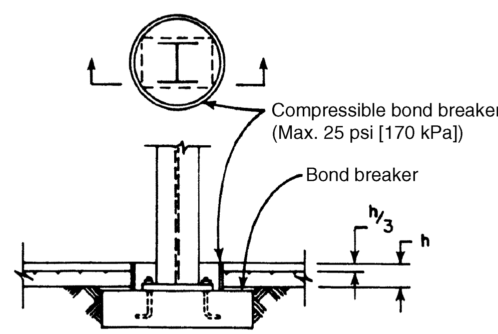
(1) For steel or concrete column.
(2) Column and base plate protected.
(3) Compressible fiber form split and placed inside box-out and for slab at the same time.
(4) No stress concentraction point because of circular hole in slab.
(5) If smaller diameter box-out is desired, see detail in Fig. 5.7.
(6) Cast box-out at least 7 days after slab if compressible material is omitted.

Fig. 5.6—Circular box-out for deep footing.



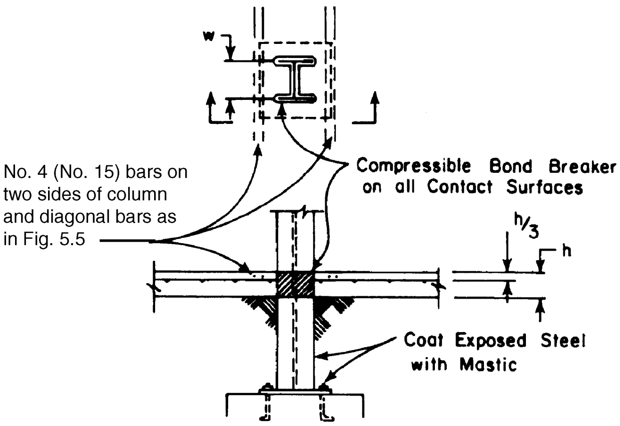
(1) Provide for smaller box-out than Fig. 5.6
(2) Same notes for Fig. 5.6 apply.

Fig. 5.7—Circular box-out for deep footing.



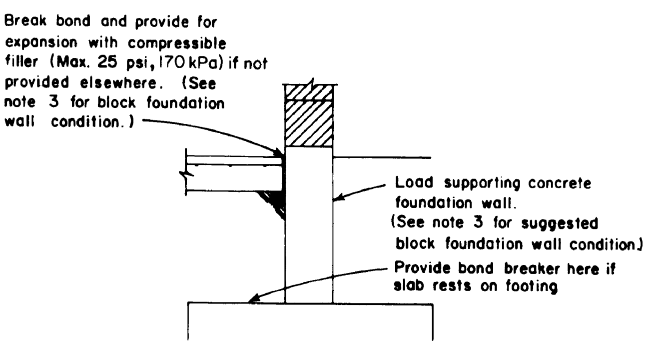
(1) Box-out must enclose base plate to prevent bonding slab to footing.
(2) Bond breaker may be any material to separate slab from footing.
(3) All other notes with Fig. 5.6 apply.

Fig. 5.8—Cicular box-out for shallow footing.



(1) No box-out provided.
(2) Isolation provided by beaking bond at all concrete-to-steel contact surfaces with compressible bond breaker (max. 25 psi [170 kPa]).
(3) Mastic below floor is for steel protection only.
(4) No. 4 (No. 15) bars placed across point stress concentration areas to reduce crack tendency

Fig. 5.9—Wrapped column with stress bars.



(1) No reinforcing steel connecting slab to wall.
(2) Provide waterstop if joint is to be watertight.
(3) Provide compressible material for thermal movement relief at inside face of wall with block foundation wall. (Max. 25 psi [170 kPa])

Fig. 5.10—Slab perimeter not tied to wall.

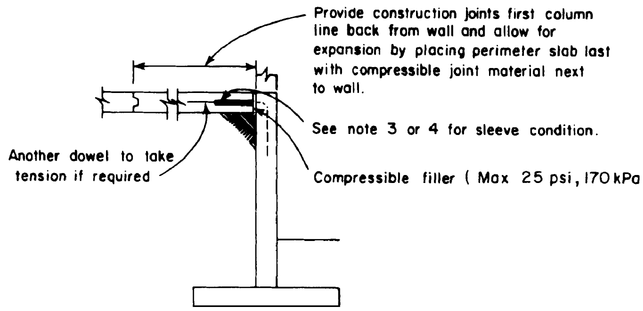
slabs. Examples of joint details for slabs-on-ground are shown in Fig. 5.12 through 5.17.

Design and detail construction joints in slabs-on-ground as formed contraction joints. This will accommodate movements that allow the joint to open. When load transfer is required, formed contraction joints should be detailed and constructed in accordance with Fig. 5.12, 5.16, or 5.17. The use of plate dowels has been described by Walker and Holland (1998).

5.4.4 *Expansion joints*—The location or design of expansion joints for the control of thermal and other movements are not changed with the use of shrinkage-compensating concrete.

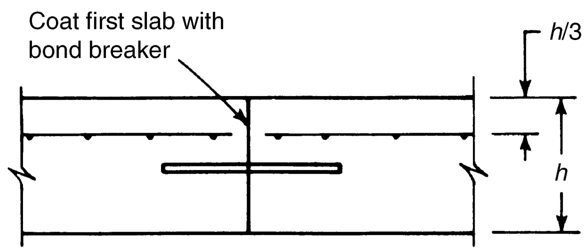
5.4.5 *Details*—Suggested details of isolation joints, construction joints, contraction joints, door openings, and wall footings are shown in Fig. 5.12 through 5.17.

5.4.6 *Placing sequence*—When reinforced per Section 5.2, placement sequence for a slab-on-ground should allow the expansive strains to occur against a free and unrestrained edge. The opposite end of the slab, when cast against a rigid element, should be free to move. A formed edge should have the brace



(1) Provide for possible slab movement at construction joint rather than cracking slab because of perimeter restraint.
(2) Place slab at sufficiently later date after exterior wall to allow for shrinkage relief.
(3) Provide temperature relief joints in interior slab perpendicular to wall.
(4) Wrap dowels to provide sleeve for horizontal movement between wall and slab if provisions in Note (3) are not feasible.
(5) Provide compressible filler between slab and wall, which will allow for expansion.

Fig. 5.11—Slab perimeter tied to wall.



(1) Top edge at joint finished flush (no tooled edge). Reinforcing does not pass through joint.
(2) Joint must be free to open due to assumed temperature contraction of the slab.
(3) Leave sufficient space in joint for expansion if not provided elsewhere.
(4) Loosen brace stakes and pins after initial set to permit early expansion.
(5) Smooth dowels are greased or wrapped to prevent bond.
(6) Dowels must be placed and maintained parallel to top surface and perpendicular to joint surface.
(7) Dowels must be removed after initial set and reinserted after form removal.
(8) Provisions may be made to allow for differential movement parallel to joint for slabs cast adjacent to previously cast slabs.

Fig. 5.12—Doweled contraction joint.

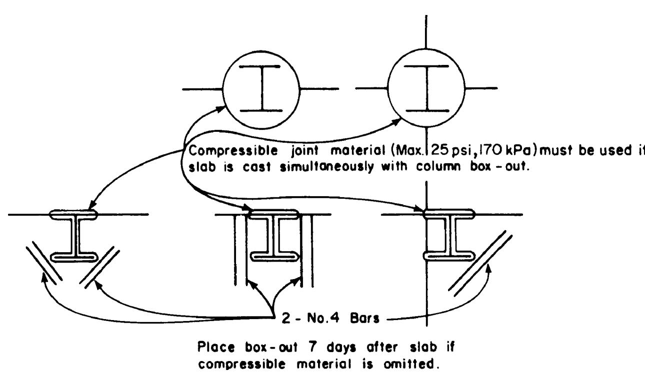
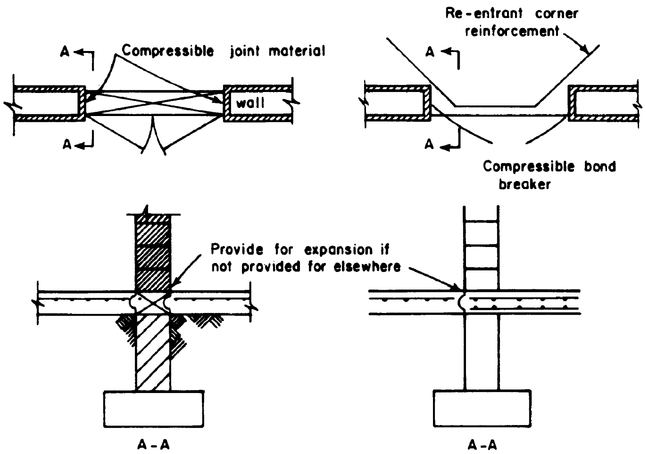


Fig. 5.13—Contraction joints at columns.

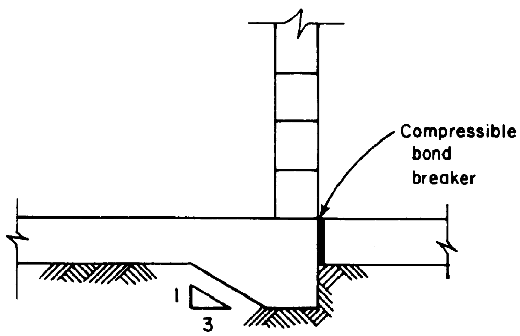
stakes or pins loosened after the concrete is set to accommodate the expansive action (Beckman and Gulyas 1986).

Organize the placing sequence so that the edges of slabs are free to move for the maximum time possible before



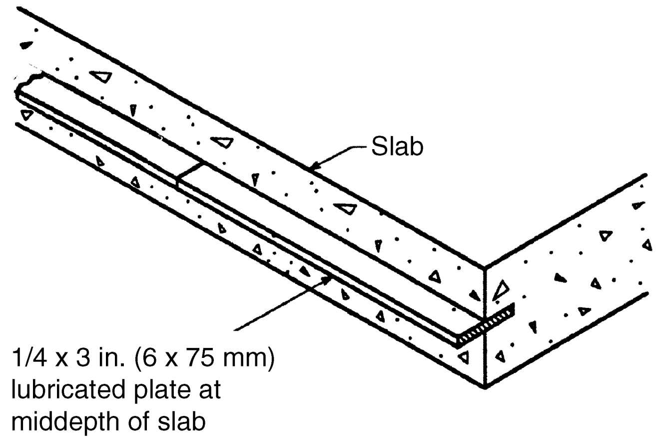
(1) Construction joints provided at door opening to allow possible slab movement parallel to wall in horizontal direction.
(2) Break bond at construction joints and along wall surface.
(3) Place concrete in opening at the same time as the slab by using metal keyway.

Fig. 5.14—Door opening.



(1) Thickened edges or thickened sections restrain slab movement due to temperature changes.
(2) Slab on one side of wall free to move independently.
(3) Construction joint at opposite end of restrained slab free to accomodate temperature movement.

Fig. 5.15—Integral footing for partition walls.



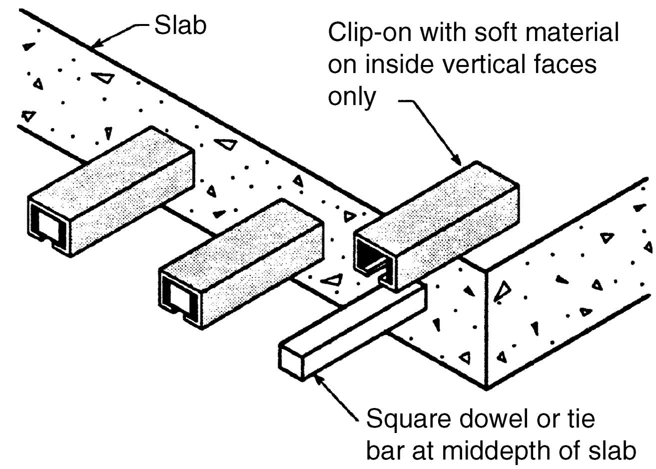


Fig. 5.16—Joint details for movement parallel and horizontally perpendicular to joint.

placing adjacent slabs. At least 70% of the maximum measured laboratory expansion, according to ASTM C878/C878M, should occur before placing slabs that are not free to expand on two opposite ends. Three examples of placement sequences are shown in Fig. 5.18 through 5.20. Checkerboard placements should not be used unless a compressible joint material is placed between the slabs before concrete placement. Compressible joint materials with a maximum compression of 25 psi (170 kPa) at 50% deformation per ASTM D1621 or D3575 should be used to accommodate the anticipated movement. Joint materials meeting ASTM D994, D1751, and D1752 may be too stiff to allow adequate expansion.

5.5—Post-tensioned structural concrete

5.5.1 *Design requirements*—Design post-tensioned concrete structures using shrinkage-compensating concrete by meeting the requirements of ACI 318 or ACI 350, and following the recommendations of ACI 423.3R.

5.5.2 *Length changes*—Shrinkage-compensating concrete reduces the net structural movements due to drying shrinkage, and thereby reduces the lateral loads on columns and walls. Although the expansion may be sufficient to offset the subsequent drying shrinkage strain, the stresses induced by expansion are lower than the subsequent stresses caused by shrinkage because the modulus of elasticity of the concrete is lower during the expansion phase. As a result, the designer should consider how much the expansion offsets the length change, forces, and prestress losses from shrinkage.

5.6—Post-tensioned slabs-on-ground

Recommendations for post-tensioned slabs-on-ground with portland-cement concrete are contained in PTI's *Design of Post-Tensioned Slabs-on-Ground* (PTI 2008). Because shrinkage-compensating concrete reduces net drying shrinkage, certain modifications can be made in post-tensioned slabs-on-ground. Although the expansion may be sufficient to offset the subsequent drying shrinkage strain, the stresses induced by expansion are lower than the subsequent stresses caused by shrinkage because the modulus of elasticity of the concrete is lower during the expansion phase. As a result, the designer should consider how much the expansion offsets the prestress loss from shrinkage. Consider using steel bars

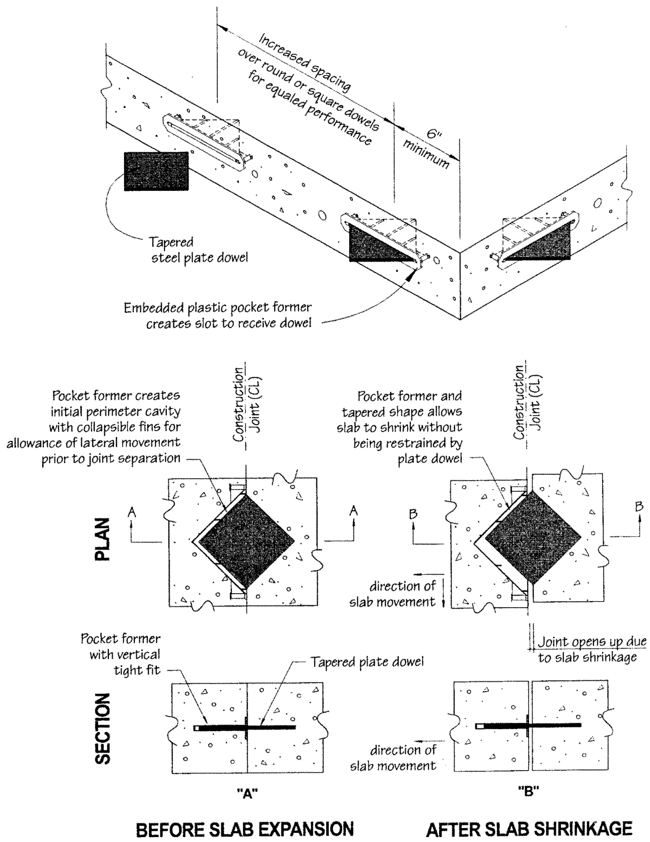


Fig. 5.17—Joint details for tapered plate dowel systems.

9	6	3
7	4	1
8	5	2

Fig. 5.18—Center adjacent slab placement pattern.

or welded wire reinforcement in the top third of the slab as temperature and shrinkage reinforcement to prevent drying shrinkage cracking before tensioning, or by removing edge forms immediately after initial set and snugly inserting the wedges into the stressing-end anchorages.

10	8	6	15
12	4	2	13
14	1	3	11
16	5	7	9

Fig. 5.19—Center rotation slab placement pattern.

9	8	6
7	5	3
4	2	1

Fig. 5.20—Lag slab placement pattern.

5.7—Walls

5.7.1 *Placing sequences*—The sequence of placing shrinkage-compensating concrete in walls is important. Placing sequence should allow one edge of the wall in each direction to expand. The top of the wall is free to expand in the vertical direction. At least one vertical construction joint remains free to allow expansion in the horizontal direction. Free edges are needed so the concrete can expand without rigid external restraint. Checkerboard placement of walls (cast a wall section, skip a wall section, cast a wall section) has been used for portland-cement concrete but is not recommended for shrinkage-compensating concrete unless provisions are made to allow wall expansion. The checkerboard method leaves no space for the concrete to increase in length. The concrete could build up compressive stresses without engaging the reinforcement. This stress could then be dissipated quickly due to the negative length change caused by shrinkage. As a result of insufficient expansion, shrinkage cracks may occur. The following paragraphs explain three different possible placing sequences that are used with shrinkage-compensating concrete. In each case, the compressible filler strip joint should be made from material that has a maximum compressibility of 25 psi (170 kPa) when it is reduced to 50% of its original thickness.

Figure 5.21(a) shows a plan of a rectangular tank with a casting sequence leaving the corners open until all side walls have been cast. The sequence may be varied as long as no wall section is restrained between two previously cast sections and the corners are cast last. The minimum time period, generally 3 to 7 days, between casting adjoining sections is sufficient to ensure that adequate expansion or volume change takes place before the next section is cast. Corner section size should be large enough to develop hooks and laps as required by design.

Figure 5.21(b) shows a plan with continuous sequential casting of a tank wall with all placements stopping short of the corners. A compressible filler strip joint is placed between the last section and the existing first corner section. The plan shows the recommended sequence for placing concrete wall sections with continuous casting. The corner sections are slightly longer so bar hooks and development lengths are incorporated. In hydraulic structures, the compressible filler joint should use a waterstop because the two concrete joint faces are separated and not bonded to each other as are the rest of the construction joints. The thickness of the compressible filler is determined by the architect/engineer, based on the length of wall and amount of expansion that takes place. The minimum thickness considered is 3/4 in. (20 mm). The compressible filler should cover the full joint face (width) as well as the full height of the wall. The minimum time period between section castings, generally 3 to 7 days, ensures that adequate expansion or volume change takes place before the next section is cast.

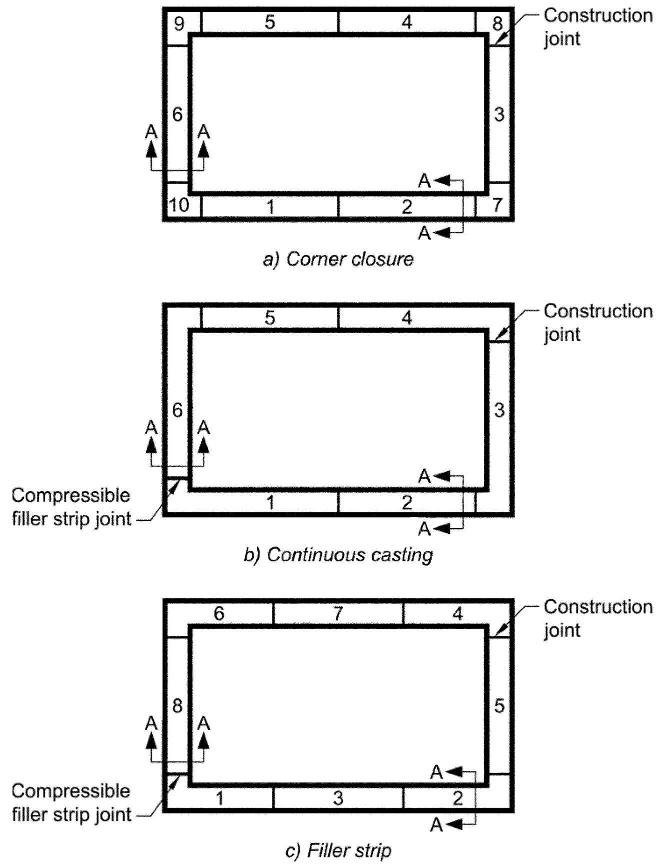
Figure 5.21(c) shows a plan with filler strip wall construction. The plan shows a variable sequence of wall construction, starting with two ends of a wall and their corners. Next, the section between the two ends is cast with compressible filler at one end and a construction joint at the opposite end. The remaining sections are cast similarly by casting another end section and then casting the infill jointed as noted previously. There is always compressible filler at one end of the wall section to allow for expansion. In all wall sequences, the architect/engineer is to determine wall length between joints.

5.7.2 *Details*—Shrinkage-compensating concrete used in the wall should expand and should not be restrained by any other element. Figure 5.22 is a typical wall base section for a fixed ended wall showing the dowel protection, shear key, and formed and smooth surface of shear key.

A shear key, as shown in Fig. 5.22, should be used. The depth of key is determined by the architect/engineer to offset the maximum force from either backfill or filled tank but is 2 in. (50 mm) minimum. The horizontal surface of the shear key is troweled smooth immediately under the vertical wall area and to a width 1/2 in. (12 mm) beyond. The smooth area is then coated with a bond breaker before concrete placement to allow wall movement during expansion. The region to be grouted remains ungrouted as long as possible and for at least 28 days. A high-strength nonshrink concrete grout is used to fill the shear key. Lateral load on the wall from backfilling or internal pressure is not applied until the grout has achieved the specified strength.

The vertical dowels have a sleeve placed around their base so there is an unbonded length of bar that bends as the wall expands. The top of the sleeve and the reinforcing bar going through this point are sealed with a suitable material to keep concrete out of the sleeve. The dowels are lapped above the sleeve for required development length. The size and length of the sleeve is explained in greater detail in the next paragraph. The architect/engineer determines sleeve heights based on the amount of expansion using the formulas given in the following.

With reference to Fig. 5.23, the vertical reinforcing dowel extending from the footing or base slab accommodates a movement Δ caused by wall expansion. The dowel is unbonded over a length L and is considered fixed at the base.



Section A-A is given in Fig. 5.22

Fig. 5.21—Wall construction sequence plans.

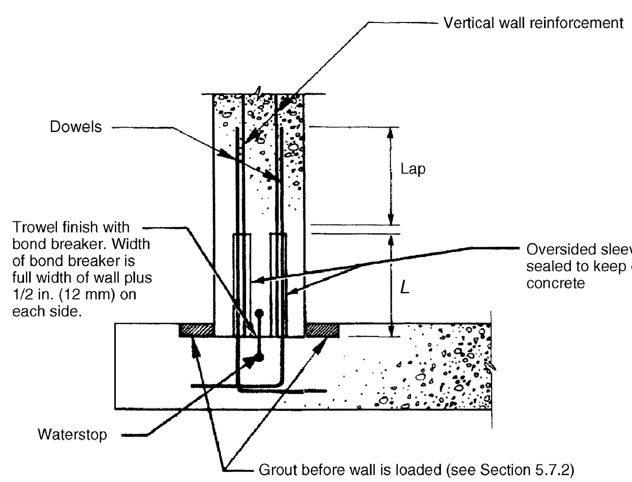


Fig. 5.22—Typical wall base: Section A-A (Fig. 5.21).

The upper end is considered free to rotate because creep takes place around the fresh concrete as it expands, and a fixed condition will not develop.

Moment in reinforcing bar = $M = 3\Delta EI/L^2$

where E is the modulus of elasticity of the bar; I is the moment of inertia of the bar; $f_y = Mc/I$ is the stress in the reinforcing bar; and c is the bar diameter/2 = $d_b/2$; therefore

$$f_y = 3\Delta EId_b/2L^2I \text{ or } 1.5\Delta Ed_b/L^2$$

Assume

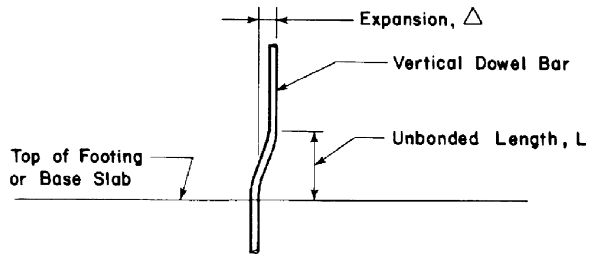


Fig. 5.23—Elevation of dowel bar.

Table 5.1—Rigid sleeve size and length

Bar size no.	Required sleeve internal diameter, in.	Standard pipe nominal internal diameter, in.	Sleeve length L, in.
3, 4	1.40	1-1/4	13
5, 6	1.65	1-1/2	16
7, 8, 9	2.03	2	19
10, 11	2.31	2-1/2	22
14	2.59	3	24
18	3.16	3-1/2	27

$E = 29 \times 10^6$ psi

Therefore

$f_y = 435 \times 10^5\, \Delta d_b/L^2$

$L = \sqrt{[(435 \times 10^5 \Delta d_b)/(f_y)]}$ or $6600\sqrt{(\Delta d_b/f_y)}$

The length of sleeve is therefore dependent on the amount of expansion, bar diameter, and yield strength of reinforcement. The length is calculated as follows. Assume that the wall will shrink approximately 0.025%. The concrete should expand 0.025% to compensate for the shrinkage. Assume a wall length of 150 ft (46 m).

Therefore, wall expansion Δ is

$\Delta = 0.00025 \times 150 \times 12 = 0.45$ in. (11.4 mm)

Values of L for f_y = 60 ksi (414 MPa) and Δ = 0.45 in. (11.4 mm) are given in Table 5.1.

Other values of L for different values of f_y and Δ are determined by the architect/engineer. The internal sleeve diameter is based on the largest reinforcing bar diameter in the grouping plus 2Δ. The reinforcing bar is centered in the sleeve to provide an all around clearance of Δ.

A compressible sleeve may be used instead of a thin rigid sleeve. It should be sufficiently stiff so that it will not compress completely under the pressure head of the concrete and be sufficiently flexible to accommodate movement during expansion and shrinkage. In this case, the internal diameter should be larger than the largest bar diameter, and the wall thickness should be at least 1.5 in. (38 mm).

Alternative details to Fig. 5.22 are shown in Fig. 5.24 through Fig. 5.26. In these details, circular voids shown in Fig. 5.24 or elliptical voids shown in Fig. 5.25, are provided in the wall forms around the vertical dowel bars extending from the footing. These voids extend to the top of the wall. To minimize the reduction in cross section, the vertical voids on opposite sides may be staggered as shown in Fig. 5.24.

The voids permit wall expansion without restraint from the dowel bars after the concrete wall is placed. After the wall

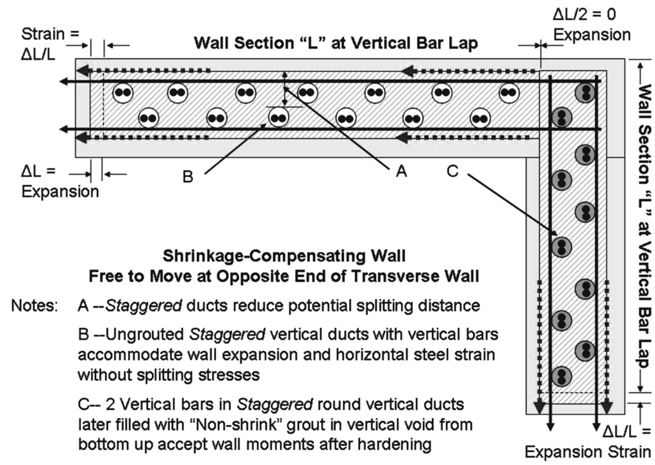


Fig. 5.24—Staggered circular void solution: shrinkage-compensating walls.

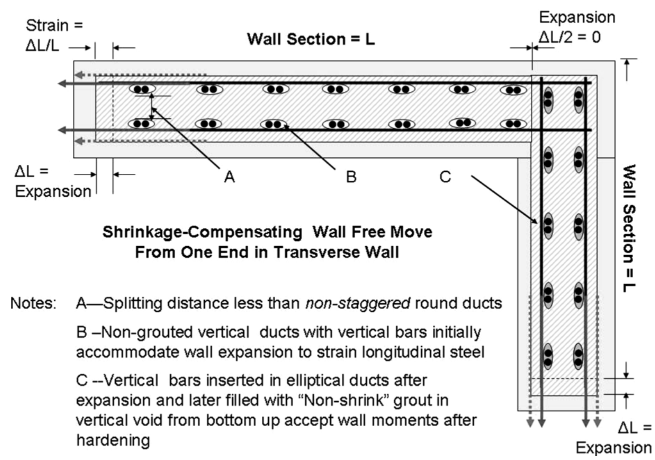


Fig. 5.25—Elliptical void solution: shrinkage-compensating walls.

concrete has hardened, the temporary tubes forming the voids are removed. Alternately, appropriate, permanent, bondable vertical form voids may remain in place if approved by the engineer. Full-length vertical bars are then inserted into the voids to provide the required splice length with the dowel bars.

If the internal surfaces of the voids are permitted to dry, after removing the void-forming material, the voids should be resaturated with water to satisfy the initial absorption of the dry concrete before grouting. Permanent bondable void forms, if approved and used, are treated in a similar fashion. A nonshrink grout suitable for deep vertical heights should be used. Grouting begins from the bottom of the void. This displaces water and air in the duct to provide full grout consolidation. It also bonds the grout to the vertical bars and the adjacent wall void circumference. A grout inlet port is shown at the bottom of the wall in Fig. 5.26. Alternatively, a vertical tube can be inserted to the bottom of the void and the grout pumped to attain the same bottom-to-top filling. Afterward, extract the tube slowly so air pockets are not formed, and the volume of the tube wall is simultaneously replaced

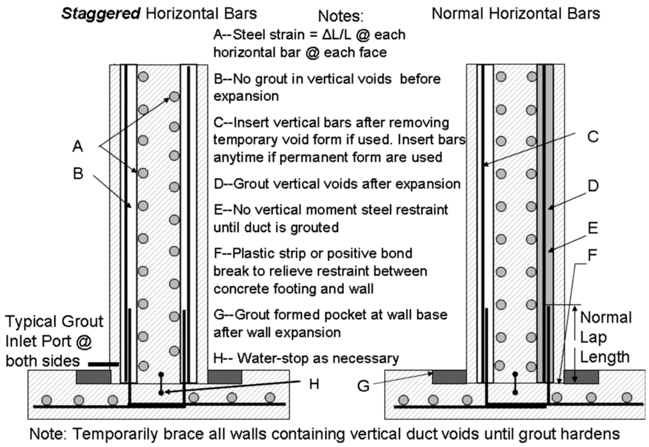


Fig. 5.26—Shrinkage-compensating wall sections: vertical void solution.

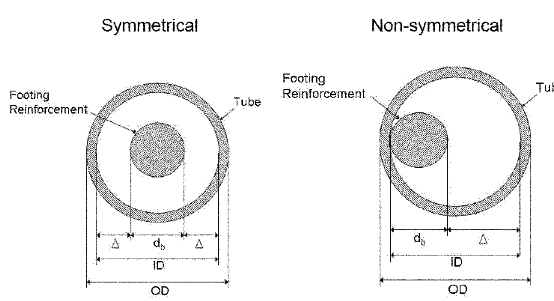
with grout. The grout should not be vibrated, as segregation can occur.

To relieve the restraint at the bottom of the wall, a detail showing a shear pocket filled with nonshrink or epoxy grout after initial expansion has occurred is used as indicated in Fig. 5.26. Plastic sheeting or a positive bond breaker is used to reduce the frictional restraint at this wall-slab pocket interface. Temporarily brace the wall before grouting the external shear key pocket and grouting the vertical voids. Similar details are referenced in ACI 372R and ACI 373R.

Depending on the direction of the expansion of the wall, the void may be symmetrical or nonsymmetrical with respect to the dowel bar from the footing. In both cases, the void is sized to meet the following criteria:

- Large enough to allow the expansion to occur without restraint from the footing reinforcement that protrudes into the hole, before the tube is removed;
- Large enough to accommodate a second bar for the wall reinforcement, after the tube is removed; and
- Sufficient space for grout.

The hole and tube size may be calculated as follows:



	Symmetrical	Non-symmetrical
Criterion 1:	$ID \geq d_b + 2\Delta + T$	$ID \geq d_b + \Delta + T$
Criterion 2:	$OD \geq 3d_b + T$	$OD \geq 3d_b + T$

where d_b is the bar diameter; Δ is the anticipated wall movement relative to footing; and T is the tolerance allowance.

For a wall free to move at both ends, the maximum $2\ell\varepsilon = \Delta$, where ε is the expansion of the wall determined from Fig. 5.1 or 5.2 and ℓ is the total length of the wall between free ends. For wall free to move at one end only, the maximum $\ell\varepsilon = \Delta$.

For most walls, Criterion 2 will control. Therefore, select an outside diameter (OD) to accommodate the two bars, select a tube wall thickness to determine the inside diameter (ID), and then check that there is sufficient room to accommodate the expansion. Maximum aggregate size of the nonshrink grout is selected based on the available space.

5.8—Toppings

Shrinkage-compensating concrete may be used in bonded or unbonded topping, but the topping should be reinforced to control shrinkage cracks in the topping concrete. In a bonded topping, the bond will act as an external restraint, allowing compressive stresses to develop, which may reduce the stresses due to subsequent shrinkage.

5.9—Formwork

Design formwork in accordance with ACI 347. Formwork should be sufficiently flexible to accommodate the small expansion of the concrete.

CHAPTER 6—CONCRETE MIXTURE PROPORTIONING

6.1—General

Correct mixture proportioning is necessary to ensure practicality of construction; placeability; and adequate expansion, strength, and hardened material properties at minimal cost. Consider the effects of mixture proportions on expansion, drying shrinkage, internal thermal stresses for massive placements, rate of strength gain, and other properties not necessarily indicated by compressive strength when selecting mixture proportions.

Mixture proportions that work well for portland-cement concrete should also produce shrinkage-compensating concrete of similar quality.

6.2—Concrete proportions

6.2.1 *Aggregates*—Follow procedures accepted for portland cement (ACI 211.1 or ACI 211.2 for lightweight concrete) for quality and proportions of fine and coarse aggregate. Fine and coarse aggregates from a known source that conform to ASTM C33/C33M or ASTM C330/C330M, and that have performed satisfactorily in concrete, may be used in the same proportions previously established.

For lightweight concrete, the aggregate producer should provide information on the most effective proportions of fine and coarse aggregates and the total uncombined volumes (dry-loose basis) required to produce a cubic yard of concrete. If information from this source is not available, use ACI 211.2, ACI 213R, and ASTM C330/C330M. Additional information on proportioning aggregates for normalweight and lightweight concrete may also be obtained from Kosmatka et al. (2002).

6.2.2 *Cement content*—As with portland cements, base the selection of an appropriate shrinkage-compensating cement content to meet specified concrete strength and expansion requirements on test results of laboratory trial batches containing the materials to be used in the specific project.

Table 6.1—Trial batch guide for shrinkage-compensating concrete

Compressive strength at 28 days, psi (MPa)	Absolute water-cementitious material ratio, by weight	
	Non-air entrained concrete	Air-entrained concrete
6000 (41.4)	0.42 to 0.45	—
5000 (34.5)	0.51 to 0.53	0.42 to 0.44
4000 (27.6)	0.60 to 0.63	0.50 to 0.53
3000 (20.7)	0.71 to 0.75	0.62 to 0.65

Select the cement content to meet the required structural strength and the required expansion.

If trial batches are made in accordance with Section 5.2.3 of ACI 318, use Table 6.1 as a guide where satisfactory performance of the shrinkage-compensating concrete has not been previously established. When strength data from laboratory trial batches or field experience are not available, use the lower value indicated in Table 6.1 as a guide to the maximum permissible water-cementitious material ratio (*w/cm*) for the concrete.

6.2.3 *Component content*—Using ASTM C878/C878M, determine the component content using trial batches to achieve the required expansion.

6.2.4 *Water requirement*—Determine water requirements using the mixture proportioning procedures discussed in Section 6.5. Shrinkage-compensating concrete requires higher water content to accommodate the water needed to hydrate the expansive component in the cement.

6.3—Admixtures

Unless there is documented experience with the specific admixtures, cement, and components, conduct ASTM C878/C878M tests to determine the effect of admixtures on expansion levels.

6.3.1 *Air-entraining admixtures*—Use air-entraining admixtures that conform to ASTM C260 for shrinkage-compensating concrete. Air-entraining admixtures have a similar effect in shrinkage-compensating concrete as with portland-cement concrete.

6.3.2 *Water-reducing, accelerating, and retarding admixtures*—Some admixtures may not be compatible with expansive cements or component systems. Make trial batches to determine any effects on the concrete. Admixtures should conform to ASTM C494/C494M. Use acceptable admixtures at the same dosage rates as used for portland-cement concrete.

6.3.3 *Accelerators*—Calcium chloride should not be used in shrinkage-compensating concrete. Test other accelerators before use to determine their effect on the concrete properties.

6.4—Consistency

Using slumps at the time of placement within the range specified by ACI 211.1 produces good results. For hot weather concreting, refer to ACI 305R. For cold weather concreting, refer to ACI 306R.

6.5—Mixture proportioning procedures

Use job materials to make trial batches in the laboratory. This helps to ensure satisfactory and economical results where there is no documented history. The following procedures are successful in developing satisfactory batching plant and job control programs under differing conditions.

6.5.1 When the time between completion of batching and placement is not more than 25 minutes, such as job-site mixing or when the batch plant is near the project, the total mixing water required is comparable to that of a portland-cement concrete for the specified slump. Trial batches to develop satisfactory aggregate proportions, cement content, and water requirement are performed. Use the mixing procedure in ASTM C192/C192M.

6.5.2 Where delivery requires normal travel time (30 to 40 minutes) in a truck mixer, whether truck-mixed (transit-mixed), shrink-mixed, or central-mixed, or when expected concrete temperature exceeds 75°F (24°C), slump loss is expected and should be compensated for by a higher initial slump to produce the slump required at the job site. Under such conditions, the following procedure for trial batch tests is used:

1. Prepare the batch using ASTM C192/C192M procedures for the specified slump;
2. Mix in accordance with ASTM C192/C192M (3 minutes mix, 3 minutes rest, 2 minutes remix) and confirm the slump;
3. Stop the mixer and cover the batch with wet burlap for 20 minutes;
4. Remix for 2 minutes and add water to produce the desired placement slump. This equals the total water (initial plus the remix water) that is required at the batching plant to provide required job-site slump after 30 to 40 minutes delivery time; and
5. Cast test specimens for ASTM C39/C39M compressive and ASTM C878 expansion tests and determine the properties of fresh concrete (unit weight, air content, and temperature).

CHAPTER 7—PLACING, FINISHING, AND CURING

7.1—Placing

The plastic characteristics of shrinkage-compensating concrete are sufficiently similar to concretes made with portland cement so that no special equipment or techniques are required for satisfactory placement. Follow the recommendations set forth in ACI 304R where applicable.

7.1.1 In hot, dry, and windy placing conditions, all concrete can lose moisture unevenly and develop plastic shrinkage cracks. Experience shows that with shrinkage-compensating concrete, plastic shrinkage cracking is more prevalent because the shrinkage-compensating concrete does not bleed. Water curing with fog spray starts immediately after final finishing. Under some conditions, the concrete surface dries during the finishing process. If this occurs, fog spray is applied to prevent surface drying. Fog spray is not applied as a finishing aid.

7.1.2 Maintain the reinforcement in its proper position during placement and for slabs-on-ground to maintain steel reinforcement in the top third of the slab.

7.1.3 Avoid delays in placement at the job site when using ready mixed concrete. A substantial increase in mixing time, over that assumed when selecting mixture proportions, increases slump loss. Water added at the job site, after slump loss, to maintain consistency, not only decreases strength but reduces expansion.

7.1.4 Concrete temperature and time in the mixer (from intermingling cement and damp aggregate) are important factors because of their effect on expansion. Concrete temperature during placement should not exceed 90°F (32°C) and the mixing time at concrete temperatures above 85°F (30°C) should be limited to 1 hour, unless an appropriate admixture is used to control the set time and plasticity without additional water. Below 85°F (30°C), the maximum mixing time should be 1-1/2 hours. Refer to ACI 306R for cold weather concreting.

7.2—Finishing

The cohesiveness inherent in shrinkage-compensating concretes provides excellent finishing qualities. There is little or no bleeding even if a relatively high slump is used. Due to the lack of bleed water, finishing operations often start earlier. If a dry shake is used, special provisions may be required to achieve proper distribution and bedding. Refer to the recommendations of ACI 304R and ACI 302.1R for satisfactory results.

7.3—Curing

Shrinkage-compensating concrete requires continuous water curing at moderate temperatures for at least 7 days after final finishing operations. Lack of curing reduces the amount of expansion available to offset later drying shrinkage. Cure concrete flatwork immediately after final finishing. It may be necessary to fog spray the surface in hot, dry, or windy weather.

For architectural or structural concrete, the practice of curing with the formwork in place is adequate. Uncovered surfaces should receive water curing for 7 days. In hot weather, soaker hoses or water sprays are used to supplement the protection of the in-place formwork.

During the initial curing period, protect shrinkage-compensating concrete against the temperature extremes of hot or cold weather periods. Refer to the methods described in ACI 305R and ACI 306R.

CHAPTER 8—REFERENCES

8.1—Referenced standards and reports

The standards and reports listed in the following were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

201.2R Guide to Durable Concrete
211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete
213R Guide for Structural Lightweight-Aggregate Concrete
301 Specifications for Structural Concrete
302.1R Guide for Concrete Floor and Slab Construction
304R Guide for Measuring, Mixing, Transporting, and Placing Concrete
305R Guide to Hot Weather Concreting
306R Guide to Cold Weather Concreting
308.1 Standard Specification for Curing Concrete
318 Building Code Requirements for Structural Concrete and Commentary
347 Guide to Formwork for Concrete
350 Code Requirements for Environmental Engineering Concrete Structures
360R Design of Slabs-on-Ground
372R Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures
373R Design and Construction of Circular Prestressed Concrete Structures with Circumferential Tendons
423.3R Recommendations for Concrete Members Prestressed with Unbonded Tendons

ASTM International

C33/C33M Standard Specification for Concrete Aggregates
C39/C39M Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C157/C157M Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
C192/C192M Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
C260 Standard Specification for Air-Entraining Admixtures for Concrete
C330/C330M Standard Specification for Lightweight Aggregates for Structural Concrete
C494/C494M Standard Specification for Chemical Admixtures for Concrete
C806 Standard Test Method for Restrained Expansion of Expansive Cement Mortar
C845 Standard Specification for Expansive Hydraulic Cement
C878/C878M Standard Test Method for Restrained Expansion of Shrinkage-Compensating Concrete
D994 Standard Specification for Preformed Expansion Joint Filler for Concrete (Bituminous Type)
D1621 Standard Test Method for Compressive Properties Of Rigid Cellular Plastics
D1751 Standard Specification for Preformed Expansion Joint Filler for Concrete Paving and Structural Construction (Nonextruding and Resilient Bituminous Types)
D1752 Standard Specification for Preformed Sponge Rubber Cork and Recycled PVC Expansion Joint Fillers for Concrete Paving and Structural Construction

D3575 Standard Test Methods for Flexible Cellular Materials Made from Olefin Polymers

These publications may be obtained from the following organizations:

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
www.concrete.org

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

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