Control of Cracking in Concrete Structures

Reported by ACI Committee 224

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The principal causes of cracking and recommended crack-control procedures are presented. The current state of knowledge in microcracking and fracture of concrete is reviewed. The control of cracking due to drying shrinkage and crack control in flexural members, overlays, and mass concrete construction are covered in detail. Long-term effects on cracking are considered and crack-control procedures used in construction are presented. Information is presented to assist in the development of practical and effective crack-control programs for concrete structures. Extensive references are provided.

Keywords: aggregates; anchorage (structural); bridge decks; cement-aggregate reactions; concrete construction; concrete pavements; concrete slabs; cooling; corrosion; crack propagation; cracking (fracturing); crack width and spacing; drying shrinkage; shrinkage-compensating concrete; heat of hydration; mass concrete; microcracking; polymer-modified concrete; prestressed concrete; reinforced concrete; restraint; shrinkage; temperature; tensile stresses; thermal expansion; volume change.

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CHAPTER 3—CONTROL OF CRACKING DUE TO DRYING SHRINKAGE

3.1—Introduction

Drying shrinkage of concrete is the reduction in volume caused by the loss of water. Drying shrinkage can be defined as the time-dependent linear strain at constant temperature measured on an unloaded specimen that is allowed to dry. From a structural point of view, there is no need to separate drying shrinkage from other kinds of phenomena, such as carbonation shrinkage and autogenous shrinkage. A typical value for the final shrinkage strain of concrete in structures is 600×10^{-6}. Because the concrete tensile-strain capacity can be 150×10^{-6} or less, cracking will result if the shrinkage is restrained in a concrete member. There is a high degree of uncertainty in predicting shrinkage of concrete structures, however, because this property varies considerably with many parameters, including concrete composition, source of aggregate, ambient relative humidity, specimen geometry, and more specifically, the ratio of the exposed surface to the volume of the structural element. Further, the slow development of shrinkage over time makes it difficult to obtain an accurate prediction for a given concrete from short-term laboratory measurements. As a result, a coefficient variation of 20% or more can be expected in predicting long-term shrinkage.

Before true moisture equilibrium has been reached within a member cross section, internal shrinkage restraint occurs because of moisture gradients. Consequently, self-equilibrating internal stresses are present with tension on the surface and compression in the interior. This stress condition can cause cracking if not relieved by creep.

Shrinkage and creep are often responsible for excessive deflections and curvature, losses in prestress, and redistribution of internal stresses and reactions in statically indeterminate members. If not controlled, drying shrinkage can lead to serviceability problems, such as excessive deflections, and durability problems, such as freeze-thaw deterioration and corrosion at cracks.

Good design and construction practices can minimize the amount of cracking and eliminate or control the visible large cracks by minimizing the restraint using adequate reinforcement and contraction joints. Further information can be found in ACI 209R. Cracking due to drying shrinkage can never be eliminated in most structures. This chapter covers cracking of hardened concrete due to drying shrinkage, factors influencing shrinkage, control of cracking, and the use of expansive cements to minimize cracking. Construction practices and specifications to minimize drying shrinkage are covered in Chapter 8.

3.2—Cause of cracking due to drying shrinkage

The contraction (due to drying shrinkage) of a concrete component within a structure is always subject to some degree of restraint from either the foundation, another part of the structure, or the reinforcing steel embedded in the concrete. The combination of shrinkage and restraint develops tensile stresses within the concrete. Due to the inherent low tensile strength of concrete, cracking will often occur (Fig. 3.1).

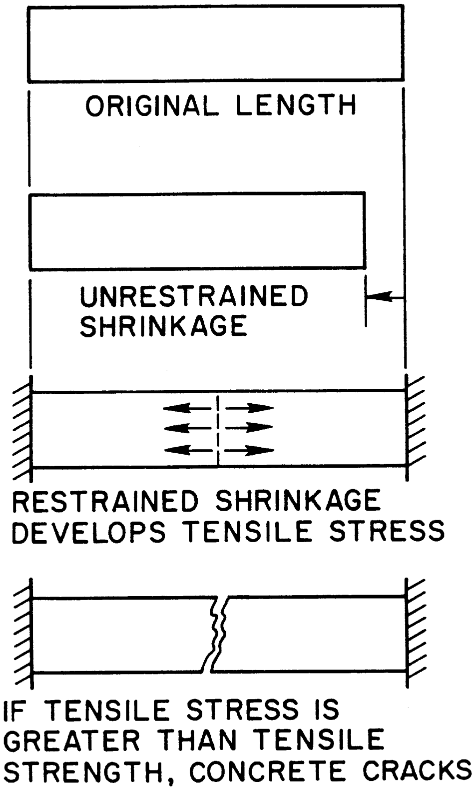


Fig. 3.1—Cracking of concrete due to drying shrinkage.

Additional restraint arises from nonuniform shrinkage. Because drying occurs nonuniformly from the surface towards the concrete core, shrinkage will create internal tensile stresses near the surface and compression in the core. Differential shrinkage can result in warping and surface cracks. The surface cracks can, with time, penetrate deeper into the concrete member as the interior portion is subject to additional shrinkage.

As illustrated in Fig. 3.2, the tensile stress induced by restraining drying shrinkage is reduced with time due to creep or stress relaxation. Cracks develop only when the net tensile stress reaches the tensile strength of concrete. The creep relief decreases with age, however, so that the cracking tendency becomes greater with increased time.

3.3—Drying shrinkage

When concrete dries, it contracts or shrinks. When it is wetted, it expands. The expansion does not occur to the same extent as shrinkage. These volume changes, along with changes in moisture content, are an inherent characteristic of hydraulic-cement concrete. The change in moisture content of cement paste causes concrete to shrink or swell. Aggregate reduces the unit volume of cement paste and provides an internal restraint that significantly reduces the magnitude of these volume changes in concrete.

In addition to drying shrinkage, the cement paste is also subject to carbonation shrinkage. Shrinkage results from the

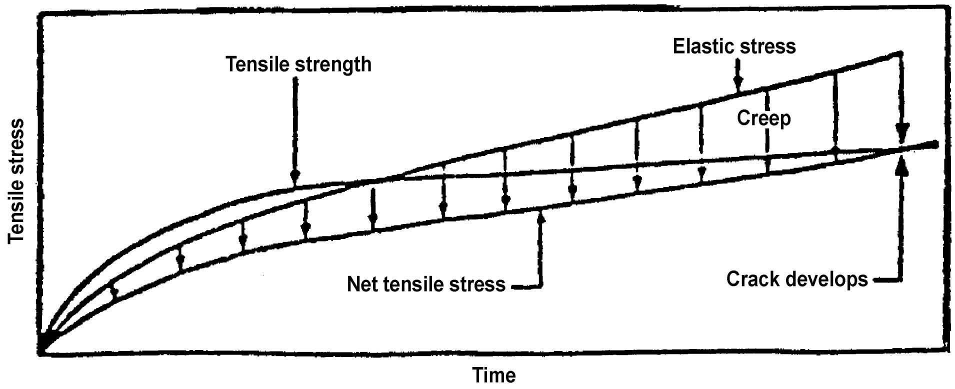


Fig. 3.2—Effect of creep on tensile stress.

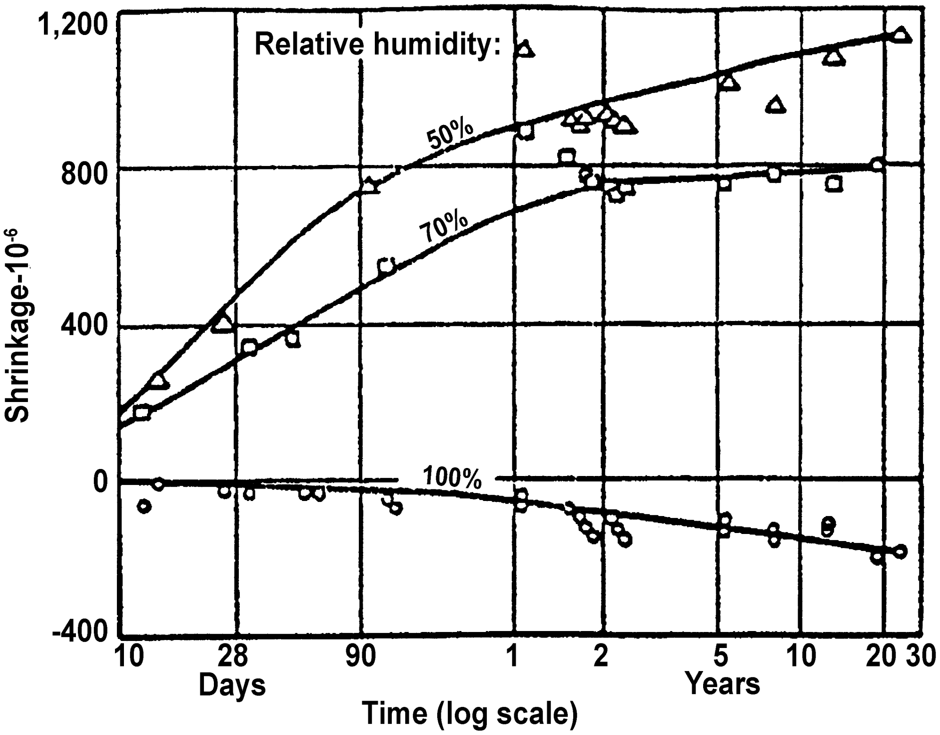


Fig. 3.3—Relations between shrinkage and time for concretes stored at different relative humidities. Time reckoned since end of wet curing at 28 days (Troxell, Raphael, and Davis 1958).

effects of carbon dioxide on the chemical changes of calcium-silicate hydrate and crystalline-hydration products and the drying of the pores by removing absorbed water. Calcium hydroxide will form calcium carbonate by reacting with atmospheric carbon dioxide. Because carbon dioxide does not penetrate more than about 12 mm (0.5 in.) into the surface of high-quality concrete with low porosity, carbonation shrinkage is of minor importance in the overall shrinkage of most concrete structures. Carbonation does, however, play an important role in the shrinkage of small laboratory test specimens and structures constructed with low-quality, porous concrete, particularly when subjected to long-term exposure to drying. The amount of carbonation shrinkage observed on a small laboratory specimen can be greater than the shrinkage of the concrete in the structure. This effect results from the greater surface area to volume ratio in smaller specimens. Shrinkage due to carbonation is discussed in detail by Verbeck (1958).

3.4—Factors controlling drying shrinkage of concrete

The major factors controlling ultimate drying shrinkage of concrete include relative humidity, aggregate type and content (or paste content), water content, and *w/cm*. The rate of moisture loss and shrinkage of a given concrete is influenced by the size of the concrete member, the relative humidity, distance from the exposed surface, and drying time.

3.4.1 *Relative humidity and drying time*—Relative humidity has a major influence on ultimate shrinkage and the rate of

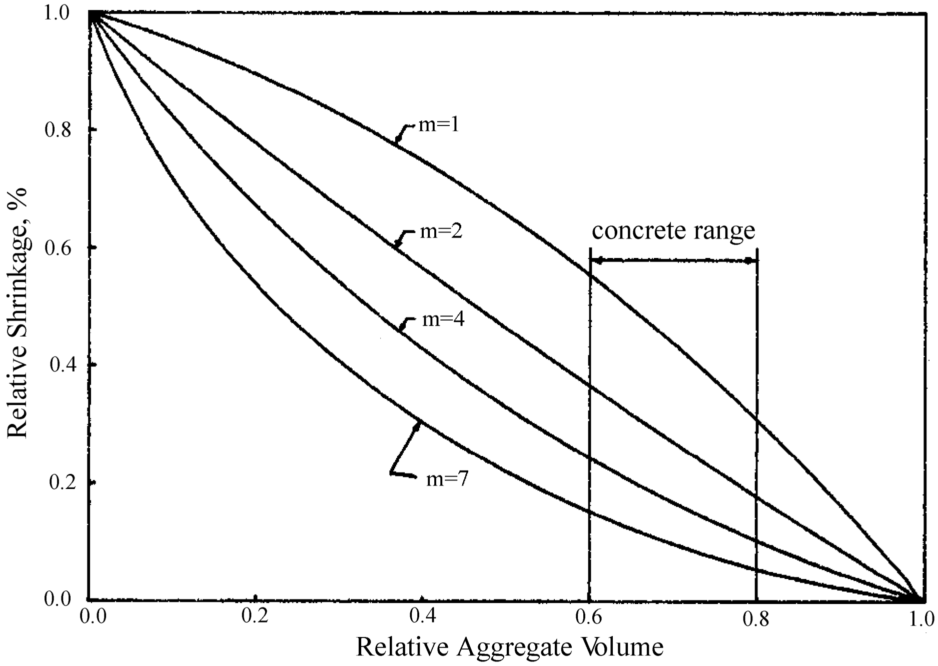


Fig. 3.4—Effect of relative aggregate content and modulus ratio on drying shrinkage of concrete (Hansen and Almudaiheem 1987).

Table 3.1—Effect of aggregate type on concrete shrinkage (after Carlson [1938])

Aggregate	Specific gravity	Absorption	1-year shrinkage, %
Sandstone	2.47	5.0	0.116
Slate	2.75	1.3	0.068
Granite	2.67	0.8	0.047
Limestone	2.74	0.2	0.041
Quartz	2.66	0.3	0.032

shrinkage. Results by Troxell, Raphael, and Davis (1958) showed that the lower the relative humidity, the greater the ultimate shrinkage and rate of shrinkage (Fig. 3.3). Figure 3.3 also illustrates that expansion occurs if concrete is exposed to a continuous supply of water; this process is known as swelling. Swelling is small compared with shrinkage in ordinary concrete and occurs only when the relative humidity is maintained above 94% (Lorman 1940). Swelling can, however, be significant in lightweight concrete (Neville and Brooks 1985). Figure 3.3 also shows that drying is a slow process. It can take many years before ultimate shrinkage is reached because the loss of water from hardened concrete is diffusion controlled.

3.4.2 *Influence of quantity and type of aggregate on shrinkage*—Concrete shrinkage is due primarily to shrinkage of the hardened cement paste. The presence of aggregate in concrete reduces the total shrinkage by providing elastic restraint to paste shrinkage. Concrete shrinkage, however, is not solely related to the relative aggregate content; there is another effect due to the ratio of elastic modulus of aggregate to that of the hydrated paste. When using high-quality aggregates, which are characterized mainly by low absorption capacity, this ratio is typically between four and seven (Hansen and Almudaiheem 1987). This is also illustrated in Fig. 3.4, where an elastic modulus ratio between 1 and 2 indicates an aggregate stiffness that is much smaller than that of normalweight aggregate.

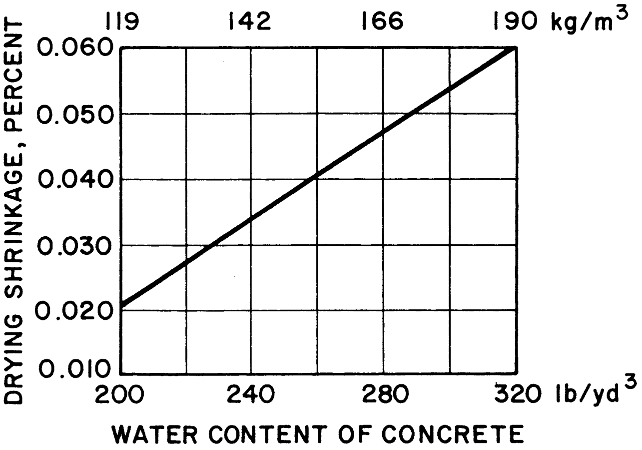


Fig 3.5—Typical effect of water content of concrete on drying shrinkage (USBR 1981).

Pickett (1956) and Hansen and Almudaiheem (1987) developed constitutive models for predicting the influence of relative aggregate content and modulus ratio on ultimate concrete shrinkage. The latter model clearly explains why lightweight concrete for the same relative aggregate content exhibits considerably more shrinkage than ordinary concrete. This is also illustrated in Fig. 3.4 when the modulus ratio is between one and two because the aggregate stiffness is much smaller than that of normalweight aggregate.

The influence of aggregate-absorption capacity on concrete shrinkage was investigated by Carlson (1938) and is illustrated

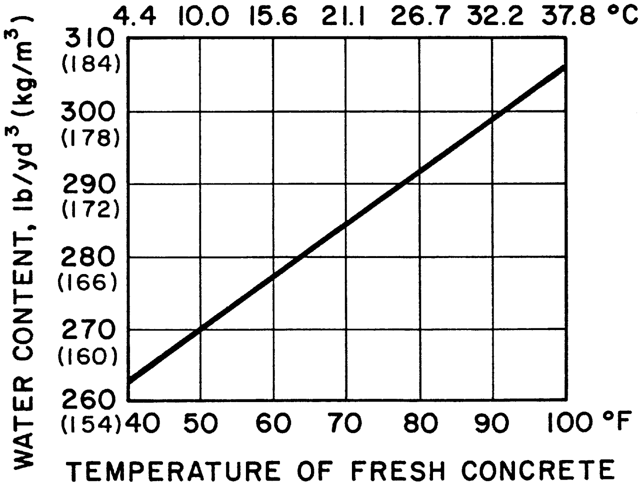


Fig. 3.6—Effect of temperature of fresh concrete on its water requirement (USBR 1981).

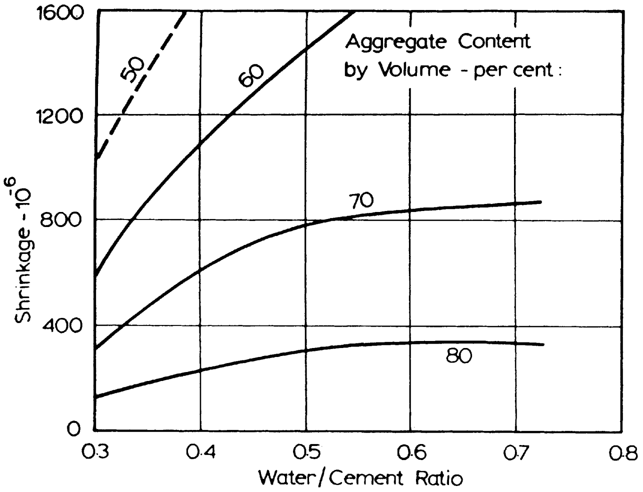


Fig. 3.7—Influence of w/c *and aggregate content on shrinkage (Odman 1968).*

in Table 3.1; the concrete had identical cements and *w/cm*s. The absorption of an aggregate, which is a measure of porosity, influences its modulus or compressibility. A low elastic modulus is usually associated with high absorption.

Quartz, limestone, dolomite, granite, feldspar, and some basalts can be classified as higher-modulus aggregates, which result in lower shrinkage properties of concrete. High-shrinkage concrete often contains sandstone, slate, hornblende, and some types of basalts. Because the rigidity of certain aggregates, such as granite, limestone, or dolomite, can vary over a wide range, their effectiveness in restraining drying shrinkage varies.

Although compressibility is the most important property of aggregate governing concrete shrinkage, the aggregate itself can shrink during drying. This is true for sandstone and other aggregates of high-absorption capacity. In general, aggregate with a high modulus of elasticity and low absorption will produce a concrete with low ultimate shrinkage.

3.4.3 *Paste content and* w/cm—Consistency, as measured by the slump test, is an important parameter in proportioning concrete. The amount of mixing water needed to achieve a given slump is dependent on the maximum aggregate size used because the maximum size influences the total aggregate surface area that needs to be covered with cement paste. Decreasing maximum aggregate size increases the total surface area to be covered with paste. Therefore, more water and cement are needed to achieve a given slump. For the same *w/cm*, concrete shrinkage increases with increasing water content because the paste volume increases; this agrees with the predictions in Fig. 3.4 and results obtained by the U.S. Bureau of Reclamation (1975) shown in Fig. 3.5. For a constant *w/cm*, there is an approximately linear relationship between water content (paste content as well) and concrete shrinkage within the range of water contents listed. Temperature also has an influence on the water requirements of the fresh concrete for same slump (Fig. 3.6). A reduction in water content, which reduces the paste content, will reduce the ultimate drying shrinkage of concrete. Therefore, the water content (and paste content) of a concrete mixture should be kept to a minimum to minimize potential drying shrinkage and the cracking tendency of the concrete.

Figure 3.7 illustrates that concrete shrinkage increases with *w/cm* for a given aggregate content. This effect is more pronounced with lower aggregate contents (Odman 1968).

3.4.4 *Influence of member size*—The size and shape of a concrete member and the porosity of the cement paste influences the drying rate of concrete and, therefore, influences the shrinkage rate. The shape affects the ratio of the surface area to volume of the member, and a higher ratio results in a higher drying rate. For a given concrete, the observed shrinkage at a given time decreases with an increase in the size of the specimen. This effect is illustrated in Fig. 3.8 (Bryant and Vadhanavikkit 1987) in which long-term shrinkage results were obtained on concrete prisms up to 400 mm (8 in.) thick. Ultimate shrinkage may not be reached for structural members during the intended service life.

Another consequence of moisture diffusion is that a moisture gradient develops from the surface to the interior. For a specimen that has moisture evaporation from all surfaces, shrinkage strain is greatest at the surface where moisture content is lowest, and shrinkage strain decreases toward the center where moisture content is highest. Nonuniform self-equilibrating internal stresses develop. Tensile stresses occur at and near the surfaces and compressive stresses develop at and near core, as shown in Fig. 3.9.

Warping occurs if drying takes place in an unsymmetrical manner, either due to drying from one side or due to a nonsymmetrical structure. In slabs-on-grade, the warping mechanism is a primary cause of cracking. Moisture evaporates from the top surface only, which causes higher shrinkage at the top. The concrete near the top surface is partially restrained from shrinking because it is attached to concrete lower in the slab that is more moist and does not shrink as much as the top surface. This restraint produces tensile stresses at and near the top surface, which results in the slab warping or curling, and the free edges of the slab can lift off

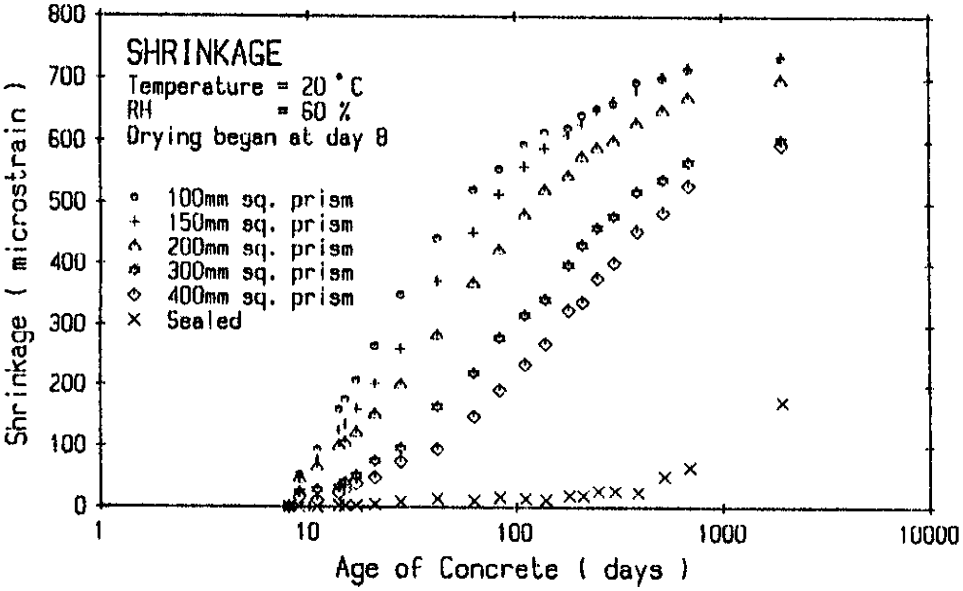
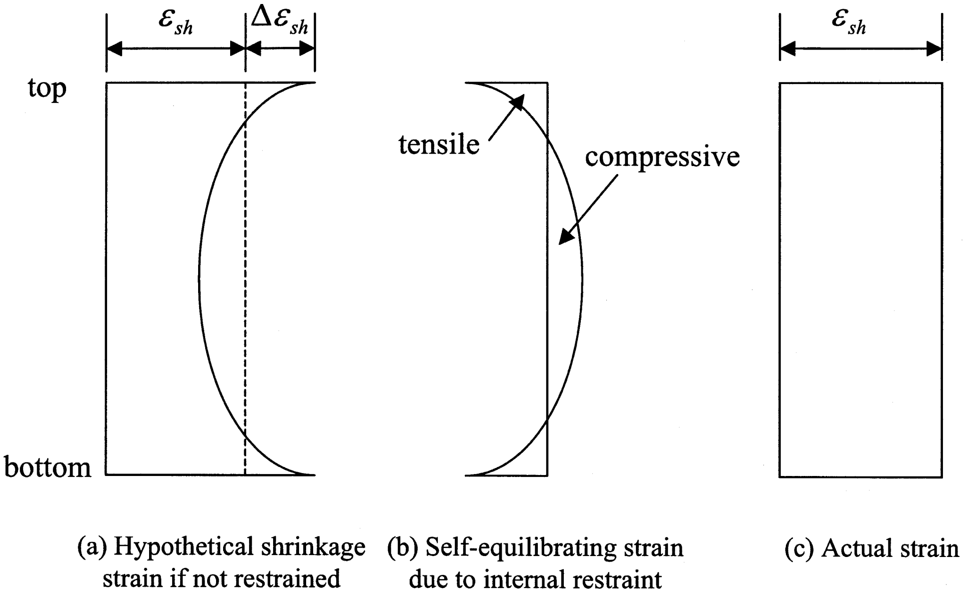


Fig. 3.8—Influence of specimen size on shrinkage (Bryant and Vadhanavikkit 1987).



(a) Hypothetical shrinkage strain if not restrained (b) Self-equilibrating strain due to internal restraint (c) Actual strain

Fig 3.9—Internal restraint of shrinkage.

the ground. If the edges of the slab are restrained from movement, such as footings, and the slab is not allowed to warp, then the top surface has higher tensile stresses. Cracking can result if the tensile stresses from restrained shrinkage exceed the tensile strength of the concrete. Cracking may also result near the edge of the slab when a vertical load is applied on the warped cantilever.

3.4.5 *Effect of curing on shrinkage*—Carlson (1938) reported that the duration of moist curing of concrete does not have much effect on ultimate drying shrinkage. Test results from the California Department of Transportation (1963) show that substantially the same shrinkage occurred in concrete that was moist-cured for 7, 14, and 28 days before drying started. As far as the cracking tendency of the concrete is concerned, prolonged moist curing may not be beneficial. A general recommendation is to continue moist curing for at least 7 days. (For further information, refer to ACI 309.)

Sealed curing is curing without loss or addition of water. It eliminates other kinds of shrinkage so that all the resulting shrinkage will be autogenous. Autogenous shrinkage is a result of the fact that the products of hydration occupy a smaller volume than the original volume of cement and water. Self-dessication is a problem in low *w/c* concretes under sealed conditions in which the pores dry out and hydration slows down. Autogenous shrinkage strain is typically about 40 to 100×10^{-6} (Davis 1940). Houk, Paxton, and Houghton (1969) found that autogenous shrinkage increases with increasing temperature, cement content, and cement fineness.

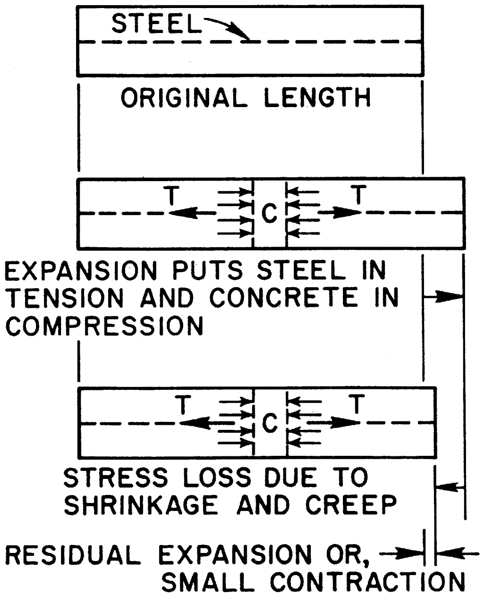


Fig. 3.10—Basic concept of shrinkage-compensating concrete.

3.4.6 *Effect of admixtures*—The effect of admixtures on concrete shrinkage is unclear. As an example, early-age shrinkage appears to increase by about 100% in the presence of calcium chloride, whereas later-age shrinkage is increased by about 40% compared with control specimens (ACI 212.3R).

Air-entrainment does not seem to increase shrinkage by more than 10% for air contents up to about 5% (Carlson 1938).

Results by Ghosh and Malhotra (1979), Brooks, Wainwright, and Neville (1979), and Feldman and Swenson (1975) indicated that the use of high-range water-reducing admixtures increases shrinkage. According to Ytterberg (1987), high-range water-reducing admixtures do not necessarily reduce shrinkage in proportion to their ability to reduce water content.

3.5—Control of shrinkage cracking

Concrete tends to shrink due to drying whenever its surfaces are exposed to air of low relative humidity or high winds. Because various kinds of restraint prevent the concrete from contracting freely, cracking should be expected, unless the ambient relative humidity is kept near 100%. The control of cracking consists of reducing the cracking tendency to a minimum, using adequate and properly positioned reinforcement, and using contraction joints. The CEB-FIP Model Code (1990) gives quantitative recommendations on the control of cracking due to shrinkage by listing various coefficients to determine the shrinkage levels that can be expected. Control of cracking by correct construction practices is covered in Chapter 8.

Cracking can also be minimized by using expansive cements to produce shrinkage-compensating concrete. This is discussed in Section 3.6.

3.5.1 *Reduction of cracking tendency*—Most measures that can be taken to reduce concrete shrinkage will also reduce the cracking tendency. Drying shrinkage can be reduced by using less water in the mixture and the largest practical maximum-size aggregate. A lower water content can be achieved by using a well-graded aggregate, stiffer consistency, and lower initial temperature of the concrete.

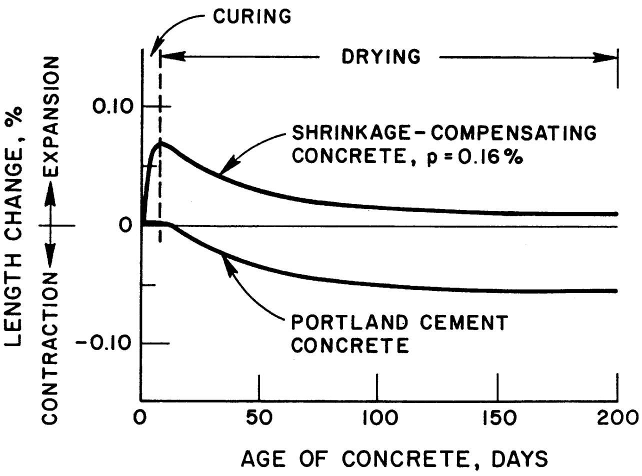


Fig. 3.11—Length-change characteristics for shrinkage-compensating and portland cement concrete (relative humidity = 50%).

Concrete can withstand higher tensile strains if the stress is slowly applied; therefore, it is desirable to prevent rapid drying of concrete. Prevention of rapid drying can be attained by using curing compounds, even after water curing.

3.5.2 *Reinforcement*—Properly placed reinforcement, used in adequate amounts, will reduce the number and widths of cracks, reducing unsightly cracking. By distributing the shrinkage strains along the reinforcement through bond stresses, the cracks are distributed so that a larger number of narrow cracks occur instead of a few wide cracks. Although the use of reinforcement to control cracking in a relatively thin concrete section is practical, it is not needed in massive structures, such as dams, due to the low drying shrinkage of these mass concrete structures. The minimum amount and spacing of reinforcement to be used in structural floors, roof slabs, and walls for control of temperature and shrinkage cracking is given in ACI 318 or in ACI 350R. The minimum-reinforcement percentage, which is between 0.18 and 0.20%, does not normally control cracks to within generally acceptable design limits. To control cracks to a more acceptable level, the percentage requirement needs to exceed about 0.60%.

3.5.3 *Joints*—The use of joints is the an effective method of preventing the formation of unsightly cracking. If a sizeable length or expanse of concrete, such as walls, slabs, or pavements, is not provided with adequate joints to accommodate shrinkage, the concrete will make its own joints by cracking.

Contraction joints in walls are made, for example, by fastening wood or rubber strips to the form, which leave narrow vertical grooves in the concrete on both faces of the wall. Cracking of the wall due to shrinkage should occur at the grooves, relieving the stress in the wall and preventing the formation of unsightly cracks between the joints. These grooves should be sealed to prevent moisture penetration.

Sawed joints are commonly used in pavements and slabs-on-grade. Joint location depends on the particulars of placement. Each element should be studied individually to determine where the joints should be placed. ACI 224.3R discusses the use of joints in concrete construction. Guidance on joint sealants and contraction joint location in slabs is available in ACI 504R and ACI 302.1R.

3.6—Shrinkage-compensating concrete

Shrinkage-compensating concrete made with expansive cements can be used to minimize or eliminate shrinkage cracking. The properties and use of expansive cement concrete are summarized in ACI 223, ACI 223 (1970), ACI SP-38, and ACI SP-64. Of the several expansive cements produced in the past, Type K shrinkage-compensating cement (ASTM C 845) is currently the only one available in the United States. Several component materials are available to produce shrinkage-compensating concrete.

In reinforced shrinkage-compensating concrete, the expansion of the cement paste during the first few days of hydration will develop a low level of prestress, inducing tensile stresses in the steel and compressive stresses in the concrete. The level of compressive stresses developed in the shrinkage-compensating concrete ranges from 0.2 to 0.7 MPa (25 to 100 psi). Normal shrinkage occurs when water starts to evaporate from the concrete. The contraction of the concrete will result in a reduction or elimination of its precompression. The initial expansion of the concrete reduces the magnitude of any tensile stress that develops due to restrained shrinkage. This basic concept of using expansive cement to produce a shrinkage-compensating concrete is illustrated in Fig. 3.10. To allow for adequate expansion, special details may be needed at joints.

A typical length-change history of a shrinkage-compensating concrete is compared to that of a portland cement concrete in Fig. 3.11. The amount of reinforcing steel normally used in reinforced concrete made with portland cements is usually more than adequate to provide the elastic restraint needed for shrinkage-compensating concrete. To take full advantage of the expansive potential of shrinkage-compensating concrete in minimizing or preventing shrinkage cracking of exposed concrete surfaces, it is important that positive and uninterrupted water curing (wet covering or ponding) be started immediately after final finishing. For slabs on well-saturated subgrades, curing by sprayed-on membranes or moisture-proof covers has been successfully used. Inadequate curing of shrinkage-compensating concrete can result in an insufficient expansion to elongate the steel and subsequent cracking from drying shrinkage. Specific recommendations and information on the use of shrinkage-compensating concrete are contained in ACI 223R.