

Standard Practice for the Use of Shrinkage-Compensating Concrete

Reported by ACI Committee 223

Henry G. Russell
Chairman

Edward K. Rice
Secretary

Gerald H. Anderson	Terry J. Fricks	Robert S. Lauderbach
Carl Bimel	Herbert G. Gelhardt III	Harry L. Patterson
Richard L. Boone	James R. Golden	William F. Perenchio
Bayard M. Call	Paul W. Gruner	Robert E. Price
David A. Crocker	Robert J. Gulyas	Edward H. Rubin
Boris Dragunsky	Patrick J. Harrison	Edward D. Russell
Leo J. Elsbernd	George C. Hoff	Joe V. Williams, Jr.

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.

ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

CONTENTS

Chapter 1—Introduction, p. 223-2

- 1.1—Background
- 1.2—Purpose of shrinkage-compensating concrete
- 1.3—Scope and limits
- 1.4—Definitions
- 1.5—General considerations
- 1.6—Preconstruction meeting

Chapter 2—Materials, p. 223-3

- 2.1—Shrinkage-compensating cements
- 2.2—Aggregates
- 2.3—Water
- 2.4—Admixtures
- 2.5—Concrete

Chapter 3—Structural design considerations, p. 223-6

- 3.1—General
- 3.2—Restraint
- 3.3—Reinforced structural slabs
- 3.4—Reinforced slabs on grade
- 3.5—Post-tensioned structural concrete
- 3.6—Post-tensioned slabs on grade
- 3.7—Walls
- 3.8—Toppings
- 3.9—Formwork

ACI 223-98 became effective February 1, 1998.
Copyright © 1998, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietor.



Documents

Document Sharing Hub

Chapter 4—Concrete mix proportioning, p. 223-17

- 4.1—General
- 4.2—Concrete proportions
- 4.3—Admixtures
- 4.4—Consistency
- 4.5—Mix proportioning procedures

Chapter 5—Placing, finishing, and curing, p. 223-20

- 5.1—Placing
- 5.2—Finishing
- 5.3—Curing

Chapter 6—References, p. 223-21

- 6.1—Specified or recommended references
- 6.2—Cited references

Appendix A—Design of shrinkage-compensating concrete slabs, p. 223-23**Appendix B—Tensile strain capacity, p. 223-24****Appendix C—Application of shrinkage-compensating concrete in post-tensioned structures, p. 223-24**

- C.1—Volume change effects on different construction techniques
- C.2—Column moment reductions
- C.3—Expansion of structure
- C.4—Conclusions

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 $C_4A_3\bar{S}$ (where $C = CaO$, $A = Al_2O_3$, and $\bar{S} = SO_3$), calcium sulfate ($CaSO_4$), and lime (CaO). The $C_4A_3\bar{S}$ 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 $C_{12}A_7$), 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-handling, 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 (C_3A) 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 ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 - 30-32H_2O$) also written as $Ca_6[Al(OH)_6]_2 \cdot 24H_2O[(SO_4)_3 \cdot 1\frac{1}{2}H_2O]$; 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 SO_3) and usually, but not always, a higher percentage of aluminate (typically 5 to 9 percent total Al_2O_3). The free lime (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 $CaSO_4$ and the Al_2O_3 become available for ettringite formation during the appropriate period after the curing water is added. Determination of these proportions is based on the

Table 1—Types of shrinkage-compensating cements and their constituents

Expansive cement	Principal constituents	Reactive aluminates available for ettringite formation
K	(a) Portland Cement (b) Calcium sulfate (c) Portland-like cement containing $C_4A_3\bar{S}$	$C_4A_3\bar{S}$
M	(a) Portland cement (b) Calcium sulfate (c) Calcium-aluminate cement (CA and $C_{12}A_7$)	CA and $C_{12}A_7$
S	(a) Portland cement high in C_3A (b) Calcium sulfate	C_3A

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 SO_3 or Al_2O_3 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 CO_2 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 normalweight, 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 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 manufactured 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, etc. 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.

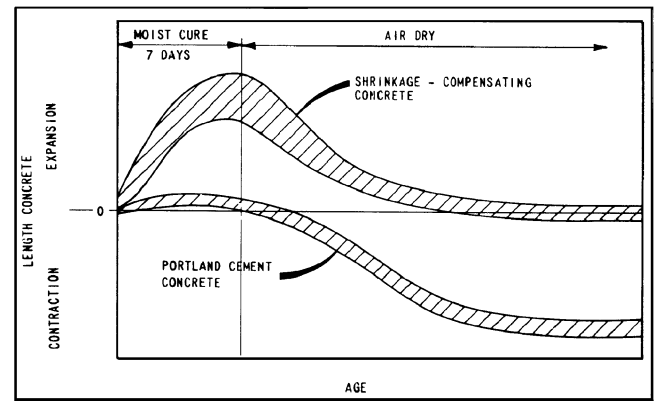


Fig. 2.5.3—Typical length change characteristics of shrinkage-compensating and portland cement concretes.

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 cement 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 2-1/2 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

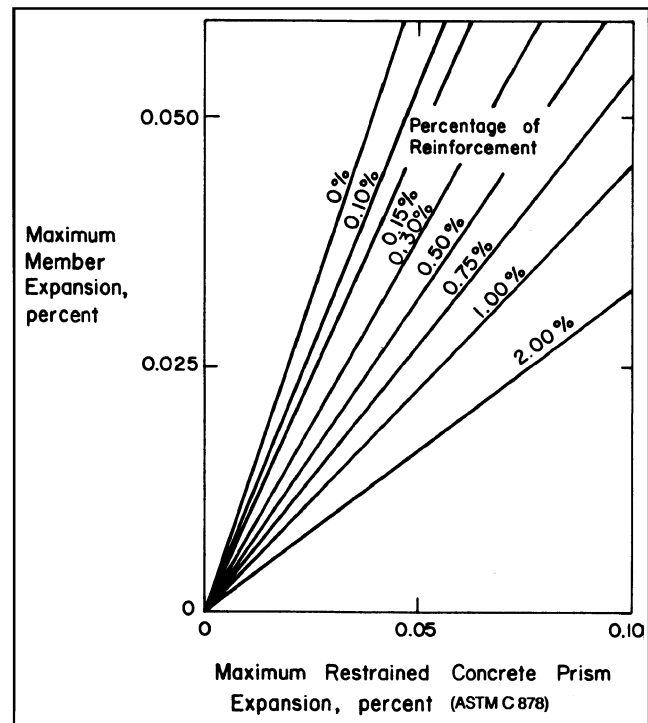


Fig. 3.2.3—Estimation of member expansion from prism data.

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 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.

Figure 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 ϵ_c .

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

Tensile force in steel = $\epsilon_c E_s A_s$

Compressive force in concrete = $\epsilon_c E_s A_s$

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

Total length change $\Delta = L \epsilon_c$

where

E_s = modulus of elasticity of steel

ρ = 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 29×10^6 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 attempting to counteract shrinkage. Concrete strain should stay expanded 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 conditions should be calculated using the procedure outlined in Appendix A.

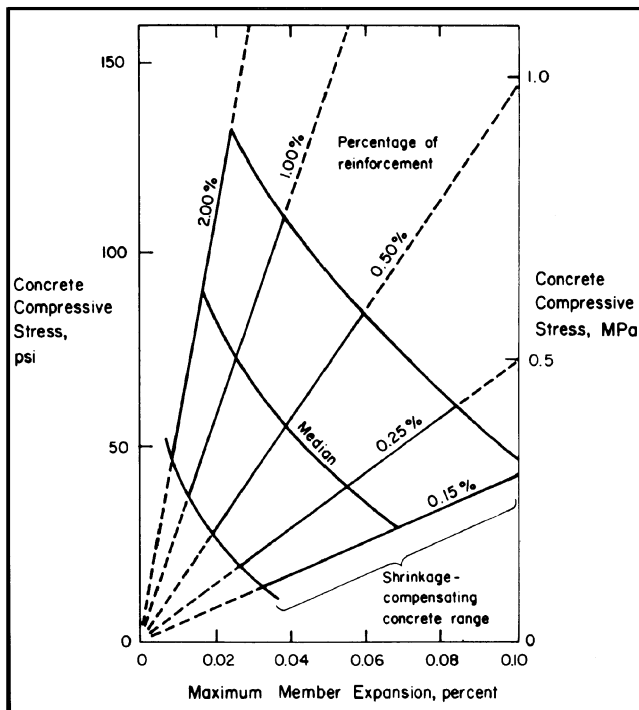


Fig. 3.3.1—Calculated compressive stresses induced by expansion.

or by other methods. In most situations, the specified 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 performance since a higher load is required to produce first cracking. 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 fewer cracks will occur in shrinkage-compensating reinforced concrete members. This has been confirmed in field observations (Randall, 1980; Rosenlund, 1980).

3.3.4 Cracking moment—The use of shrinkage-compensating concrete does not affect the flexural strength of reinforced 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 compressive stress in shrinkage-compensating concrete. By contrast, 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 shrinkage-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. Therefore, reinforcement in slabs on grade is primarily used to control crack widths caused by bending and drying shrinkage.

Research (Pfeifer, 1973; Pfeifer and Perenchio, 1973; Seeber et al., 1973; Spellman et al., 1973; Kesler, 1976; Russell, 1980) has shown that portland cement concrete has approximately 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 concrete, 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 effect indicates residual restrained expansive strains to be greater at the top surface than at the bottom, so reversed curling conditions develop. Warping stresses tend to be counterbalanced 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 the usual action, these joints shall be used to accommodate the initial