Standard Practice for the Use of Shrinkage-Compensating Concrete

Reported by ACI Committee 223

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Shrinkage-compensating concrete is used extensively in various types of construction to minimize cracking caused by drying shrinkage. Although its characteristics are in most respects similar to those of portland cement concrete, the materials, selecting of proportions, placement, and curing must be such that sufficient expansion is obtained to compensate for subsequent drying shrinkage. This standard practice sets forth the criteria and practices necessary to ensure that expansion occurs at the time and in the amount required. In addition to a discussion of the basic principles, methods and details are given covering structural design, concrete mix proportioning, placement, finishing, and curing.

Keywords: admixtures; aggregates; calcium aluminate; concrete construction; concrete finishing (fresh concrete); concretes; curing; drying shrinkage; ettringite; expansive cement concretes; expansive cements; expansive cement K; expansive cement M; expansive cement S; formwork (construction); grouts; joints (junctions); mix proportioning; placing; reinforced concrete; restraints; shrinkage-compensating concretes; structural design.

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CHAPTER 1—INTRODUCTION

1.1—Background
In an earlier state of knowledge report (ACI 223, 1970) and in the recommended practice (ACI 223, 1977), ACI Committee 223 described research investigations, structures, design procedures, and field practices involving expansive cements used in the production of shrinkage-compensating concrete. The state of knowledge report outlined the theory and results of studies into the general behavior of such concretes, including the effects of concrete materials, admixtures, mixing, and curing conditions, as well as the success of early field applications.

The recommended practice summarized the theoretical aspects of the previous report and recommended design considerations, mix proportioning techniques, and placing, finishing, and curing practices for the utilization of shrinkage-compensating cements and concretes. This standard practice applies the present state of knowledge to the design and field practices for shrinkage-compensating concrete in such areas as reinforced and post-tensioned structural slabs and slabs-on-grade, walls, toppings, and environmental structures.

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

The amount of drying shrinkage that occurs in concrete depends on the characteristics of the materials, mix proportions, placing methods, curing, and restraint. When a pavement, floor slab, or structural member is restrained by subgrade friction, reinforcement, or other portions of the structure during drying shrinkage, tensile stresses develop. While portland cement concretes normally possess tensile strengths in the range of 300 to 800 psi (2.1 to 5.5 MPa), drying shrinkage stresses are often large enough to exceed the tensile strength of the concrete, resulting in cracking. Significant early age drying shrinkage stresses can occur before these tensile strengths are developed. Furthermore, because of the probable existence of additional stresses imposed by loads, temperature changes, settlement, etc., the inherent tensile strength of the concrete cannot be relied on to resist shrinkage stresses. The frequency and size of cracks that develop in many structures depend on the amount of shrinkage and restraint.

Shrinkage-compensating concrete is proportioned so the concrete will increase in volume after setting and during early age hardening. When properly restrained by reinforcement or other means, expansion will induce tension in the reinforcement and compression in the concrete. On subsequent drying, the shrinkage, instead of causing a tensile stress that might result in cracking, merely reduces or relieves the expansive strains caused by the initial expansion of the shrinkage-compensating concrete.

1.3—Scope and limits
This standard practice is directed mainly toward the use of shrinkage-compensating concrete in structures (reinforced and post-tensioned slabs, both on grade and elevated) and pavements. Recommendations are included for proportioning, mixing, placing, finishing, curing, and testing based on data presented in the committee’s previous reports, and on the experience of producers, users, consultants, and contractors.

Shrinkage-compensating concrete can be produced using expansive cements or expansive components. The scope of this standard practice is limited to shrinkage-compensating concrete made with expansive cements.

The recommendations of this standard practice are not applicable to self-stressing expansive cement concretes proportioned to produce a prestressed concrete structure for load-bearing purposes. Procedures for proportioning, handling, and curing of self-stressing concretes are often radically different from procedures for shrinkage-compensating concretes used to compensate for normal drying shrinkage.

1.4—Definitions
The following terms relating to shrinkage-compensating concrete are used in this standard practice:

Expansive cement (general)—A cement that when mixed with water forms a paste that, after setting, tends to increase in volume to a significantly greater degree than portland cement paste; the cement is used to compensate...
for volume decrease due to shrinkage, or to induce tensile stress in reinforcement.

**Expansive cement K**—A mix of portland cement, anhydrous tetracalcium trialuminate sulfate $\text{C}_4\text{A}_3\text{S}$ (where $\text{C} = \text{CaO}, \text{A} = \text{Al}_2\text{O}_3,$ and $\text{S} = \text{SO}_3$), calcium sulfate ($\text{CaSO}_4$), and lime ($\text{CaO}$). The $\text{C}_4\text{A}_3\text{S}$ is a constituent of a separately burned clinker interground with portland cement, ground separately and blended with portland cement, or alternatively, formed simultaneously with portland cement clinker compounds during the burning process.

**Expansive cement M**—Interground or blended mixes of portland cement, calcium-aluminate cement (CA and $\text{C}_{12}\text{A}_7$), and calcium sulfate suitably proportioned. The expansive cement M produced in the United States is not to be confused with the stressing cement (SC) produced in the former Soviet Republics also from portland cement, calcium aluminate cement, and gypsum. The SC product is proportioned so that quick-setting, fast-hardening, and high early strength are obtained and, therefore, it is not used in conventional concrete.

**Expansive cement S**—Portland cement containing a large computed tricalcium aluminate ($\text{C}_3\text{A}$) content and more calcium sulfate than usually found in portland cement.

**Shrinkage-compensating cement**—An expansive cement so proportioned that when combined with suitable amounts of aggregate and water forms a shrinkage-compensating concrete or mortar.

**Shrinkage-compensating concrete**—A concrete that, when properly restrained by reinforcement or other means, expands an amount equal to, or slightly greater than, the anticipated drying shrinkage. Subsequent drying shrinkage will reduce these expansive strains but, ideally, a residual expansion will remain in the concrete, thereby eliminating shrinkage cracking.

**Ettringite**—A mineral, high-sulfate calcium sulfoaluminate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 30-32\text{H}_2\text{O}$) also written as $\text{Ca}_6[\text{Al}($OH$)_6]_2 \cdot 24\text{H}_2\text{O}[(\text{SO}_4)_2 \cdot 1^{1/2}\text{H}_2\text{O}]$; occurring in nature or formed by sulfate attack on mortar and concrete; the product of the principal expansion-producing reaction in expansive cements; designated as “cement bacillus” in older literature.

Further explanation and definitions can be obtained by reference to the previous ACI Committee 223 “State of Knowledge” report (ACI 223, 1970), and “Cement and Concrete Terminology,” ACI 116R.

1.5—General considerations

The same basic materials and methods necessary to produce high quality portland cement concrete are required to produce satisfactory results in the use of shrinkage-compensating concrete. The performance of the expansive cement in minimizing cracking in concrete depends in large measure on early curing. In some instances special procedures are necessary to ensure adequate hydration at the proper time. Consequently, it is essential that early and thorough curing and adequate protection of the concrete be provided. Similarly, the mix proportions must ensure adequate expansion to offset subsequent drying shrinkage. Details of the essential requirements necessary for successful application are dealt with in the following chapters. The physical characteristics of the cured shrinkage-compensating concrete are usually similar to other types of concrete. The durability of shrinkage-compensating concrete should be judged on the same basis as portland cement concrete.

### 1.6—Preconstruction meeting

The owner’s representative should be responsible, in cooperation with the Architect/Engineer and general contractor, for setting up a preconstruction meeting after all necessary expansion tests have been completed, but not less than 1 week before the first concrete is to be placed. The purpose of the meeting is to review, discuss, and agree to the proper procedures for placing, finishing, and curing the concrete in order to meet the specifications under the anticipated field conditions. Responsible representatives of all contractors and material suppliers, including the manufacturer of the expansive cement, the ready-mix producer, and testing laboratory should attend and actively participate in this meeting.

### CHAPTER 2—MATERIALS

#### 2.1—Shrinkage-compensating cements

**2.1.1 Types**—The three different shrinkage-compensating cements described in ASTM C 845 are designated as K, S, and M. The expansion of each of these cements when mixed with sufficient water is due principally to the formation of ettringite.

**2.1.2 Composition**—Seventy-five to 90 percent of shrinkage-compensating cements consist of the constituents of conventional portland cement, with added sources of aluminate and calcium sulfate. For this reason, the oxide analysis on mill test reports does not differ substantially from that specified for portland cement in ASTM C 150, except for the larger amounts of sulfate (typically 4 to 7 percent total $\text{SO}_3$) and usually, but not always, a higher percentage of aluminate (typically 5 to 9 percent total $\text{Al}_2\text{O}_3$). The free lime ($\text{CaO}$) content may also be somewhat higher.

The three types of expansive cements differ from each other in the form of the aluminate compounds from which the expansive ettringite is developed, as shown in Table 1.

The kind of aluminate used influences the rate and amount of ettringite formation at early ages and thus, the total expansion. Total potential expansion is governed by the type and amount of aluminates and calcium sulfate and the rate at which they form ettringite. As with other types of portland cements, the compressive strength is principally due to the hydration of the calcium silicates.

**2.1.3 Cement proportioning**—These cements are manufactured to produce the proper amount of expansion without adversely affecting the concrete quality and retaining the normal range of concrete shrinkage. An important requirement is the
selection of material proportions so that the CaSO₄ and the Al₂O₃ become available for ettringite formation during the appropriate period after the mixing water is added. Determination of these proportions is based on the results of laboratory tests, outlined in Section 2.1.8, conducted under standard conditions similar to those used for other portland cements.

2.1.4 Hydration process—Two basic factors essential to the development of expansion are the appropriate amount of soluble sulfates and the availability of sufficient water for hydration. Ettringite begins to form almost immediately when the water is introduced, and its formation is accelerated by mixing. To be effective, however, a major part of the ettringite must form after attainment of a certain degree of strength; otherwise the expansive force will dissipate in deformation of the plastic or semiplastic concrete. For this reason, mixing more than required to ensure a uniform mix is detrimental since the ettringite formed during the prolonged mixing will reduce the amount available later for expansion. With proper curing, ettringite formation continues during and after hardening, until either the SO₃ or Al₂O₃ is exhausted.

2.1.5 Heat of hydration—The heat of hydration or temperature rise depends on the characteristics and type of the portland cement portion. In general, the heat of hydration falls within the range of the variation of the heat of hydration of the particular portland cement used.

2.1.6 Fineness—The surface area determined by air permeability methods (Blaine fineness measured by ASTM C 204) is not directly comparable to the surface area of portland cements. Shrinkage-compensating cement contains significantly more calcium sulfate than portland cement. Because the calcium sulfate grinds more readily than clinker, it contributes a greater part of the total Blaine fineness value obtained.

The specific surface has a major influence on the expansion as well as the early strength of concrete. As the surface area increases above the optimum for a given shrinkage-compensating cement with a specific calcium sulfate content, the formation of ettringite is accelerated in the plastic concrete. Thus, less expansion will be obtained in the hardened concrete. Shrinkage-compensating cement, like portland cement, produces a higher early strength if it has a higher surface area.

2.1.7 Handling and storage—These cements are affected adversely by exposure to atmospheric levels of CO₂ and moisture in a manner similar to portland cements. Additionally, such exposure can reduce the expansion potential of these cements. If there is any question as to the expansive potential because of method or length of storage and exposure, the cement should be laboratory tested before use.

2.1.8 Testing—The expansion characteristics of shrinkage-compensating cements are determined by measuring the length changes of restrained 2 x 2 x 10 in. (50 x 50 x 254 mm) standard sand mortar prisms according to ASTM C 806. These tests measure the expansive potential of the cement and should be used to assess compliance with specifications for the cement. Levels of expansion will be different when job materials are used in the concrete mix.

2.2—Aggregates
Concrete aggregates that are satisfactory for portland cement concretes can also be used for shrinkage-compensating cement concretes. Good results can be obtained with normal-weight, lightweight, and high-density aggregates meeting the appropriate ASTM requirements. The aggregate type used, however, has a significant influence on the expansion characteristics and drying shrinkage. For example, results of laboratory tests have shown that after a year, a shrinkage-compensating concrete containing river gravel retained a residual expansion of 0.03 percent, whereas concrete made with the same shrinkage-compensating cement but containing sandstone aggregate had 0.02 percent net shrinkage (Klieger, 1971).

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 sands, tend to decrease expansion and increase drying shrinkage. For these reasons, it is recommended that job aggregates be used in the laboratory trial mix proportioning tests.

2.3—Water
Mixing water should be of the same quality as used in portland cement concrete (PCA, 1988). If the use of mixer wash water or water containing sulfates or chlorides is contemplated, the water should be used in trial mixes to disclose possible adverse effects on the desired expansion levels of shrinkage-compensating concrete.

2.4—Admixtures
The effect of air-entraining admixtures, water-reducing admixtures, retarding admixtures, and accelerating admixtures on the expansion of a specific type or brand of shrinkage-compensating cement may be either beneficial or detrimental. The cement and admixture producers should be consulted as to past experience and compatibility of a specific type or brand of admixture with the cement that is to be used. Data obtained from laboratory testing and field experience show that the performance of admixtures is greatly influenced

<table>
<thead>
<tr>
<th>Expansive cement</th>
<th>Principal constituents</th>
<th>Reactive aluminates available for ettringite formation</th>
</tr>
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<tbody>
<tr>
<td>K</td>
<td>(a) Portland Cement</td>
<td>C₄A₃S</td>
</tr>
<tr>
<td></td>
<td>(b) Calcium sulfate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(c) Portland-like cement containing C₃A₃S</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>(a) Portland cement</td>
<td>CA and C₁₂A₇</td>
</tr>
<tr>
<td></td>
<td>(b) Calcium sulfate</td>
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<tr>
<td></td>
<td>(c) Calcium-aluminate cement (CA and C₁₂A₇)</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>(a) Portland cement high in C₃A</td>
<td>C₃A</td>
</tr>
<tr>
<td></td>
<td>(b) Calcium sulfate</td>
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</tr>
</tbody>
</table>
by the composition of the cement, the ambient temperature, and the mixing time.

In all cases, admixtures should be tested in trial mixes with job materials and proportions under simulated ambient conditions. 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. In general:

a. Air-entraining admixtures are as effective with shrinkage-compensating concrete as with portland cement concrete in improving freezing and thawing resistance and scaling resistance in the presence of deicing chemicals.

b. Some water-reducing and water-reducing and retarding admixtures may be incompatible with shrinkage-compensating concrete due to acceleration of the ettringite reaction. This usually has the effect of decreasing expansion of the concrete.

c. Calcium chloride will reduce expansion and increase shrinkage of the concrete.

d. Fly ash and other pozzolans may affect expansions and also influence strength development and other physical properties of the concrete.

Since the methods of mixing and placing can influence admixture performance, laboratory results may not always correlate with job results.

Further details on the use and influence of admixtures are given in Chapter 4.

2.5—Concrete

2.5.1 Strength—The tensile, flexural, and compressive strength development after expansion has been completed is similar to that of portland cement concrete under both moist and steam-curing conditions.

The water requirement is greater than that of portland cement concrete for a given consistency. Compressive strengths, however, are at least comparable to portland cement concrete made from the same clinker and having the identical cement content and aggregate proportions since the extra water is required for hydration of the expansive material. As with portland cement concrete, the lower the water-cementitious material ratio, the greater the compressive strength.

2.5.2 Modulus of elasticity—The modulus of elasticity of shrinkage-compensating concrete is generally comparable to that of portland cement concrete.

2.5.3 Volume change—After expansion, the drying-shrinkage characteristics of a shrinkage-compensating concrete are similar to those of portland cement concrete. The drying shrinkage of shrinkage-compensating concrete is affected by the same factors as portland cement concrete. These include water content of the concrete mix, type of aggregate used, cement content, and water temperature. The water content influences both the expansion during curing and subsequent shortening due to drying shrinkage. Fig. 2.5.3 illustrates the typical length change characteristics of shrinkage-compensating and portland cement concrete prism specimens tested in accordance with ASTM C 878.

The minimum recommended amount of concrete expansion is 0.03 percent, when measured in accordance with ASTM C 878. This is lower than the minimum expansion of 0.04 percent specified for a mortar when measured in accordance with ASTM C 806. ASTM C 806 uses a larger diameter threaded rod, a higher cement content, and a smaller cross-sectional area of prism than does ASTM C 878. The expansion of a portland cement concrete rarely exceeds 0.01 percent when tested using the same test methods.

Shrinkage-compensating concrete of relatively high unit water content may develop some tensile stress at later ages, as shown in Fig. 2.5.3, instead of remaining in compression.

2.5.4 Creep—Data available 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.

2.5.5 Poisson’s ratio—There has been no observed difference between Poisson’s ratio in shrinkage-compensating concrete and portland cement concrete.

2.5.6 Coefficient of thermal expansion—Tests have shown that the coefficient of thermal expansion is similar to that of corresponding portland cement concrete.

2.5.7 Durability—When properly designed and adequately cured, shrinkage-compensating concrete made with expansive cements K, S, or M is equally resistant to freezing and thawing, and resistance to 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. Recommendations of ACI 201.2R should be followed. Before being exposed to extended freezing in a severe exposure, it is desirable that the concrete 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.

Shrinkage-compensating concrete, when properly proportioned and cured, has an abrasion resistance from 30 to 40 percent higher than portland cement concrete of comparable mix proportions. (ACI 223, 1970; Nagataki and Yoneyama, 1973; Klieger and Greening, 1969).

The type of shrinkage-compensating cement and particularly, the composition of the portland cement portion can
have a significant effect on the durability of the concrete to sulfate exposure. Shrinkage-compensating cement made with a Type I portland cement may be undersulfated with respect to the aluminate available and therefore susceptible to further expansion and possible disruption after hardening when exposed to an external source of additional sulfates. On the other hand, 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).

2.5.8 Testing—Compressive, flexural, and tensile strengths should be determined in the same manner and using the same ASTM methods as for portland cement concrete. In a shrinkage-compensating concrete, the amount of expansion is as important as strength. Consequently, the performance of a shrinkage-compensating concrete should be tested in accordance with ASTM C 878 to determine the quantity of shrinkage-compensating cement required to achieve the desired concrete expansion. When other methods (Gaskill and Jacobs, 1980; Liljestrom and Polivka, 1973; Williams and Liljestrom, 1973) are used, particularly to determine field expansions, they should be correlated with expansions determined by ASTM C 878 in the laboratory at the same ages.

CHAPTER 3—STRUCTURAL DESIGN CONSIDERATIONS

3.1—General

The design of reinforced concrete structural elements using shrinkage-compensating concrete shall conform to the requirements of applicable ACI standards. At the same time, adequate concrete expansion should be provided to compensate for subsequent drying shrinkage to minimize cracking. Since the final net result of expansion and shrinkage is essentially zero, no structural consideration need normally be given to the stresses developed in the concrete during this process. Provision for dead and live loads required by building codes and specifications will result in at least the same structural integrity with shrinkage-compensating concretes as with portland cement concretes. However, provisions shall be made for initial expansive movements.

3.2—Restraint

3.2.1 Types of restraint—A resilient type of restraint, such as that provided by internal reinforcement, shall be provided to develop shrinkage compensation. Other types of restraint, such as adjacent structural elements, subgrade friction, and integral abutments are largely indeterminate and may provide either too much or too little restraint. Subgrade frictional coefficients in the range of 1 to 2\(\frac{1}{2}\) have been found satisfactory. Values of the coefficient of friction for different bases and sub-bases are given in ACI 360. High restraint will induce a high compressive stress in the concrete but provide little shrinkage compensation. Wherever possible, the design shall, therefore, specify the reinforcement recommended in Section 3.2.2. Alternatively, the design shall be performed using the procedures of Section 3.2.3 or other criteria that address the issues of shrinkage-compensation.

3.2.2 Minimum reinforcement and location—Established engineering design practices for structural elements will normally provide a sufficient amount of steel. In some non-load-bearing members, slabs on grade, and lightly reinforced structural members, the usual amount of steel reinforcement may be less than the minimum amount necessary for shrinkage-compensating concretes. For such designs, a minimum ratio of reinforcement area to gross concrete area of 0.0015 shall be used in each direction that shrinkage compensation is desired. This minimum is approximately that recommended by ACI 318 for temperature and shrinkage stresses. However, when procedures outlined in Section 3.2.3 are followed, a reinforcement ratio less than the above minimum may be used.

In structural members, the reinforcement location will be determined from design requirements. This may result in an over-concentration of reinforcement in one section—particularly in flat plate construction. Experience has shown that warping caused by concentrated reinforcement is not a problem in structural slabs because dead weight tends to counteract the warping deflection. However, when the location of the reinforcement is not determined by structural considerations, it shall be positioned to minimize warping. For example, in slabs on grade, where most of the drying occurs in the top portion, the reinforcement should be placed in the upper half of the slab (preferably \(\frac{1}{3}\) of the depth from the top), while still allowing for adequate cover.

3.2.3 Estimation of maximum expansions—When structural design considerations result in a reinforcement ratio greater than the recommended minimum, such as bridge
decks (Gruner and Plain, 1993), or when it is desired to use less than the minimum reinforcement of Section 3.2.2, the level of expansion in structural members should be estimated from Fig. 3.2.3. This graph shows the relationship between member expansion, prism expansion, and percentage reinforcement when the member and prism are made from the same concrete and are mixed and cured under identical conditions. The prism expansion test is defined in ASTM C 878. The figure is based on published data (Russell, 1973) but modified to allow use of the ASTM C 878 test. Fig. 3.2.3 indicates that for a given prism expansion, a higher amount of reinforcement will reduce expansion.

Fig. 3.2.3 may also be used to estimate the required expansion of control prisms to obtain a given expansion in a structural member without external restraint. To provide satisfactory shrinkage compensation, the required expansion in the reinforced structural member is recommended to be greater than, or at least equal to, the anticipated shrinkage. Consider a concrete member where the anticipated shrinkage is 0.025 percent. The required expansion for complete shrinkage compensation is also 0.025 percent. If the member contains 0.5 percent reinforcement, then a restrained prism expansion of 0.04 percent is required for complete compensation. On the other hand, if the restrained prism expansion is 0.05 percent, then a reinforcement percentage up to 0.75 percent may be used and shrinkage compensation can still be achieved.

For a concrete member containing less than the minimum reinforcement specified in Section 3.2.3, the same procedure may be used (Gulyas and Garrett, 1981). Consider an anticipated shrinkage of 0.025 percent in a slab containing 0.1 percent reinforcement. Using Fig. 3.2.3, the restrained prism expansion required to offset shrinkage is 0.025 percent. A member expansion in excess of the shrinkage will increase the likelihood that complete shrinkage compensation will be obtained.

Concrete member expansion is reduced as the amount of reinforcement is increased. Shrinkage is also reduced, but to a lesser extent. Consequently, to achieve complete shrinkage compensation, the expansive potential should be higher for more heavily reinforced members. Increased expansion can be obtained with a higher cement content. However, expansion as measured using ASTM C 878 shall not be greater than 0.1 percent and, in general, should not be less than 0.03 percent.

When the amount of reinforcement in a member varies from area to area, an average expansion shall be used. The lightly reinforced areas will then be overcompensated and the heavily reinforced areas undercompensated. In determining the anticipated shrinkage, the effects of member thickness and concrete materials on shrinkage should be considered. An example showing the influence of member thickness on required levels of expansion is given in Appendix A.

3.2.4 Reinforcing steel—Reinforcement should be either welded wire fabric or deformed bars meeting the requirements of ACI 318. Plain bar reinforcement shall not be used because adequate bond cannot be developed. To ensure accurate positioning, deformed bars placed on chairs or tied to other fixed rods, concrete supports, or portions of the structure should be used. Where wire fabric is used in lieu of deformed bars, it should be in flat sheets or mats rather than rolls. The use of rolled wire fabric is not recommended. However, if rolled wire fabric is used, it should be unrolled on a hard flat surface to remove all curvature before being placed in final position. The wire fabric may be sandwiched between two layers of plastic concrete or supported on chairs or blocks. Hooking or pulling the wire fabric off the form or subgrade should not be permitted. Working the wire fabric in from the top may be permitted if it can be demonstrated that the reinforcement will be at the correct depth from the top surface throughout the slab.

3.3—Reinforced structural slabs

3.3.1 Structural design—To provide proper safety factors, the design shall be based on the strength design provisions of ACI 318. This procedure will avoid consideration of the amount of stress in the reinforcement caused by the expansion of the concrete since in the strength analysis, the previous state of prestress does not influence the capacity of the section. In structural members, however, where it is anticipated that there will be high concrete expansion combined with loading at an early age, it is desirable to check that the net steel stresses caused by the expansion and loading conditions do not exceed permissible values.

The magnitude of concrete stresses induced by tension in the reinforcement may be determined as follows:

Consider a reinforced concrete member that expands an amount $\varepsilon_c$.

If the areas of concrete and steel are $A_c$ and $A_s$, respectively, then

\[ E_s = \frac{E_c}{A_s} \]

Tensile force in steel $= \varepsilon_c E_s A_s$

Compressive force in concrete $= \varepsilon_c E_s A_s$

Stress in concrete $= \varepsilon_c \cdot (E_s A_s/A_c) = \varepsilon_c \rho E_s$

Total length change $\Delta = L \varepsilon_c$

where

$E_s$ = modulus of elasticity of steel

$\rho$ = reinforcement ratio $= A_s/A_c$

$L$ = length of concrete that is going to expand or shrink.

This relationship is shown graphically in Fig. 3.3.1 where $E_s$ is taken as $29 \times 10^6$ psi (200 GPa).

As an example, a concrete member containing 0.15 percent steel that expands 0.10 percent has an induced compressive stress of 43.5 psi (300 kPa), whereas a member that only expands 0.02 percent but contains 2 percent steel has a compressive stress of 116 psi (800 kPa) (providing the expansive potential of the concrete is not exceeded).

The induced compressive stress is a function of the amount of reinforcement as well as the expansion of the concrete. The induced compressive stress causes an elastic shortening of the concrete that for practical reinforcement ratios (up to $1/2$ percent) is small compared to the errors in predicting the shrinkage. As the amount of reinforcement in a member increases, the compressive stress developed in the concrete also increases. The expansive strains of a highly reinforced member are...
usually low, requiring only a small amount of shrinkage for
the member to return to its original length and then develop
shrinkage strains and concrete tension. Strain in concrete and
steel is the most important element to consider when attempt-
ing to counteract shrinkage. Concrete strain should stay ex-
panded since shrinkage strains indicate the concrete is going
into tension. The range and median of expansions generally
obtained with shrinkage-compensating concretes are shown
in Fig. 3.3.1.

The Architect/Engineer should specify the minimum level
of expansion for each project. The required level of expansion
as measured using ASTM C 878 under laboratory con-
ditions should be calculated using the procedure outlined in
Appendix A or by other methods. In most situations, the speci-
fied level of expansion should not be less than 0.03 percent.

3.3.2 Deflection—The deflection analysis to satisfy load
performance criteria shall be made in the same manner as for
portland cement concrete. Any residual compressive stress
caused by expansion will improve the service load perfor-
mance since a higher load is required to produce first crack-
ing. Residual compressive stress, however, shall not be taken
into account when calculating deflections.

3.3.3 Crack spacing—In two independent investigations,
(Pfeifer, 1973; Cusick and Kesler, 1976) where shrinkage-
compensating concrete was compared with portland cement
concrete, it was observed that the number of cracks were less
in the shrinkage-compensating concrete. This occurred for
reinforced concrete specimens loaded in flexure (Pfeifer,
1973) and in direct tension (Cusick and Kesler, 1976). Since
the comparisons in each case were made on specimens with
the same length, the data can be interpreted to mean that few-
er cracks will occur in shrinkage-compensating reinforced
concrete members. This has been confirmed in field observa-
tions (Randall, 1980; Rosenlund, 1980).

3.3.4 Cracking moment—The use of shrinkage-compen-
sating concrete does not affect the flexural strength of rein-
forced concrete members. However, it does influence the
moment at which flexural cracking occurs. Tests (Pfeifer,
1973; Russell, 1980) have shown that members made with
shrinkage-compensating concrete crack at a 15 to 59 percent
higher bending moment than corresponding members made
with portland cement concrete. The increase occurs because
shrinkage-compensating concrete members have an induced
concrete compressive stress caused by the expansion. This is
equivalent to a mild prestressing. Therefore, a shrinkage-
compensating concrete can resist a higher applied moment
before cracking occurs.

At later ages, drying shrinkage reduces the concrete com-
pressive stress in shrinkage-compensating concrete. By con-
trast, restrained drying shrinkage in a portland cement
concrete will always cause tensile stress. Consequently, even
at later ages, shrinkage-compensating concrete can resist a
higher applied moment than portland cement concrete before
 cracking occurs.

3.4—Reinforced slabs on grade
Because shrinkage-compensating concrete expands
shortly after setting, reinforced slabs on grade with shrink-
age-compensating concrete will initially behave differently
from portland cement concrete slabs. Certain differentiating
items are discussed in the following sections.

3.4.1 Tensile strains—Portland cement concrete generally
is assumed to possess limited tensile strain capacity. There-
fore, reinforcement in slabs on grade is primarily used to con-
trol crack widths caused by bending and drying shrinkage.

Research (Pfeifer, 1973; Pfeifer and Perenchio, 1973; See-
ber et al., 1973; Spellman et al., 1973; Kesler, 1976; Russell,
1980) has shown that portland cement concrete has approxi-
mately 0.02 percent tensile strain capacity before cracking.
Shrinkage-compensating concrete has a higher tensile strain
capacity than comparably reinforced portland cement concrete
when the former is allowed to expand and elongate the
reinforcement. A more detailed discussion of tensile strains
is given in Appendix B.

3.4.2 Warping—Because of the subgrade restraint and the
internal top steel restraint against the expansion of the con-
crete, differential expansive strains between top and bottom
can be expected. During drying shrinkage, expansive strains
are relieved more quickly at the top drying surface than at the
subgrade. Research (Keeton, 1979) has shown that the net ef-
fec t indicates residual restrained expansive strains to be
greater at the top surface than at the bottom, so reversed curl-
ing conditions develop. Warping stresses tend to be counter-
balanced by the dead weight of the slab itself.
The function of the top reinforcement is to balance the restraint of the subgrade, in addition to providing resilient restraint against the expansion.

If the subgrade restraint is too low in comparison to restraint from heavy top reinforcement, curling may occur. This condition can develop with a heavily reinforced slab on polyethylene. An increase in subgrade friction with sand placed on top of the polyethylene or placing reinforcement in the top half to one-third of depth will reduce the curling.

If the internal restraint is moved to the bottom third of the slab or below, warping stresses are not offset by the top reinforcement, and cracking may occur upon drying.

3.4.3 Isolation joints—Joints used to accommodate vertical movement or horizontal movement shall be provided at junctions with walls, columns, machine bases, footings, or other points of external restraint, for example, pipes, sumps, and stairways. In addition to their normal action, these joints shall be used to accommodate the initial expansion of the concrete. Details of isolation joints are shown in Fig. 3.4.3(a) through 3.4.3(g).

Thickness of compressible material shall be estimated from Fig. 3.2.3, as described in Appendix A.

Rigid exterior restraint shall not be used since it prevents expansion of the concrete and a small amount of shrinkage later will result in negative strains and tensile stress in the concrete. In addition, large forces will be imposed on the restraining members. Laboratory tests (Russell, 1973) have shown that rigid restraints result in compressive stresses as high as 170 psi (1.2 MPa).

Stresses of this magnitude could produce sufficient force to damage the restraining structure. Footings, pits, walls, drains, and similar items should be protected by isolation joints to prevent damage during the expansion stage and to allow the necessary expansive strain to develop. Compressible filler strips or joint materials shall be used to control this behavior.

Isolation joints shall be composed of a material that is compressible enough to deform under the expansive action of the concrete. If too stiff, some rigid asphaltic isolation materials may act as external restraint and restrict the expansion of the concrete. A material with a maximum compression of 25 psi (170 kPa) at 50 percent deformation according to ASTM D 1621 or D 3575 should be used. Joint materials meeting ASTM D 994, D 1751, and D 1752 may be too stiff to allow adequate expansion.

Column box-outs may be reduced or eliminated if a compressible material is provided. A compressible bond breaker wrapped around the column or compressible cardboard forms brought to floor level have been satisfactory in permitting vertical movement. At the same time, the reinforcement or mesh should be increased locally in the column area where high stresses are likely to develop. This will restrict the width of any cracks that occur.

3.4.4 Construction joints—With the use of shrinkage-compensating concrete, slab placement patterns of approximately 20 to 30 ft (6 to 9 m) used with portland cement concrete may be enlarged. Slabs located inside enclosed structures, or where temperature changes are small, may be placed in areas as large as 16,000 ft² (1500 m²) without joints. For areas where temperature changes are larger or where slabs are not under enclosed structures, slab placements are normally reduced to 7000 to 12,000 ft² (650 to 1100 m²). The area shall not be larger than a work crew can place and finish in a day.

Building slab sections should be placed in shapes as square as possible. For pavements, which are thicker and more heavily reinforced than building slabs, successful installations have been made with length-to-width ratios as high as 5:1 (Keeton, 1979; Randall, 1980; Williams, 1973). In these installations, joints shall be designed for the anticipated expansion and also become a form of contraction joint. Examples of joint details for slab on grade are shown in Fig. 3.4.4(a) through 3.4.4(f).

Provision should be made to accommodate differential movement between adjacent slabs in the direction parallel to the joint between the two slabs. Differential movement may be caused by expansion of the shrinkage-compensating concrete, differential shrinkage of the adjacent slabs, and thermal expansion from heat of hydration of the new slabs. If provision is not made for this movement, cracking perpendicular to the joint may occur in one or both slabs. Two commercially available details that allow for movement parallel and perpendicular to the joint and provide vertical load transfers are shown in Fig. 3.4.4(f). Both details have a patent or patent pending. Other details may be developed to perform the same functions.

Supporting data should be available showing that the load transfer devices are specifically designed for use in concrete, and that the systems will provide essentially immediate vertical load transfer with essentially no horizontal restraint. Where applicable, the system should be designed to eliminate or minimize potential problems due to corrosion, abrasion, or repeated loads.

Unless specifically required for unusual conditions, the load transfer device should not undergo more than 0.01 in. (0.25 mm) of vertical deformation under the service vertical load.

In some cases, these details are different from those used with portland cement concrete.

Construction joints typically should be designed and detailed as contraction joints to accommodate temperature movements, allowing the opportunity for the joint to open, relieving the tensile stress acting on the slab. When load transfer is required, slip dowels at the joint should be used rather than deformed bars. Tongue and grooved joints may be used when large temperature contractions are not present and high load transfer is not required.

Bonded joints with deformed reinforcement (bars or mesh) passing through the joint may be used, provided that only two slabs are locked together in each direction. Movements from temperature, expansion, and shrinkage strains must then be accommodated at the perimeter edges of the two slabs.

3.4.5 Contraction (control) joints—These joints are sawed, formed, or otherwise placed in slabs between other...
joints. Their primary purpose is to induce controlled drying shrinkage cracking along the weakened planes (joints). With shrinkage-compensating concrete, larger distances may be used between contraction joints. For exposed areas, a maximum spacing of 100 ft (30.5 m) between joints is recommended. Where the area is protected from extreme fluctuations in temperature and moisture, joint spacings of 150 to 200 ft (45.7 to 61 m) have been used. Contraction joints may be made in the same way as for portland cement concrete. Normally, contraction joints are eliminated with shrinkage-compensating concrete except in high stress areas.

The larger joint spacing with a shrinkage-compensating concrete will produce larger movement at the joint. This shall be taken into account when designing load transfer and joint sealing details.

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

However, joints for thermal movements shall be designed to ensure that adequate expansion can take place during the expansion phase. An expansion of 0.06 percent is equivalent to a 100 F temperature change. In the event of high load transfer, slip plates or dowel bars should be provided, as shown in Fig. 3.4.4(f).

3.4.7 Details—Suggested details of isolation joints, construction joints, contraction joints, door openings, and wall footings are shown in Fig. 3.4.3(a) through 3.4.3(g), and 3.4.4(a) through 3.4.4(f). Additional details using the same basic principles shall be developed by the Architect/Engineer as required.

3.4.8 Placing sequence—For a slab on grade, placement sequence shall allow the expansive strains to occur against a free and unrestrained edge. The opposite end of a slab when cast against a rigid element shall be free to move. A formed edge should have the brace stakes or pins loosened after the
The placing sequence shall be organized so that the edges of slabs are free to move for the maximum time possible prior to placing adjacent slabs. At least 70 percent of the maximum measured laboratory expansion according to ASTM C 878 should occur prior to placing slabs that are not free to expand on two opposite ends. Three examples of placement patterns are shown in Fig. 3.4.8(a) through 3.4.8(c). Checkerboarded placements should not be used unless a compressible joint material is placed between the slabs prior to concrete placement. The compressible joint materials as described in 3.4.3 shall be used to accommodate the anticipated movements.

Before establishing the pour sequence, it is desirable to have a series of tests made in accordance with ASTM C 878, based on the proposed concrete mix design. A minimum level of prism expansion of 0.03 percent is recommended for slabs on grade. It is essential that the tested mix design use materials identical to those that will be used in construction and be tested at the proposed slump that will be used in the field and as much as possible under the weather conditions anticipated in the field.

3.4.9 Connections—Connections between prefabricated shrinkage-compensating concrete members or cast-in-place members are designed in the same manner as for portland cement concrete. The design shall be checked to ensure that neither the expansive strain nor the shrinkage of the adjacent member produce any undesirable movement.

3.5—Post-tensioned structural concrete

3.5.1 Design requirements—Design of post-tensioned concrete structures using shrinkage-compensating concrete should meet requirements of ACI 318, and follow recommendations of ACI 423.3R.

3.5.2 Length changes—All concrete structures are affected by shrinkage and creep. Post-tensioning introduces elastic shortening and additional creep. Shrinkage, creep, elastic shortening, and, in some structures, temperature produce negative volume changes in a structure (ACI SP-27). The framed structural elements become shorter in length and width. As a result of these movements, the supporting columns must be designed for higher moments and shears. This is particularly true for the columns between the foundation and first framed structural element. In this case, the foundations are a fixed distance apart and the framed elements shorten and pull the columns inward. The higher moments will require additional reinforcement and the higher shear will sometimes result in a larger section.
With shrinkage-compensating concrete, the Architect/Engineer shall calculate movements caused by expansion and subsequent shrinkage. An example is given in Appendix C.

3.6—Post-tensioned slabs on grade

Recommendations for post-tensioned slabs on grade with portland cement concrete are contained in the Post-Tensioning Institute manual (1980).

Because shrinkage-compensating concrete expands during early hydration, certain modifications can be made in post-tensioned slabs on grade because of the initial expansion.

3.6.1 Restraint—Shrinkage-compensating concrete expands more in an unrestrained condition than restrained. This tendency for expansion can be restrained externally in post-tensioned concrete slabs. Compression is developed rather than tension during the initial phases.

Comparative stress levels (Russell, 1973) are shown in Fig. 3.6.1 for slabs with different amounts of reinforcement for externally restrained slabs. If adequate restraint is applied externally, the level may approach 70 to 100 psi compression within 5 to 10 days after casting. But, it is dissipated quickly unless the post-tensioning cables are stressed before the concrete shrinks. The data shown in Fig. 3.6.1 indicate that the shrinkage-compensating concretes developed higher tensile stresses than the portland cement concrete after an age of about 28 days.

3.6.2 Subgrade restraint—Restraint of the expansion can be obtained by the frictional forces imposed by the subgrade. Coefficients ranging from 2.0 for rough-textured sub-base materials to 0.8 for vapor barrier substrates are commonly found to cause tensile stresses in portland cement concretes upon shrinkage. For shrinkage-compensating concrete, the same subgrade friction working against the expansion will produce compression in the concrete, thereby offsetting the tensile stresses.

Because of the compression on the concrete, there is no need to post-tension the slab at an early age to induce early compression. This eliminates the phased post-tensioning or...
partial post-tensioning required in many slab on grade applications to prevent cracking with portland cement concrete.

3.6.3 Placing sequence—Unlike conventionally reinforced slabs, post-tensioned shrinkage-compensating concrete slabs require restraint to provide early compression in the concrete. The formed edge should be reasonably stiff to provide adequate restraint against the expansion. Placement of subsequent concrete after form removal will also provide some restraint to induce compression.

3.6.4 Design implications—Research (Nagataki and Yoneyama, 1973) has shown that compression developed against external or subgrade restraint can be effectively utilized to reduce the loss of post-tensioning force due to subgrade friction with the use of shrinkage-compensating post-tensioned concrete. To be effective, the mechanical pre-stressing force must be introduced before the shrinkage-compensating concrete starts to shrink, generally within 7 days. The compression developed by the external restraint can be utilized in reducing the total mechanical force applied to the slab by using less stressing steel (Nagataki and Yoneyama, 1973).

3.6.5 Details—Stiffened bulkheads should be used at construction joints unless metal forms are used with frequently pinned stakes.

Pour strips used to relieve shrinkage in portland cement concrete slabs should not be used. Construction joints are suggested.

Typical details are shown in Fig. 3.6.5. These details can be modified by the Architect/Engineer for specific applications. To accommodate movements parallel to the construction joint, the details shown in Fig. 3.4.4(f) may be used.

3.7—Walls

3.7.1 Placing sequences—The sequence of placing shrinkage-compensating concrete in walls is very important. The sequence of placing should allow one edge of the wall in each direction to remain free to expand. The top of the wall is free to expand in the vertical direction. At least one vertical construction joint shall remain free to allow expansion in the horizontal direction. Free edges are needed so the concrete can expand without rigid external restraint. The method of checkerboard placement of walls (cast a wall section, skip a wall section, cast a wall section) that has been used for portland cement concrete is not recommended for shrinkage-compensating concrete unless provision is made to allow expansion of the wall. The checkerboard method where concrete is cast directly against adjacent concrete leaves no space for the concrete to increase in length. The concrete would build up compressive stresses, which would 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 can be used successfully with shrinkage-compensating concrete. In each case, the compressible filler strip joint should be made from a material that has a maximum compressibility of 25 psi (170 kPa) when the material is reduced to 50 percent of its original thickness.

Fig. 3.7.1(a) shows a plan of a rectangular tank with a casting sequence leaving the corners open until all side walls have been cast.
The recommended sequence for placing concrete wall sections is also shown. The sequence may be varied as long as no wall section is restrained between two previously cast sections and the corners are cast last. Each cast section shown is based on a maximum length of 150 ft (46 m). The minimum time period, generally 3 to 7 days, between casting adjoining sections should be sufficient to ensure that adequate expansion or volume change can take place before the next section is cast. The size of the corner section shall be just large enough to develop hooks and laps as required by design. This figure shows the preferred sequence of wall placement.

Fig. 3.4.8(a)—Center adjacent slab placement pattern.

Fig. 3.4.8(b)—Center rotation slab placement pattern.

Fig. 3.4.8(c)—Lag slab placement pattern.

The recommended sequence for placing concrete wall sections is also shown. The sequence may be varied as long as no wall section is restrained between two previously cast sections and the corners are cast last. Each cast section shown is based on a maximum length of 150 ft (46 m). The minimum time period, generally 3 to 7 days, between casting adjoining sections should be sufficient to ensure that adequate expansion or volume change can take place before the next section is cast. The size of the corner section shall be just large enough to develop hooks and laps as required by design. This figure shows the preferred sequence of wall placement.

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Fig. 3.4.8(c)—Lag slab placement pattern.

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Fig. 3.4.8(a)—Center adjacent slab placement pattern.

Fig. 3.4.8(b)—Center rotation slab placement pattern.

Fig. 3.4.8(c)—Lag slab placement pattern.

Fig. 3.6.1—Stress in slab with full external restraint (Russell, 1973).

Fig. 3.6.5—Details for post-tensioned slab on grade.

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 length of each cast section shown is the same as stated for Fig. 3.7.1(a) except at
the corners. The corner sections are slightly longer so bar hooks and development lengths can be incorporated. In hydraulic structures, this joint must utilize a waterstop since the two concrete joint faces are separated and not bonded to each other as are the rest of the joints. The thickness of the compressible filler shall be determined by the Architect/Engineer, based on the length of wall and amount of expansion that will take place. The minimum thickness that should be 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, shall be sufficient to ensure that adequate expansion or volume change can take place before the next section is cast.

Fig. 3.7.1(c) shows a plan with filler strip wall construction. The plan shows the sequence of wall construction, starting with two ends of a wall and their corners. Next, the section between the two ends is cast with a compressible filler at one of the construction joints. The remaining sections would be cast similarly by casting another end section and then casting the infill section with a compressible filler in one of the construction joints. The length of the section cast could be as long as 150 ft (46 m) since there is always a compressible filler at one of the construction joints to allow expansion.

In all wall sequences, the Architect/Engineer shall determine if 150 ft (46 m) is too far between joints.

3.7.2 Details—The shrinkage-compensating concrete used in the wall must be able to expand and shall not be restrained by some element of its construction. Fig. 3.7.2(a) 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, such as shown in Fig. 3.7.2(a), should be used. The depth of key should be determined by the Architect/Engineer to offset the maximum force from either backfill or filled tank but in no case should be less than 2 in. (50 mm). The horizontal surface of the shear key should be troweled smooth immediately under the vertical wall area and to a width approximately 1/2 in. (12 mm) beyond. The smooth area should then be coated with a bond breaker prior to concrete placement to allow the wall to move during the expansion period. The region to be grouted should remain ungrouted as long as possible and for at least 28 days. A high strength nonshrink concrete grout should then be used to fill the shear key. Lateral load on the wall from backfilling or internal pressure should not be applied until the grout has achieved the specified strength.

The vertical dowels should have a sleeve placed around their base so there is an unbonded length of bar that can bend as the wall expands. The top of the sleeve and the reinforcing bar going through this point shall be sealed with a suitable material to keep concrete out of the sleeve. The dowels shall be 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 can determine sleeve heights based on the amount of expansion using the formulas given below.

With reference to Fig. 3.7.2(b), the vertical reinforcing dowel extending from the footing or base slab must be able to accommodate a movement \( \Delta \) caused by expansion of the wall.

The dowel is unbonded over a length \( L \) and is considered to be fixed at the base. The upper end is considered free to rotate since creep will take place around the fresh concrete as it expands, and a fixed condition will not develop.

Moment in reinforcing bar = \( M = 3 \Delta E I / L^2 \)

where

\[
E = \text{modulus of elasticity of bar} \\
I = \text{moment of inertia of bar} \\
c = \text{bar diameter}/2 = d_b/2
\]

<table>
<thead>
<tr>
<th>Bar size no.</th>
<th>Required sleeve internal diameter, in.</th>
<th>Standard pipe internal diameter, in.</th>
<th>Sleeve length ( L ), in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, 4</td>
<td>1.40</td>
<td>1 1/4</td>
<td>13</td>
</tr>
<tr>
<td>5, 6</td>
<td>1.65</td>
<td>1 1/2</td>
<td>16</td>
</tr>
<tr>
<td>7, 8, 9</td>
<td>2.03</td>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>10, 11</td>
<td>2.31</td>
<td>2 1/2</td>
<td>22</td>
</tr>
<tr>
<td>14</td>
<td>2.59</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>18</td>
<td>3.16</td>
<td>3 1/2</td>
<td>27</td>
</tr>
</tbody>
</table>
Therefore
\[ f_y = 3 \Delta E_d / 2L^2 \text{ or } 1.5 \Delta E_d / L^2 \]

Assume
\[ E = 29 \times 10^6 \text{ psi} \]

Therefore
\[ f_y = 435 \times 10^5 \Delta d_b / L^2 \]

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

The length of sleeve is therefore dependent on the amount of expansion, bar diameter, and yield strength of reinforcement. The length may be calculated as follows:

Assume that the wall will shrink about 0.025 percent. The concrete must expand 0.025 percent to compensate for the shrinkage. Assume a wall length of 150 ft (46 m). Therefore, wall expansion \( \Delta \) is

\[ \Delta = 0.00025 \times 150 \times 12 = 0.45 \text{ in. (11.4 mm)} \]

Values of \( L \) for \( f_y = 60 \text{ ksi (414 MPa)} \) and \( \Delta = 0.45 \text{ in. (11.4 mm)} \) are given in Table 2.

Other values of \( L \) for different values of \( f_y \) and \( \Delta \) shall be determined by the Architect/Engineer. The sleeve internal diameter is based on the largest reinforcing bar diameter in the grouping plus 2\( \Delta \). The reinforcing bar is centered in the sleeve to provide an all-around clearance of \( \Delta \).

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

Alternative details to Fig. 3.7.2(a) are shown in Fig. 3.7.2(c) and 3.7.2(d).

In these cases, a filler strip is used in the base slab close to the wall. The filler strip is placed after the expansion and as much shrinkage as possible has taken place in the wall and slab. The filler strip may be cast with portland cement concrete or shrinkage-compensating concrete. However, if a shrinkage-compensating concrete is used, it is unlikely that shrinkage compensation will occur because the high restraint parallel and perpendicular to the wall will prevent expansion.

Details other than shown may be used provided the details allow for adequate expansion and subsequent shrinkage.

**3.7.3 Expansion of circular tanks**—To achieve shrinkage compensation in circular concrete tanks, the wall of the tank must be free to expand horizontally. Special attention is therefore required at the base of the tank to ensure that movement can take place without excessive restraint from the base slab. Expansion in the circumferential direction results in an increase in the tank radius equal to the product of expansive strain times the radius. The expansive strain should be calculated using the procedures of Section 3.2.3. The radial movement can be accommodated using the details shown in Fig. 3.7.2(a) and using the calculation procedure described in Section 3.7.2, or using the details in Fig. 3.7.2(c) and 3.7.2(d). Alternately, a sliding base may be used. In this case, horizontal pressure is resisted by hoop tension alone. Selection
of fixed, pinned, or sliding base condition should be determined from structural design considerations and cost.

3.8—Toppings

3.8.1 Unbonded—Concrete topping placed over existing asphalt base, poor quality concrete, or a concrete base that has many joints or shrinkage cracks should be isolated from these base elements by the use of No. 30 building paper or 1 to 3 in. (25 to 75 mm) of sand to prevent the new slab from bonding to the base. Sand should be used when concrete is cast out in the open, vulnerable to hot, dry, and windy conditions. On the other hand, sand should not be used where water has access to the sand and frost can occur. The slab should contain the minimum amount of reinforcement as described in Section 3.2. Extra care shall be taken to ensure proper location of reinforcement in the topping. The construction joints should be placed as described in Section 3.4.4.

3.8.2 Bonded portland cement concrete—When the base slab is shrinkage-compensating concrete, casting of the topping slab should be delayed for at least 7 days after casting the base slab. During this time, the base slab is expanding and has not reached its maximum length. If a topping is placed too early, the expansion of the base slab, along with the shrinkage of the topping, will weaken the bond between the two slabs and cause a delamination of the topping. After the 7-day delay period, the two materials will shrink together. Shrinkage of the base slab can be prevented by keeping the base slab wet until the topping is placed. Both slabs will then shrink together. For added insurance that the two slabs are bonded, a suitable bonding agent or procedure should be used. This could consist of a bonding mix made up into cement slurry and scrubbed into the base slab surface just ahead of the topping placement, an ASTM C 881 Type V bonding agent, or ASTM C 1059 mortar tested by ASTM C 1042 methods. In all cases, the base slab must be thoroughly cleaned of debris and laitence that would prevent bond. The topping construction joints should be in the same location as the base slab joints (Gulyas, 1980).

3.8.3 Bonded shrinkage-compensating concrete—A base slab made of either portland cement concrete or shrinkage-compensating concrete will probably be in the shrinkage stage when the topping is placed. The shrinkage-compensating topping should have a minimum thickness of 3 in. (75 mm) at any point. The bond between the two slabs is very important, particularly as the base slab is shortening and the topping slab is expanding. If not bonded properly, the two slabs will delaminate. The base slab should be thoroughly cleaned of debris and laitence that would prevent bond. A suitable bonding agent or procedure should be used on the surface. This could consist of a bonding mix made into a cement slurry and scrubbed into the base slab surface just ahead of the topping placement. Alternatively, a bonding agent may be used. The topping slab should have minimum reinforcement as called for in Section 3.2, and located in the upper third of the slab no closer to the top surface than 3/4 or 1 1/2 in. (20 or 40 mm) where deicing salts are used. The topping construction joints should be in the same location as the base slab joints. The exception to these joint placements would be in precast construction. The construction joint of the topping should be located over a precast member transverse joint and a joint must be provided at all support beams. The joint at the support beams should be located at the end of the precast member bearing on the support. This joint is very important since the precast member will deflect with loading and produce rotation at the support beam.

3.9—Formwork

Formwork should be designed in accordance with ACI 347R. Although most of the expansion in shrinkage-compensating concrete takes place while still in the forms, there is insufficient knowledge of the stresses created by concrete expansion to accurately assess the loading. However, no additional strengthening of the formwork has been found necessary with properly reinforced members or slabs. Generally, formwork is sufficiently flexible to accommodate the expansion of the concrete. Formwork removal is related to placement sequences as discussed in Sections 3.4.8, 3.6.3, and 3.7.1.

Further details on formwork for post-tensioned slabs on grade are given in Section 3.6.5.

CHAPTER 4—CONCRETE MIX PROPORTIONING

4.1—General

As with portland cement concrete, shrinkage-compensating concrete cannot be expected to properly perform its design function without proper mix proportions. Correct mix proportioning is necessary to ensure 1) practicality of construction or field placeability, and 2) adequate expansion, strength, and hardened material properties at minimal cost. The effects of mix proportions on expansion, drying shrinkage, internal thermal stresses for massive placements, rate of strength gain, and other properties not necessarily indicated by compressive strength should be considered when selecting mix proportions.

In general, concrete mix proportions that work well with normal portland cements will also produce shrinkage-compensating concrete of similar quality, although a minor increase in mix water may be necessary, and an increase in cement content for lean mixes may be needed to obtain the required expansion.

4.2—Concrete proportions

4.2.1 Aggregates—Quality and proportions of fine and coarse aggregates should follow procedures accepted for portland cement concrete (ACI 211.1). Fine and coarse aggregates from a known source 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, ACI 211.2 and ACI 213R are recommended guides.
Additional information on proportioning aggregates for normal and lightweight concrete may also be obtained from "Design and Control of Concrete Mixtures" (PCA, 1988).

4.2.2 Cement content—As with portland cements, the selection of an appropriate shrinkage-compensating cement content to meet specified concrete strength and expansion requirements should be based on test results of concrete mixes containing the materials to be used in the specific project. The required strength may then be interpolated from the combined use of a water-cementitious material ratio versus compressive strength curve and a cement factor versus compressive strength curve. If data on past performance of the shrinkage-compensating cement are not available, Table 3 may be used as a guide for establishing a trial mix program.

When determining the required water-cementitious material ratio and corresponding cement content, the effect of restrained expansion should be considered. Expansion increases as the cement content increases and decreases as the cement content decreases. A lower limit of 515 lb of cement per yd³ (306 kg/m³) of concrete is recommended to achieve the required expansion with minimum reinforcement (0.15 percent). Fig. 4.1 can be used as a guide to selection of an appropriate cement content for the desired amount of restrained expansion.

Expansion of the concrete should be determined by means of restrained prism specimens as described in ASTM C 878. The effect of amount of reinforcement on expansion of shrinkage-compensating concrete is discussed in Chapter 3. The minimum required expansion is dependent on the amount of reinforcement as shown in Fig. A.1 and the difference between laboratory measured expansion and that attained in production concrete. For this reason, an over-design in expansion should be provided. This is similar to the over-design required for strength.

When shrinkage-compensating concretes are specified for structures that are designed and constructed in accordance with ACI 318, the requirements of Chapter 4—Durability Requirements and Chapter 5—Concrete Quality, Mixing and Placing will control strength, concrete proportions, and evaluation of concrete. To properly apply the provisions of ACI 318, it is necessary to become thoroughly familiar with the commentary to ACI 318 and follow the suggestions and instructions for initial trial batches.

If trial batches are made in accordance with Section 5.2.3 of ACI 318, Table 3 should be used 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, the lower value indicated in Table 3 should be used as the maximum permissible water-cementitious material ratio for the concrete.

4.2.3 Water requirement—The water requirement of some shrinkage-compensating concretes may be 10 to 15 percent more than Type I or Type II portland cement concretes. Increased water requirements can be attributed to variations in the hydration rates that are influenced by the chemical composition of the cement and such physical properties as cement fineness, concrete temperatures, and mixing procedure. The additional water combines with the expansive component at a very early age so the free water available at time of placement is approximately the same as for portland cement concrete.

Experience and test results of job concrete have shown that a properly proportioned mix containing shrinkage-compensating cement with an initially higher water requirement will produce strengths comparable to the same mix containing portland cement with a lower water content and equivalent cement contents.

The additional water requirement may be determined by the mix proportioning procedures discussed in Section 4.5. Water added to any concrete mix beyond that required in the initial proportioning will result in reduced strengths. The fact that shrinkage-compensating concrete is expected to have a slightly higher mix water demand should not be used as an excuse for arbitrarily adding excessive water that can lead to lower strength, less durability, higher permeability, and other detrimental effects that are common with normal portland cement concrete when excessive water is added.

4.3—Admixtures

Generally, ASTM C 878 tests to determine the effect of admixtures on expansion levels should be conducted before
a project, unless there is experience with the specific admixtures, cement, and aggregates.

4.3.1 Air-entraining admixtures—Air-entraining admixtures that comply with ASTM C 260 may be used for shrinkage-compensating concrete. Generally, the same amount of a given air-entraining admixture will produce a comparable percentage of entrained air, all other conditions being equal.

4.3.2 Water-reducing and water-reducing and retarding admixtures, both normal and high-range (HRWR)—Some ASTM C 494 Type A, D, F, and G admixtures are not compatible with certain shrinkage-compensating cements. The effects of Type F and G admixtures are continuing to be investigated. Chemical formulations of many admixtures, especially Types F and G, are occasionally revised, modified, and improved by some of the producers so the behavior experienced with an outdated formulation may not be the same as for a current formulation from the same producer. The cement manufacturer and admixture producer should be consulted as to past experience and compatibility of their cement and specific admixtures (Section 2.4). Special attention should be given to the admixture’s effect on slump, restrained expansion, drying shrinkage, and in some cases, temperature gain control. The use of certain admixtures with some shrinkage-compensating cements has resulted in excessive shrinkage. These effects may be experienced for both normal range and high-range admixtures. However, both field and laboratory work by Bond (1985) indicates that some high-range admixtures, Types F and G, are beneficial to shrinkage-compensating concretes in terms of temperature gain control, slump-loss reduction, improved expansion due to increased water reduction, and generally good performance in highly plastic mixes or mixes at the high end of the slump range. This performance is based on using, as a guide, the water-cementitious material ratio values in Table 3 and utilizing the HRWR for improved control and placing characteristics.

Generally, admixtures that are acceptable may be used at the normal dosage rates recommended for Type I or Type II portland cement concrete under moderate temperature conditions. During hot weather, higher than normal dosages of acceptable ASTM C 494 water-reducing retarders, Types D and G, have been used successfully to retard the initial setting time of some shrinkage-compensating concretes.

4.3.3 Accelerators—Calcium chloride is generally not recommended for use in shrinkage-compensating concrete due to its effect in reducing expansion and increasing subsequent drying shrinkage. It is recommended that tests using ASTM C 878 be made to determine the effect of non-chloride accelerating admixtures on expansion levels.

4.4—Consistency

Good results can be obtained using slumps at time of placement within the maximum range specified by ACI 211.1 for the work involved when concrete temperatures do not exceed 75 F (24 C). At higher concrete temperatures, the following maximum slumps at point of placement are recommended when not using a high-range water reducer:

<table>
<thead>
<tr>
<th>Type of construction</th>
<th>Slump, in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced foundation with walls and footings</td>
<td>5 (125)</td>
</tr>
<tr>
<td>Plain footings, caissons, and substructure walls</td>
<td>4 (100)</td>
</tr>
<tr>
<td>Slabs, beams, reinforced walls</td>
<td>6 (150)</td>
</tr>
<tr>
<td>Building columns</td>
<td>6 (150)</td>
</tr>
<tr>
<td>Pavements</td>
<td>4 (100)</td>
</tr>
<tr>
<td>Heavy mass construction</td>
<td>4 (100)</td>
</tr>
</tbody>
</table>

With ready-mixed concrete operations, the delivery time of concrete between the batch plant and placement may be as long as 1 1/2 hr. Ettringite will begin to form during this period in some shrinkage-compensating concretes, resulting in a premature stiffening and slump loss of 2 to 3 in. (50 to 75 mm). It is therefore essential that sufficient slump within maximum allowable water limits be provided at the batch plant to ensure that the specified or desired slump is obtained at the job site.

It must be understood that if, because of ambient conditions at the time of placement, acceptable extended mixing times, or other factors, additional water is added to the mix at the jobsite to increase the slump to the point that it approaches the maximum limit specified, close control must be kept over the amount of added mix water so that the total water in the mix does not exceed the water content established by the design mix proportions. To do so could reduce strengths and offset the effectiveness of the expansion in controlling shrinkage cracks. The importance of taking this slump loss into account in selecting proportions for shrinkage-compensating concretes cannot be overemphasized. It becomes even more important during hot weather when concrete temperatures are relatively high and chemical reactions are accelerated. While normal delivery time of ready-mixed portland cement concrete under adverse hot weather conditions results in a significant slump loss, some shrinkage-compensating concretes develop even greater slump loss under the same hot weather conditions. Slump loss controls in hot weather that are successful for portland cement concrete are equally effective for shrinkage-compensating concrete. Because of the possibly greater slump loss, more liberal use and stricter enforcement of these controls is recommended when shrinkage-compensating concretes are used. Recommended controls include using chilled mix water, using evaporated cooling on coarse aggregate stockpiles, reducing the speed of the truck mixer drum to a minimum during travel and waiting time at the jobsite, and efficient truck scheduling so as to reduce the period between mixing and delivery to an absolute minimum. When job locations require extended travel time, dry batched truck delivery with jobsite mixing is effective as long as the cement is charged on top of the aggregates without turning the drum so that moisture in the aggregate does not effectively contribute to the start of the hydration process and production of ettringite in the bulk quantity of cement. This batching procedure mandates the use of mixers in excellent condition.
For a more complete discussion of hot weather concreting, refer to ACI 305R, which deals with hot weather control of concrete properties, production, and delivery. The objectives are to identify hot weather problems and recommend concreting practices that will alleviate adverse effects likely to be experienced.

4.5—Mix proportioning procedures

Trial mixes using job materials should be made in the laboratory at the approximate concrete temperatures anticipated in the field. The following procedures have been successful in developing satisfactory batching plant and job control programs under differing conditions.

4.5.1 When the time between addition of mix water and placement is not more than 15 min, such as jobsite mixing or when the batch plant is near the project, the total mixing water required will be comparable to that of a Type I or Type II portland cement concrete for the specified slump. Trial batches to develop satisfactory aggregate proportions, cement content, and water requirement should follow the recommendations set forth in Section 4.1. The mixing procedure in ASTM C 192 should be used.

4.5.2 When the water is added at the batch plant and where delivery will require normal travel time (30 to 40 min) in a truck mixer whether truck or central-mixed, or when expected concrete temperature will exceed approximately 75 F (24 C), some slump loss can be expected and must be compensated for by a relatively high initial slump to produce the slump required at the jobsite. Under such conditions, both of the following procedures for trial batch tests have been used successfully.

Procedure A

1. Prepare the batch using ASTM C 192 procedures but add 10 percent additional water over that normally used for Type I cement.
2. Mix initially in accordance with ASTM C 192 (3 min mix followed by 3 min rest and 2 min remix).
3. Determine the slump and record as initial slump.
4. Continue mixing for 15 min.
5. Determine the slump and record as placement slump.

Experience has shown that this slump correlates with that expected for a 30 to 40 min delivery time. If this slump does not meet the required placement specification limits, discard and repeat the procedure with an appropriate water adjustment.

6. Cast test specimens for compressive and expansion tests and determine the properties of fresh concrete—unit weight, air content, and temperature.

Procedure B

1. Prepare the batch using ASTM C 192 procedures for the specified slump.
2. Mix in accordance with ASTM C 192 (3 min mix, 3 min rest, and 2 min remix) and confirm the slump.
3. Stop the mixer and cover the batch with wet burlap for 20 min.
4. Remix 2 min, adding water to produce the specified placement slump. The total water (initial plus the remix water) that is required at the batching plant to give the proper jobsite slump after a 30 to 40 min delivery time.
5. Cast test specimens for compressive and expansion tests and determine the properties of fresh concrete—unit weight, air content, and temperature.

4.5.3—Whenever possible, trial mixes should be made to ensure satisfactory and economical results. If a trial batch is not made, either of the following approximations have often given satisfactory results when time and concrete temperature conditions are the same as in Section 4.5.2.

1. Add approximately 10 percent more water to the shrinkage-compensating mix than that used for a mix made with a Type I or Type II cement proportioned under ACI 211.1 and ACI 211.2.
2. Use a water-reducing admixture known to be compatible with the shrinkage-compensating cement used, and maintain the same amount of mix water as if no admixture was used.

CHAPTER 5—PLACING, FINISHING, AND CURING

5.1—Placing

The plastic characteristics of all three types of shrinkage-compensating concrete are sufficiently similar to concretes made with Type I or II portland cement so that no special equipment or techniques are required for satisfactory placement. The recommendations set forth in ACI 304R shall be followed where applicable. Successful placements have been made by wheelbarrow, mixer truck, bucket, conveyor, pump, and shotcrete. In general, shrinkage-compensating concrete is more cohesive than portland cement concrete and has less tendency to segregate. For this reason, it is especially adaptable to pumping, and a large percentage of shrinkage-compensating concrete has been placed by that method. Shrinkage-compensating concrete has also been used without difficulty in the manufacture of pipe in precast operations and in paving machines.

Placing recommendations given in ACI 304 for portland cement concrete are equally applicable for shrinkage-compensating concrete. However, the characteristics of shrinkage-compensating concrete require that good concreting practices be followed so as to ensure adequate expansions and satisfactory results. If adequate expansion is not achieved, compensation for drying shrinkage is not available and cracking may occur.

5.1.1 Where the plastic concrete will be in contact with an absorptive material such as dry soil or previously placed dry concrete, the base or subgrade shall be thoroughly wetted. Sprinkling lightly is not sufficient. Soak the base material the evening before placement and sprinkle ahead of placement as necessary if base has dried. A quick check is to obtain a handful of subgrade or base material and squeeze it into a ball. The retention of its volume indicates adequate moisture content, and dampening should not be necessary. In hot weather, wet the forms and reinforcement.
5.1.2 In hot, dry, and windy placing conditions, all concrete tends to lose moisture unevenly and may develop plastic shrinkage cracks. Experience has shown that with shrinkage-compensating concrete, plastic shrinkage cracking is more prevalent because of water required for the early formation of ettringite. Finishing difficulties may be increased because of nonuniform moisture loss between top and bottom surfaces during the drying period, particularly when the concrete is placed directly over a vapor barrier.

5.1.3 Where a vapor barrier is required, it should be placed directly on the subgrade and covered with 2 to 3 in. (50 to 75 mm) of granular, compatible, self-draining trimmable fill material. The fill material should be thoroughly dampened before concrete placement. This practice results in more uniform moisture loss of the shrinkage-compensating concrete, less plastic shrinkage cracking, and protection of the vapor barrier during placement. Care shall be taken during placement of concrete to maintain a uniform layer of fill material. In protected environments where a vapor barrier is required, a fill material layer may be eliminated. When either this fill layer or a vapor barrier is used, consideration shall be given to larger than normal joint openings due to the reduction of the subgrade friction factor.

5.1.4 If plastic shrinkage cracking is likely, sheeting, monomolecular films (either sprayed or rolled on), as well as very fine fog sprays of water, have been used quite successfully in arresting this tendency. The purpose of fog spraying is to replace necessary surface water that has been lost due to an excessive rate of evaporation. Consequently, very fine sprays are recommended. Heavy applications of water shall be avoided until concrete has taken its final set.

5.1.5 Care must be taken to maintain the reinforcement in its proper position during placement and consolidation to assure that it provides the required restraint. The actual positioning of the steel can be checked by inserting a wooden, plastic, or metal gage into the plastic concrete. The reinforcement prevents further embedment of the gage, and depth of cover is indicated by the wet concrete on the gage. Proper consolidation of the concrete ensures good bond with the steel.

5.1.6 Special precautions shall be taken to avoid placing delays at the jobsite when using ready-mixed concrete. A substantial increase in mixing time over that assumed when selecting mix proportions increases the slump loss. Any water added at the jobsite, after slump loss, to maintain consistency not only decreases the strength but may also reduce the expansion to unacceptable levels.

5.1.7 Concrete temperature and time in the mixer (from intermingling cement and damp aggregate) are important factors because of their effect on expansion. It is recommended that the temperature at the time of placement not exceed 90 F (32 C) and the mixing time at temperatures above 85 F (30 C) be limited to 1 hr. Below 85 F (30 C), the maximum mixing time shall be 1 1/2 hr. During cold weather concreting, the methods recommended are those described in ACI 306R to provide adequate strength gain and expansion. When using some ASTM C 494 Type F and G admixtures, the upper temperature limits may be increased providing that it can be demonstrated that the ASTM 878 expansion values are not decreased, the strength and slump loss values are not adversely affected, and that continuous moist curing is utilized for 7 days after placement. Note that curing water temperature should be in accordance with the recommendations contained in ACI 308.

5.1.8 Placement sequence is important in developing the proper strain on the internal reinforcement of shrinkage-compensating concrete (Section 3.4.8—Placing sequence).

5.1.9 Although the successful combination of shrinkage-compensating concrete and vacuum dewatering has been reported, it is generally not recommended unless proven by measurement of expansion and shrinkage of prisms in accordance with ASTM C 878.

5.2—Finishing

The cohesiveness inherent in shrinkage-compensating concretes leads to excellent finishing qualities. Its behavior is similar to air-entrained concrete but this usually presents no problems. Similarly, there is little or no bleeding even though a relatively high slump may be used. Due to lack of bleed water, however, there is a tendency to begin finishing too soon. On the other hand, in warm weather, shrinkage-compensating concrete will typically set faster than Type I or Type II portland cement concretes and finishing may start somewhat sooner than normal. If a dry shake will be used, special provisions may be required to achieve proper distribution and bedding of the dry shake.

In general, satisfactory results will be obtained when the recommendations of ACI 304R are followed, together with the more detailed recommendations of ACI 302R.

5.3—Curing

Shrinkage-compensating concrete, as with all portland cement concrete, requires continuous curing at moderate temperatures for several days after final finishing operations to prevent early drying shrinkage and to develop strength,
durability, and other desired properties. Any deficiencies in the method of curing may also reduce the amount of initial expansion that is needed to offset later drying shrinkage. The typical effects of different methods of curing on expansion can be seen in Fig. 5.3.1.

When the effect of curing is considered, the properties of the mix may be modified to ensure adequate expansion. For example, the cement factor may be increased. The usually-accepted methods of curing are satisfactory for shrinkage-compensating concrete; however, those that provide additional moisture to the concrete such as ponding, continuous sprinkling, and wet coverings are preferred to ensure adequate water for ettringite formation and expansion. Other methods such as moisture-proof covers and sprayed-on membranes have been successfully utilized, provided that coverage is complete so that it prevents loss of moisture from the entire concrete surface. Curing of shrinkage-compensating concrete shall be continued for a minimum of 7 days.

Curing of concrete flatwork shall commence immediately after final finishing. It may be necessary to fog spray or cover the surface of the concrete temporarily if other methods of curing are delayed, especially in hot, dry, or windy weather. If a liquid curing membrane is used, it shall conform to ASTM C 309 and be applied in two directions, at a coverage rate suggested by the manufacturer, immediately following the final finishing as it progresses. To accomplish this, power spray equipment capable of covering large areas more rapidly shall be used rather than small, portable spray tanks.

For architectural or structural concrete, the normally accepted practice of curing with the formwork in place is adequate. Uncovered surfaces shall receive additional curing by one of the accepted methods. In hot weather, soaker hoses or water sprays shall be used to supplement the protection of the in-place formwork. If the forms must be removed prior to 7 days, one of the other accepted methods of curing shall then be employed for the balance of the curing period.

Shrinkage-compensating concrete shall be protected during the initial curing period against extremes of temperatures during either cold or hot weather periods. The methods recommended are those described in ACI 305R and ACI 306R.

CHAPTER 6—REFERENCES

6.1—Specified or recommended references

The documents of the various standards-producing organizations referred to in this document are listed with their serial designation. The documents listed were the latest effort at the time this document was revised. Since some of these documents are revised frequently, generally in minor detail only, the user of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Concrete Institute

116R Cement and Concrete Terminology
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 Lightweight Concrete
213R Guide for Structural Lightweight Aggregate Concrete
224R Control of Cracking in Concrete Structures
302.1R Guide for Concrete Floor and Slab Construction
304R Guide for Measuring, Mixing, Transporting, and Placing Concrete
305R Hot Weather Concrete
306R Cold Weather Concrete
318 Building Code Requirements For Reinforced Concrete
347R Guide to Formwork for Concrete
360R Design of Slabs on Grade
423.3R Recommendations for Concrete Members Prestressed with Unbonded Tendons

ASTM
C 150 Specification for Portland Cement
C 192 Test Method of Making and Curing Concrete Test Specimens in the Laboratory
C 204 Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus
C 260 Specification for Air-Entraining Admixtures for Concrete
C 309 Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C 494 Specification for Chemical Admixtures for Concrete
C 806 Test Method for Restrainted Expansion of Expansive Cement Mortar
C 845 Specification for Expansive Hydraulic Cement
C 878 Test Method for Restrained Expansion of Shrinkage-Compensating Concrete
C 881 Specification for Epoxy-Resin Bonding Systems for Concrete
C 1042 Test Method for Bond Strength of Latex Systems Used with Concrete by Slant Shear
C 1059 Specification for Latex Agents for Bonding Fresh to Hardened Concrete
D 994 Specification for Preformed Expansion Joint Filler for Concrete (Bituminous Type)
D 1621 Test Method for Compressive Properties of Rigid Cellular Plastics
D 1751 Specification for Preformed Expansion Joint Fillers for Concrete Paving and Structural Construction (Nonextruding and Resilient Bituminous Types)
D 1752 Specification for Preformed Sponge Rubber and Cork Expansion Joint Fillers for Concrete Paving and Structural Construction
D 1754 Test Method for Effect of Heat and Air on Asphaltic Materials (Thin-Film Oven Test)
D 3575 Test Methods for Flexible Cellular Materials Made from Olefin Polymers

The previously listed publications may be obtained from the following organizations:
American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

ASTM
100 Bar Harbor Drive
West Conshohocken, PA 19428

6.2—Cited references


ACI Committee 223 (1977). “Recommended Practice for the Use of Shrinkage-Compensating Concrete (ACI 223-77),” American Concrete Institute, Farmington Hills, Mich., 21 pp.


Kesler, C. E. (1976). “Control of Expanrive Concretes during Construc-

Design A

- Determine the required prism expansion to ensure complete shrinkage compensation in a 6-in.-(150-mm)-thick slab on grade drying from the top face only and containing 0.15 percent reinforcement.

- For complete shrinkage compensation, the amount of expansion in the slab will be equal to the anticipated amount of shrinkage. Hence, it is first necessary to determine the amount of shrinkage. The shrinkage will vary depending on the particular materials of the mix and the volume/surface area ratio of the member.

- If values of shrinkage for the particular mix are not known, the data in Fig. A.1 may be used.

Fig. A.1 is identical to Fig. 3.2.3 except that circumferential lines showing shrinkage for different volume-to-surface area ratios have been added (Russell, 1973). The restrained expansion of the member must be equal or greater than the...
anticipated restrained shrinkage of the member for full shrinkage compensation.

A 6-in.- (150-mm)-thick slab drying from one face has a volume-to-surface area ratio of 6.0 in. (150 mm). The intersection of the curves for volume/surface area ratio of 6.0 and percentage of reinforcement of 0.15 percent is denoted by Point A on Fig. A.1. The corresponding slab expansion is 0.0305 percent and the restrained prism expansion is 0.032 percent. The required slab expansion for complete shrinkage compensation is 0.0305 percent. This may be achieved with a restrained prism expansion (ASTM C 878) of 0.032 percent. Alternatively, if the drying shrinkage is known, it may be used as the ordinate in Fig. A.1 to obtain the abscissa corresponding to the percentage of reinforcement line of 0.15 percent.

A.2—Design B

Determine the amount of expansion that will occur in a 100-ft-(30.5-m)-long shrinkage-compensating slab containing 0.5 percent reinforcement when the concrete has a restrained prism expansion (ASTM C 878) of 0.06 percent.

Enter Fig. A.1 at an abscissa of 0.06 percent, go up to the 0.5 percent reinforcement line, and then go across to the ordinate of 0.038 percent, which is the slab expansion. This may be achieved with a restrained prism expansion (ASTM C 878) of 0.032 percent.

Alternatively, if the drying shrinkage is known, it may be used as the ordinate in Fig. A.1 to obtain the abscissa corresponding to the percentage of reinforcement line of 0.15 percent.

A.2—Design B

Determine the amount of expansion that will occur in a 100-ft-(30.5-m)-long shrinkage-compensating slab containing 0.5 percent reinforcement when the concrete has a restrained prism expansion (ASTM C 878) of 0.06 percent.

Enter Fig. A.1 at an abscissa of 0.06 percent, go up to the 0.5 percent reinforcement line, and then go across to the ordinate of 0.038 percent, which is the slab expansion. This may then be compared with the anticipated amount of shrinkage. For heavily reinforced slabs, the amount of expansion will be less than the anticipated shrinkage so only partial shrinkage compensation will be obtained.

A 100-ft-(30.5-m)-long slab expanding at only one end will have a movement of 100 x 12 x 0.00038 = 0.46 in. (12 mm). A slab edge compressible filler with a thickness at least equal to twice the slab expansion or 0.92 in. (24 mm) will be required.

In compressing to 50 percent of its original thickness, the stress on the filler should be less than 25 psi (172 kPa).

APPENDIX B—TENSILE STRAIN CAPACITY

Research has shown that cracking tensile strain capacity of shrinkage-compensating concrete may be compared to portland cement concrete, as shown in Table B.1 for a slab with 1.02 percent symmetrical reinforcement when both specimens are subjected to direct tension (Cusick and Kesler, 1976).

For the two specimens compared in Table B.1, the improvement in stress and strain capacity for shrinkage-compensating concrete compared to portland cement concrete was about 23 percent. Larger percentages of stress and strain capacity can be expected for lower steel percentages since reinforcement percentage affects restrained expansion more than restrained shrinkage.

Comparative net strain values from drying with various percentages of restraining steel and different amounts of expansion have been reported for shrinkage-compensating concrete (Seeber et al., 1973; Kesler, 1976; Russell, 1980; Spellman et al., 1973; Pfeifer, 1973; Pfeifer and Perenchio, 1973). Values of strains due to expansion and subsequent shrinkage in a 50 percent relative humidity environment are given in Tables B.2 and B.3.

Various levels of internal restraint are given for normal-weight and lightweight concrete. The data in Table B.3 have been selected to make a simple comparison between Type I and K cements. Corresponding comparisons with S and M cements are contained in the original report (Russell, 1980). The data in Tables B.2 and B.3 indicate that there are two types of strain for shrinkage-compensating concretes: expansive strains that increase length and shrinkage strains that produce a net shortening of the concrete. With portland cement concrete, only a shrinkage strain condition develops.

Typical strains at the top and bottom of two 15-in.- (380-mm)-deep slabs are shown in Table B.4 for three different amounts of reinforcement (Keeton, 1979). This indicates that reverse curling of slabs will occur if the top reinforcement is less than 0.2 percent and if the slab has an opportunity to expand.

APPENDIX C—APPLICATION OF SHRINKAGE-COMPENSATING CONCRETE IN POST-TENSIONED STRUCTURES

This section describes the application of shrinkage-compensating concrete in post-tensioned structures.
To give some examples of structural movement, assume the following structural details: structure length = 210 ft (64 m); structural member area = 96 in.² (0.062 m²); concrete strength = 4000 psi (28 MPa); concrete stress from prestressing = 250 psi (1.72 MPa); and column spacing = 30 ft (9.1 m).

In addition, assume that the structure has no shearwalls or other restraint that would prevent the volume change from taking place about the center of the structure. The largest dimensional change will take place at the outermost columns.

Five different construction methods will be investigated for shortening effects. Fig. C.1 illustrates these five comparative post-tensioned construction methods.

| Method 1 | Portland cement concrete with 36-in. (915-mm) cast strip in center of structure left open for 30 days. Effective length of structure is 103.5 ft (32 m) with half the movement occurring at each end. After 30 days, structure will be continuous with a total length of 210 ft (64 m). |
| Method 2 | Portland cement concrete with expansion joint in center of structure. The structure will be 105-ft (32-m) long for all movements. Movement at outer columns will be caused by 52.5 ft (16 m) length. |
| Method 3 | Portland cement concrete with no cast strip or expansion joint. The structure will be 210-ft (64-m) long for all movements. All movements at outer column will be caused by 105 ft (32 m) length. |
| Method 4 | Shrinkage-compensating concrete with no cast strip or expansion joint. The structure will be 210-ft (64-m) long for all movements. All movements at outer column will be caused by 105 ft (32 m) length. |
| Method 5 | Shrinkage-compensating concrete with 36-in. (915-mm) cast strip in center of structure left open for 30 days. Movements at outer column prior to casting strip will be caused by a length of 51.75 ft (16 m). After 30 days, movement at each outer column will be caused by a length of 105 ft (32 m). |

### Table B.2—Comparative residual strains for reinforced normal weight concrete

<table>
<thead>
<tr>
<th>$A/A_c$, percent</th>
<th>Strain,² millionths</th>
<th>0.15</th>
<th>0.75</th>
<th>1.40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>S</td>
<td>I</td>
<td>K</td>
<td>S</td>
</tr>
<tr>
<td>Expansion</td>
<td>600</td>
<td>60</td>
<td>660</td>
<td>340</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>-400</td>
<td>-450</td>
<td>-530</td>
<td>-270</td>
</tr>
<tr>
<td>Net Strain</td>
<td>200</td>
<td>-390</td>
<td>130</td>
<td>70</td>
</tr>
<tr>
<td>Differential:³</td>
<td>S</td>
<td>+590</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>K</td>
<td>—</td>
<td>—</td>
<td>+520</td>
<td>—</td>
</tr>
</tbody>
</table>

1. Source: Seeber et al., 1973, after 120 days of drying at 50 percent relative humidity.
2. Expansion is positive, shortening is negative.
3. Differential = net strain of shrinkage-compensating concrete minus net strain of Type I concrete.

### Table B.3—Comparative residual strains for reinforced lightweight concrete

<table>
<thead>
<tr>
<th>$A/A_c$, percent</th>
<th>Strain,² millionths</th>
<th>0.28</th>
<th>0.46</th>
<th>1.72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>I</td>
<td>K</td>
<td>I</td>
<td>K</td>
</tr>
<tr>
<td>Expansion</td>
<td>—</td>
<td>273</td>
<td>—</td>
<td>239</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>-344</td>
<td>-283</td>
<td>-360</td>
<td>-266</td>
</tr>
<tr>
<td>Net strain</td>
<td>-344</td>
<td>-10</td>
<td>-360</td>
<td>-27</td>
</tr>
<tr>
<td>Differential:³</td>
<td>—</td>
<td>+334</td>
<td>—</td>
<td>+333</td>
</tr>
</tbody>
</table>

1. Source: Russell, 1980, after 250 days of drying at 50 percent relative humidity.
2. This reference also includes data for S and M cements and position of reinforcement.
3. Expansion is positive, shortening in negative.
4. Differential = net strain of K concrete minus net strain of Type I concrete.

### C.1—Volume change effects on different construction techniques

To give some examples of structural movement, assume the following structural details: structure length = 210 ft (64 m); structural member area = 96 in.² (0.062 m²); concrete strength = 4000 psi (28 MPa); concrete stress from prestressing = 250 psi (1.72 MPa); and column spacing = 30 ft (9.1 m). In addition, assume that the structure has no shearwalls or other restraint that would prevent the volume change from taking place about the center of the structure. The largest dimensional change will take place at the outermost columns. Five different construction methods will be investigated for shortening effects. Fig. C.1 illustrates these five comparative post-tensioned construction methods.

Method 1—Portland cement concrete with 36-in. (915-mm) cast strip in center of structure left open for 30 days. Effective length of structure is 103.5 ft (32 m) with half the movement occurring at each end. After 30 days, structure will be continuous with a total length of 210 ft (64 m). Subsequent movement at each outer column will be caused by a length of 105 ft (32 m).
The shrinkage-compensating concrete will be assumed to have an unrestrained expansion of 0.038 percent. Length changes will be calculated as follows:

**EXPANSION**
Length change = \(0.00038 \times \text{length} = 380 \times 10^{-6} \times \text{length}\).

**ELASTIC SHORTENING**
Modulus of elasticity of concrete = \(57,000 \sqrt{4000} = 3.6 \times 10^6\) psi.
Prestress on concrete = 250 psi.
Length change = \(\frac{250}{3.6 \times 10^6} \times \text{length} = 69.4 \times 10^{-6} \times \text{length}\).

**SHRINKAGE**
Assume total shrinkage of \(300 \times 10^{-6}\) and 45 percent occurs before strip is cast.
Length change from 45 percent of shrinkage = \(0.45 \times 300 \times 10^{-6} \times \text{length} = 135 \times 10^{-6} \times \text{length}\).
Length change from 55 percent of shrinkage = \(0.55 \times 300 \times 10^{-6} \times \text{length} = 165 \times 10^{-6} \times \text{length}\).

**CREEP**
Creep shortening = \(K \times \text{elastic shortening}\).
Let \(K = 3.0\) and assume 45 percent of creep occurs before strip is cast.
Length change from 45 percent of creep = \(0.45 \times 3 \times 69.4 \times 10^{-6} \times \text{length} = 93.7 \times 10^{-6} \times \text{length}\).
Length change from 55 percent of creep = \(0.55 \times 3 \times 69.4 \times 10^{-6} \times \text{length} = 114.5 \times 10^{-6} \times \text{length}\).

**TOTAL**
Total movement is equal to summation of length changes caused by expansion, elastic shortening, shrinkage, and creep.

Table C.1 shows calculated length changes at outer column for expansion, elastic shortening, shrinkage, and creep for each construction method.
The least column movement with a portland cement concrete occurs with Method 2. However, an expansion joint must be provided at center of structure. On the other hand, when the construction or expansion joint is omitted, the negative column movement is considerably less when a shrinkage-compensating concrete is compared with a portland cement concrete.

### Table B.4—Strain differentials in slabs

<table>
<thead>
<tr>
<th>Strain, (A_2/A_1) millionths</th>
<th>0.06</th>
<th>0.11</th>
<th>0.17</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expansive strain</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top</td>
<td>1095</td>
<td>965</td>
<td>790</td>
</tr>
<tr>
<td>Bottom</td>
<td>605</td>
<td>585</td>
<td>550</td>
</tr>
<tr>
<td>Difference</td>
<td>490</td>
<td>380</td>
<td>240</td>
</tr>
<tr>
<td><strong>Residual strain at 1 yr 50 percent relative humidity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top</td>
<td>912</td>
<td>782</td>
<td>607</td>
</tr>
<tr>
<td>Bottom</td>
<td>577</td>
<td>557</td>
<td>522</td>
</tr>
<tr>
<td>Difference</td>
<td>335</td>
<td>225</td>
<td>85</td>
</tr>
<tr>
<td><strong>20 percent relative humidity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top</td>
<td>357</td>
<td>272</td>
<td>552</td>
</tr>
<tr>
<td>Bottom</td>
<td>569</td>
<td>549</td>
<td>514</td>
</tr>
<tr>
<td>Difference</td>
<td>288</td>
<td>178</td>
<td>38</td>
</tr>
</tbody>
</table>

1 | Source: Keeton, 1979.
2 | Expansion is positive; shortening is negative.

Length change = \(250/3.6 \times 10^{-6} \times \text{length} = 69.4 \times 10^{-6} \times \text{length}\).

### Table C.1—Length change at outer column

<table>
<thead>
<tr>
<th>Movement</th>
<th>Construction method(^{1,2,3,4,5})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>EXPANSION</strong></td>
<td></td>
</tr>
<tr>
<td>Length, ft</td>
<td>0</td>
</tr>
<tr>
<td>Length change, in.</td>
<td>0</td>
</tr>
<tr>
<td><strong>ELASTIC</strong></td>
<td></td>
</tr>
<tr>
<td>Length, ft</td>
<td>51.75</td>
</tr>
<tr>
<td>Length change, in.</td>
<td>-0.0431</td>
</tr>
<tr>
<td>45 percent <strong>SHRINKAGE</strong></td>
<td></td>
</tr>
<tr>
<td>Length, ft</td>
<td>51.75</td>
</tr>
<tr>
<td>Length change, in.</td>
<td>-0.0838</td>
</tr>
<tr>
<td>55 percent <strong>SHRINKAGE</strong></td>
<td></td>
</tr>
<tr>
<td>Length, ft</td>
<td>105.0</td>
</tr>
<tr>
<td>Length change, in.</td>
<td>-0.2079</td>
</tr>
<tr>
<td>45 percent <strong>CREEP</strong></td>
<td></td>
</tr>
<tr>
<td>Length, ft</td>
<td>51.75</td>
</tr>
<tr>
<td>Length change, in.</td>
<td>-0.0582</td>
</tr>
<tr>
<td>55 percent <strong>CREEP</strong></td>
<td></td>
</tr>
<tr>
<td>Length, ft</td>
<td>105.0</td>
</tr>
<tr>
<td>Length change, in.</td>
<td>-0.1443</td>
</tr>
<tr>
<td><strong>COLUMN MOVEMENT, in.</strong></td>
<td>-0.5373</td>
</tr>
</tbody>
</table>

\(^{1}\) Metric equivalent: 1 in. = 25.4 mm
\(^{2}\) = Portland cement concrete with no cast strip or expansion joint.
\(^{3}\) = Portland cement concrete with expansion joint in centre of building.
\(^{4}\) = Shrinkage-compensating concrete with no cast strip or expansion joint.
\(^{5}\) = Shrinkage-compensating concrete with 56 in. (14 mm) cast strip left open for 30 days after maximum expansion (approximately 77 days after placement).
C.2—Column moment reductions

By the use of a shrinkage-compensating concrete, column moments caused by length changes of slabs can be reduced. The amount of moment reduction will vary based on the type of horizontal structure. The solid two-way slab will be able to receive the most reduction in moment. The one-way beam and girder or one-way joist and girder will have less moment reduction than the two-way slab. The reason for the two different moment reductions is the forming systems. The two-way slab cast onto flat, even, plywood forms has very little restraint against the concrete length change. The columns below and the form bulkheads are the only items that serve to minimize concrete volume change during the early stages of concrete expansion. Removal of bulkheads at an early stage will allow for maximum expansion. The one-way joist, beam, and girder structures have more elements of the forming system working against the volume change during concrete expansion. This will reduce the amount of moment reduction.

Moment reductions are achieved in the early stages of concrete expansion. Then, as shrinkage, creep, and elastic shortening take place after post-tensioning, the negative volume change is subtracted from the expanded volume change. Column moments are created due to the concrete expanding. In some cases, the moments caused by expansion are as large as the moments caused by subsequent shrinkage. These moments due to expansion are the largest at 7 days, or up to the time when post-tensioning steel is stressed. These moments start to decrease in size as elastic shortening, creep, and shrinkage take place. The column and horizontal element should be checked with no live load and just frame axial dead load when maximum expansion occurs. The most critical element will be the column between the foundation and the first framed structural element where dead load is least when the expansion length change is greatest. As the frame axial dead load increases due to additional frame at each level, the expansion moments are decreasing due to the time interval between casting upper frame elements.

C.3—Expansion of structure

A series of 3 x 3 x 10-in. (75 x 75 x 255-mm) concrete bars should be tested according to ASTM C 878 using the proposed concrete mix proportions that are intended for final construction. The results of these tests can be used with Fig. 3.2.3 to determine if there is going to be a balance between expansion volume change and shortening volume change similar to that shown in Table C.1. The concrete is assumed to be unrestrained in an unbonded system prior to post-tensioning. However, when nonprestressed reinforcement is included, an average percentage of nonprestressed reinforcement should be assumed when using Fig. 3.2.3 to determine expansions. The test results are in percent of expansion. The probable expansion is equal to \( L \times \text{percent expansion} \) where \( L \) = length.
C.4—Conclusions

The five examples described in Section C.1 showed that Method 4 with no expansion joint and shrinkage-compensating concrete had the least calculated shortening. The next least amount of movement occurred with Method 5 with a cast strip and shrinkage-compensating concrete.

Method 2 had the least movement with a portland cement concrete. However, extra columns at expansion joint, expansion joint covers, post-tensioning anchorages, and additional forming are needed. These will result in additional costs. In addition, Method 2 has four outer column rows with the highest moment and shears due to the shortening effects. Methods 4 and 5 have only two outer column rows. The amount of shortening for Method 5 is slightly greater than for Method 4 and may require more column reinforcement. However, Method 5 provides the option of placing the post-tensioning anchorages in the cast strip. The Architect/Engineer should consider these examples and determine which type of structure will result in least cost.