Report on Factors Affecting Shrinkage and Creep of Hardened Concrete

Reported by ACI Committee 209

David B. McDonald[*]
Chair

W. Jason Weiss
Secretary

Akthem A. Al-Manaseer[*]
Zdenek P. Bazant
Jeffrey J. Brooks
Ronald G. Burg[*]
Domingo J. Carreira

Mario A. Chiorino
Marwan A. Daye
Walter H. Dilger
N. John Gardner[*]
Will Hansen

Mohsen A. Issa
Hesham Marzouk
Baquan Miao
Harald S. Mueller
Lawrence C. Novak

Klaus A. Rieder
Ian Robertson
Kenji Sakata
Nam K. Shiu
Carlos Videla

*Members of subcommittee that prepared this report.

This guide describes the effects of numerous variables on shrinkage and creep of hardened concrete, including mixture proportions, environment, design, and construction. This document is aimed at designers who wish to gain further information about factors changing shrinkage and creep but does not include information on the prediction of shrinkage and creep or structural design issues associated with shrinkage and creep.

Keywords: creep; drying shrinkage; strain.

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CHAPTER 1—INTRODUCTION

1.1—Scope

Factors affecting shrinkage and creep of hardened concrete are presented to enable those involved in the evaluation and formulation of concrete mixtures to determine the effects of these factors. Section 1.2 of Chapter 1 defines terms used by those evaluating shrinkage and creep, while Chapters 2 and 3 describe effects of various factors on shrinkage and creep. This document does not include information on the prediction of shrinkage and creep or structural design issues associated with shrinkage and creep.

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This document is not intended as a primary reference source for those studying shrinkage and creep; rather, it is aimed at designers who wish to gain further understanding of the effects of materials being used. This document also provides references that provide direction for those wishing to seek additional information about shrinkage and creep.

1.2—Terminology and range of values of strains

To discuss shrinkage and creep, it is important to define the following terms:

- Total strain;
- Shrinkage;
- Autogenous shrinkage;
- Drying shrinkage;
- Carbonation shrinkage;
- Swelling;
- Load-induced strain;
- Initial strain at loading or nominal elastic strain;
- Creep strain;
- Basic creep;
- Drying creep;
- Compliance;
- Specific creep; and
- Creep coefficient.

Various terms are shown in Fig. 1.1 and are described in detail below, together with an indication of typical value ranges. The values of total strain, shrinkage, and creep are time-dependent. A thorough discussion of definitions, basic assumptions, and standard test methods for creep and shrinkage can be found in the references (RILEM TC 107-CSP 1998; Carreira and Burg 2000).

Shrinkage and creep may occur in three dimensions; however, most research suggests that total strain, shrinkage, and creep occur in each dimension independently. Thus, changes in length will be consistently used throughout this document, rather than changes in volume.

1.2.1 *Total strain*—Total strain is the total change in length per unit length measured on a concrete specimen subjected to a sustained constant load at uniform temperature. As shown in Fig. 1.1, total strain is the sum of shrinkage and load-induced strain.

1.2.2 *Shrinkage*—Shrinkage is the strain measured on a load-free concrete specimen.

Shrinkage does not include changes in length due to temperature variations, but depends on the environment and on the configuration and size of the specimen. Shrinkage strain is usually measured by casting companion load-free specimens identical to the loaded concrete specimens used to measure the total strain. These companion specimens are cast from the same concrete batch, have the same dimensions, and are stored in the same environment as the loaded concrete specimens.

Shrinkage values are given as dimensionless strains (length change over a given length) expressed as percent, mm/mm, or in./in. It is common to describe shrinkage in microstrain or millionths, as the value of strain $\times 10^6$. Thus, 1000 microstrain is equivalent to 1×10^{-3} mm/mm.

Values of long-term concrete shrinkage are typically between 200 and 800×10^{-6} mm/mm, (200 to 800 microstrain) (Zia, Ahmad, and Leming 1997) and mortar shrinkage typically between 800 and 2000×10^{-6} mm/mm (800 and 2000 microstrain) (Heath and Roesler 1999). Cement paste

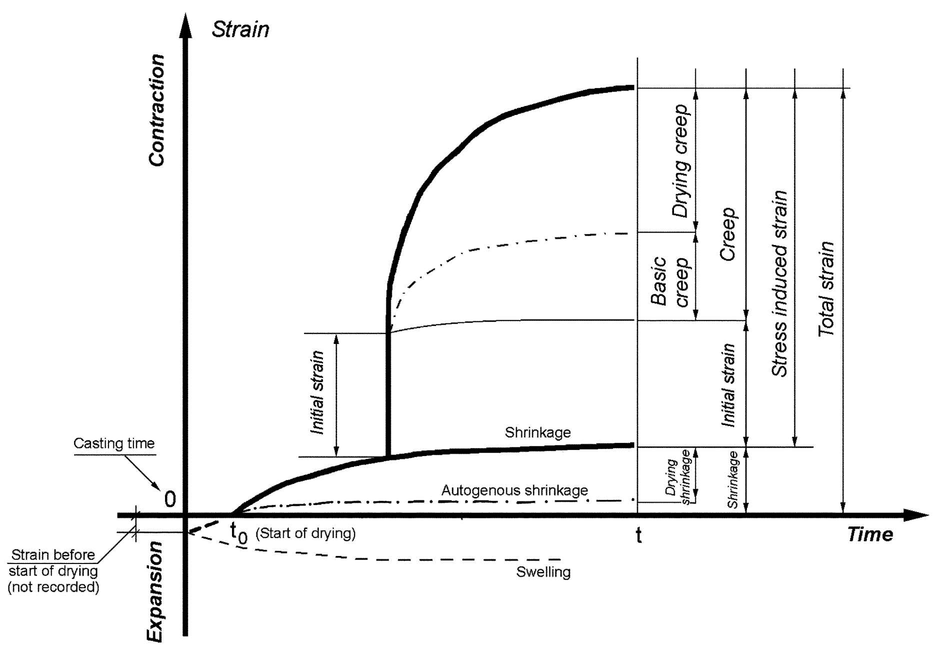

Fig. 1.1—Relationship between various measured and derived strain values. The figure shows that the concrete undergoes autogenous shrinkage before drying. Once drying commences at time t_0*, drying shrinkage occurs. Upon loading, both drying and basic creep occurs in the drying specimen.*

shrinkage values are typically between 2000 and 6000 × 10^{-6} mm/mm (2000 and 6000 microstrain) (Feldman 1969).

1.2.3 *Autogenous shrinkage*—The shrinkage occurring in the absence of moisture exchange (as in a sealed concrete specimen) due to the hydration reactions taking place inside the cement matrix is termed autogenous shrinkage. Less commonly, it is termed "basic shrinkage" or "chemical shrinkage." Autogenous shrinkage was almost never considered as a factor in research on shrinkage and creep before 1990, and it has become a greater factor with the increased use of high-performance concrete. Factors affecting, and the prediction of autogenous shrinkage, are outside the scope of this report. As development of research continues in this area, ACI Committee 209 will present additional information.

Autogenous shrinkage is usually small for many normal compressive strength concretes and can usually be neglected. For concrete with water-cement ratios (*w/c*) less than 0.40, however, autogenous shrinkage may be a significant component of the total measured shrinkage (Tazawa 1999).

1.2.4 *Drying shrinkage*—Shrinkage occurring in a specimen that is exposed to the environment and allowed to dry is called drying shrinkage. For normal-strength concrete, it is usually assumed that the entire shrinkage strain is from drying shrinkage, and any contribution from autogenous shrinkage is neglected. Because drying shrinkage involves moisture movement through the material and moisture loss, drying shrinkage depends on the size and shape of the specimen.

Due to the relationship of drying shrinkage to water loss, it may be expected to reach a final value; although, this is difficult to be confirmed experimentally due to the long duration of the drying process in normal size specimens (RILEM TC 107 1995; Al-Manaseer, Espion, and Ulm 1999; Bazant 1999). A final value has been documented for specimens of hardened cement paste thin enough to dry to an equilibrium water content (Wittman et al. 1987).

1.2.5 *Carbonation shrinkage*—Carbonation shrinkage is caused by the reaction of the calcium hydroxide within the cement matrix with carbon dioxide in the atmosphere. Factors affecting, and the prediction of carbonation shrinkage, are outside the scope of this report.

1.2.6 *Plastic shrinkage*—Plastic shrinkage is defined by ACI 116R as the shrinkage that takes place before cement paste, mortar, grout, or concrete sets. Plastic shrinkage is outside the scope of this report.

1.2.7 *Swelling*—When concrete is placed in water it swells, which has been attributed to reduced capillary forces within the concrete (Kovler 1996). Few research studies have closely recorded the magnitude of swelling and studied the factors affecting the magnitude of this phenomenon. The expansion strain due to swelling is approximately 100 × 10^{-6} mm/mm (100 microstrain) (McDonald 1990).

1.2.8 *Load-induced strain*—Load-induced strain is the time-dependent strain due to a constant sustained load applied at the age t'. Experimentally, it is obtained by subtracting from the total strain the shrinkage strain measured on load-free companion specimens with the same size and shape as the loaded specimens and placed in the same environment. The load-induced strain is frequently subdivided into an initial strain and a creep strain. The initial and creep strain components should be defined consistently so that their sum corresponds to the appropriate load-induced strain (CEB 1993; RILEM TC 107 1995; Bazant and Baweja 2000; Carreira and Burg 2000).

1.2.9 *Initial strain at loading or nominal elastic strain*—The short-term strain at the moment of loading is termed initial strain and is frequently considered as a nominal elastic strain as it contains creep that occurs during the time taken to measure the strain. It is dependent on the duration of the load application and strain reading procedures. The separation of this initial component of the load-induced strain is made for convenience, and it may be determined using standardized procedures for the experimental determination of a static elastic modulus (corresponding to the strain in a short interval after load application) (CEB 1993; RILEM TC 107-CSP 1998; Bazant and Baweja 2000; Carreira and Burg 2000). ASTM C 469 is often used to determine this value. In this test, the initial strain corresponds to a load duration of 0.01 day (approximately 15 min) (Carreira and Burg 2000).

Although often done by researchers, the committee recommends that the strain should not be separated into initial and creep strains, due to the loading rate factors that affect the estimated initial strain at loading.

1.2.10 *Creep strain*—Creep strain represents the time-dependent increase in strain under sustained constant load taking place after the initial strain at loading. It is obtained from the load-induced strain by subtracting the initial strain defined in Section 1.2.9. The creep strain may be several times greater than the initial strain. Creep strain may be subdivided into a drying and a nondrying component, termed drying and basic creep, respectively.

1.2.11 *Basic creep*—Basic creep is the time-dependent increase in strain under sustained constant load of a concrete specimen in which moisture losses or gains are prevented (sealed specimen). It represents the creep at constant moisture content with no moisture movement through the material, and is consequently independent of the specimen size and shape.

To determine basic creep, it is necessary to measure the deformations of a set of sealed specimens under constant load and to determine the total strain; and, if autogenous shrinkage cannot be neglected, deformations of companion sealed, load-free specimens should be measured. It has not been determined whether basic creep approaches a final value, even after 30 years of measurement of sealed specimens (Bazant 1975; CEB 1993).

1.2.12 *Drying creep*—Drying creep is the additional creep occurring in a specimen exposed to the environment and allowed to dry. As it is caused by the drying process, drying creep depends on the size and shape of the specimen and may be expected to show a limiting value at long term (RILEM TC 107 1995; Al-Manaseer, Espion, and Ulm 1999; Bazant 1999; Bazant and Baweja 2000).

Three sets of specimens are required to determine the drying creep: a loaded set that is allowed to dry to determine the total strain, a loaded set of sealed specimens to determine basic creep, and a load-free set at drying to determine the total shrinkage strain (Carreira and Burg 2000). This is mathematically described in Eq. (1-1).

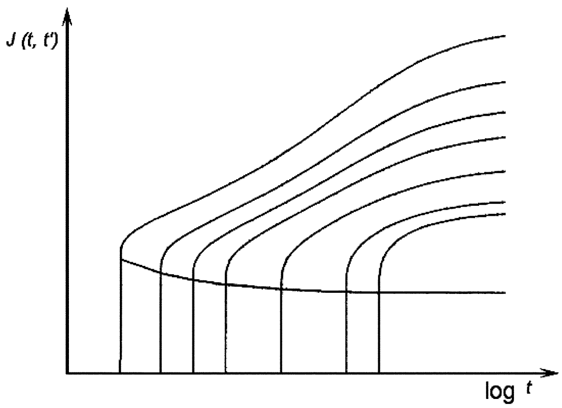

Fig. 1.2—Typical shape of a compliance for different ages at loading t′ *(logarithmic scale for time). The line through the curves indicates the initial elastic strain, which decreases with concrete age.*

$$\text{drying creep} = \text{total strain of drying specimen} - \text{total strain of sealed specimen} - \text{shrinkage of drying specimen} \quad (1\text{-}1)$$

1.2.13 *Compliance*—The compliance $J(t, t')$ describes the time-dependent strain at age t caused by a unit uniaxial sustained load applied since loading age t'. As a result of the previous definitions, the compliance is given by Eq. (1-2).

$$J(t,t') = \frac{\text{total strain} - \text{drying-shrinkage strain} - \text{autogenous shrinkage strain}}{\text{stress}} \quad (1\text{-}2)$$

where t = age of the concrete, and t' = age of the concrete at loading.

Values of compliance are given in units of 1/MPa or 1/psi. They range from 30 to 300 microstrain/MPa (0.20 to 2.00 microstrain/psi) (Bazant and Baweja 2000).

It is recommended that all the information for the prediction of the time-dependent-load-induced strains should be conveyed through the use of compliance (CEB 1993; RILEM TC 107 1995; Bazant and Baweja 2000; Gardner and Lockman 2001). Typical compliance for different values of age at loading t' are presented in Fig. 1.2 using a logarithmic scale for time.

1.2.14 *Specific creep*—Specific creep is defined as the creep strain per unit load and can be calculated as shown in Eq. (1-3).

$$\text{specific creep} = \frac{\text{creep strain}}{\text{stress}} \quad (1\text{-}3)$$

$$= \frac{\text{total strain} - \text{autogenous shrinkage} - \text{drying shrinkage} - \text{initial strain}}{\text{stress}}$$

The value of specific creep depends highly on the value of the initial strain estimated as part of the testing procedure and is not recommended by the committee.

1.2.15 *Creep coefficient*—The creep coefficient is defined as the ratio of the creep strain to the initial strain or, identically, as the ratio of the creep compliance to the compliance obtained at early ages, such as after 2 min. By definition, the creep coefficient is dimensionless.

The creep coefficient may be determined from compliance and from the nominal elastic modulus of the concrete, as shown in Eq. (1-4). Typical values of creep coefficient for long periods under sustained constant loading range from 1.2 (very low creep) to 6 (very high creep) (Gardner 2000).

$$\nu(t,t') = E(t') \cdot J(t,t') - 1 \quad (1\text{-}4)$$

where $\nu(t,t')$ = creep coefficient; $E(t')$ = elastic modulus at time t'; and $J(t,t')$ = compliance.

The creep coefficient is sensitive to the value assumed for $E(t')$, which depends on the time assumed for complete loading to occur. Care should be taken when using the creep coefficient due to the subdivision of the two components of the strain from which it is defined.

1.3—Mechanisms of shrinkage and creep

It is generally understood that shrinkage of concrete is a result of induced capillary forces occurring during drying (Lane, Scott, and Weyers 1997). Mechanisms and theories describing creep of concrete, however, are complex and not fully developed or understood. Several of the major theories are outlined below, and readers are directed to these sources for additional information.

A report issued by ACI Committee 209 in 1972 (ACI Committee 209 1972) summarized the different proposed mechanisms as:

- Viscous flow of the cement matrix caused by sliding or shear of the gel particles lubricated by layers of adsorbed water;
- Consolidation due to seepage in the form of adsorbed water or the decomposition of interlayer hydrate water;
- Delayed elasticity due to the cement matrix acting as a restraint on the elastic deformation of the skeleton formed by the aggregates; this component accompanies viscous flow and consolidation; and
- Permanent deformation caused by local fracture (microcracking and crystal failure) and recrystalization and formation of new physical bonds.

Neville, Dilger, and Brooks (1983) classified six basic theories:

- Mechanical deformation theory;
- Viscous flow;
- Plastic flow;
- Seepage of gel water;
- Delayed elasticity; and
- Microcracking.

Bazant (1999) identified seven mechanisms that allow making inferences for the proper mathematical form of the creep and shrinkage prediction model:

- Solidification as a mechanism of aging, particularly at early times;
- Microprestress relaxation as a mechanism of long-time aging;
- Bond ruptures caused by stress-influenced thermal excitations controlled by activation energy;

- Diffusion of pore water;
- Surface tension, capillarity, free and hindered adsorption, and disjoining pressure;
- Cracking caused by self-equilibrated stresses and applied load; and
- Chemical processes causing autogenous volume change and microprestress.

Further information on mechanisms influencing shrinkage and creep of concrete may be found in the references (Bazant 1986, 1988; Bazant and Carol 1993; Ulm, Le Maou, and Boulay 1999).

1.4—Areas of recommended research

The committee believes that the following factors affecting shrinkage and creep require additional study:

- Effects of aggregate;
- Characteristics and composition of cement;
- Effect of chemical and mineral admixtures;
- Effect of curing period;
- Effect of drying before loading to determine creep;
- Behavior of high-performance concrete; and
- Effect of outdoor exposures.

1.5—Additional sources

There are hundreds of studies and reports on the shrinkage and creep of concrete, mortar, and cement paste. This document is not intended to be a complete review of all references, but a guide document. ACI Committee 209 has produced two bibliographies on shrinkage and creep titled "Shrinkage and Creep in Concrete," Bibliography No. 7 (1965) and Bibliography No. 10 (1972). Bibliography No. 7 covers references from 1905 to 1965, while Bibliography No. 10 covers references from 1966 to 1970. While these references are not directly available from the American Concrete Institute, they may be found in cement and concrete or engineering reference libraries, such as that of the Portland Cement Association, and are considered invaluable basic resources for research in shrinkage and creep.

CHAPTER 2—FACTORS AFFECTING DRYING SHRINKAGE

2.1—Introduction

There are many factors that affect the magnitude and rate of drying shrinkage of concrete. Methods for reducing drying shrinkage are described below.

2.2—Effect of mixture proportions on drying shrinkage

The drying shrinkage of a given concrete mixture is governed by the shrinkage of the cement paste and the quantity and properties of the aggregate.

2.2.1 *Quantity of aggregate*—The most important factor in affecting the potential shrinkage of concrete is the total volume of aggregate in a mixture, as the aggregate restrains shrinkage of the cement paste. It has been found (Pickett 1956) that shrinkage of concrete S_C is related to shrinkage of the cement paste S_P and the volume of the aggregate content g according to Eq. (2-1).

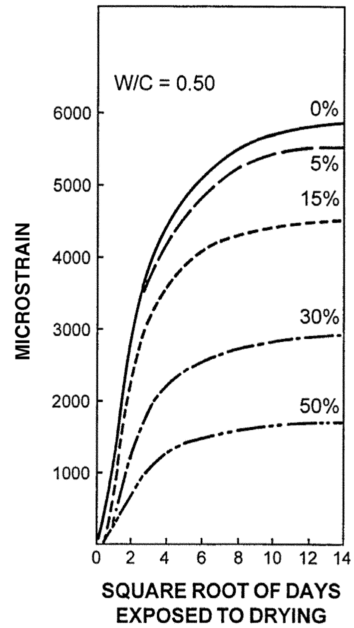

Fig. 2.1—Influence of aggregate volumetric content on concrete drying shrinkage (Pickett 1956).

$$S_C = S_P(1 - g)^n \tag{2-1}$$

where

S_P = shrinkage of paste; S_C = shrinkage of concrete; g = aggregate volumetric fraction; and n = variable.

Suggested values of n are between 1.2 and 1.7. Most concrete used in general construction has aggregate volumetric fractions between 0.6 and 0.8. The effect of aggregate fractional content on drying shrinkage from 0 to 50% is shown in Fig. 2.1 (Pickett 1956).

2.2.2 *Size and grading of aggregate*—In general, an increase in the maximum aggregate size, and concurrent decrease in paste content, will decrease drying shrinkage. The size and grading of aggregate does not directly affect the shrinkage of a concrete; however, a change in the maximum aggregate size from 6 to 150 mm (1/4 to 6 in.) can result in aggregate volume rising from 0.6 to 0.8. This would result in approximately a 50% decrease in shrinkage, as shown in Fig. 2.2. A rounder aggregate may result in a decreased paste content that will result in lower shrinkage.

2.2.3 *Water content, cement content, and slump*—Increasing the total water content will tend to increase shrinkage because the additional water or cement will decrease the aggregate content in a mixture. The combined influences of water content and cement content are shown in Fig. 2.3.

Increasing the slump of concrete by adding water will tend to increase drying shrinkage. Increased slump is typically obtained through increasing the w/c or total paste content of the concrete. These actions will both result in the decrease of aggregate volume within a concrete. Increasing the cement content from 335 to 450 kg/m^3 (564 to 752 lb/yd^3) will increase the volume of water in a 0.40 w/c concrete from 134 to 180 kg/m^3 (226 to 300 lb/yd^3). Based on Fig. 2.3, this 115 kg/m^3 (188 lb/yd^3) increase in cement content would

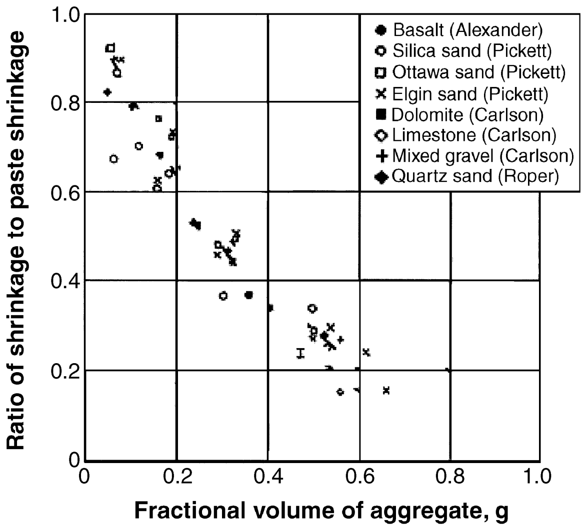

Fig. 2.2—Effect of aggregate volumetric fraction on the ratio of long-term concrete shrinkage to paste shrinkage (Hansen and Nielsen 1965). The graph shows that the shrinkage of the concrete is not linearly related to the fractional volume of aggregate.

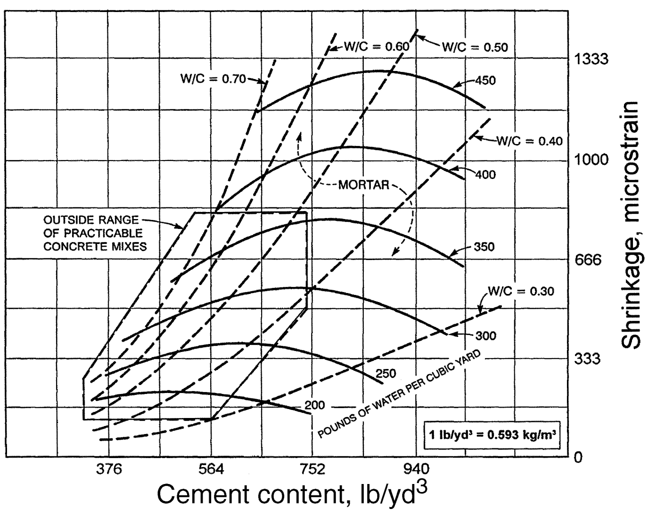

Fig. 2.3—Influence of w/c, *cement content, and water content on long-term shrinkage (Blanks et al. 1940). For any given cement content, a line is drawn vertically to intersect the line of* w/c. *A line is drawn horizontally to determine the drying shrinkage.*

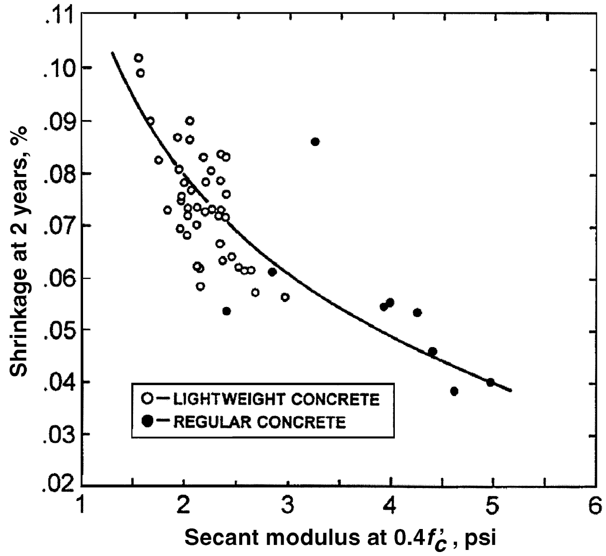

Fig. 2.4—Relation between drying shrinkage after 2 years and secant modulus of elasticity of normal (regular) and lightweight concrete tested at a stress-strength ratio of 0.4 at 28 days (Reichard 1964).

typically result in an increase of shrinkage from 290 to 560 microstrain, an increase of 90% for a *w/c* of 0.40.

2.2.4 *Elastic properties of aggregate*—The aggregate restrains the shrinkage of cement paste. Concrete containing an aggregate with a high modulus of elasticity will tend to have a lower drying shrinkage than concrete containing an aggregate with a low modulus of elasticity, as shown in Fig. 2.4.

2.2.5 *Clay-containing aggregates*—Care should be taken with aggregates containing clay minerals, such as breccia, as these tend to increase the drying shrinkage due to their high water demands (Rhoades and Mielenz 1948).

2.2.6 *Lightweight aggregates*—Lightweight aggregates tend to increase drying shrinkage of concrete; however, with appropriate selection of aggregates, lightweight concrete with moderate drying shrinkage is possible. Additional information is provided in ACI 213R, "Guide for Structural Lightweight Aggregate Concrete."

2.2.7 *Cement characteristics*—The chemistry of the cement plays a significant role in the shrinkage of cement paste and concrete. Roper (1974) conducted extensive work on the effects of various cement compositions on the shrinkage of mortar specimens. He found that cements with low quantities of sulfate may exhibit increased shrinkage. The shrinkage of concrete made with a high alumina content occurs more rapidly. Finely ground cements, as typically found in ASTM C 150 Type III cements, result in greater shrinkage than coarser ground cements.

2.2.8 *Air content*—When the total air content of the concrete is less than 8%, there is generally no effect on the magnitude of drying shrinkage (Davis and Troxell 1954).

2.2.9 *Admixtures*—Both chemical and supplementary cementitious materials affect measured drying shrinkage. The effect of admixtures on drying shrinkage is discussed by Brooks (1989, 1999) where extensive discussions are made relating to other changes that are commonly made when using these admixtures such as changes in cement content or water use.

Compared with concrete having the same mixture proportions, the effect of various ingredients on the shrinkage of concrete determined by Brooks is shown as follows:

Ingredient	Shrinkage
Water-reducing and high-range water-reducing admixtures	May increase by 20% at the same water content depending on composition
Ground slag	May increase shrinkage with increase in replacement
Fly ash	No change
Silica fume (less than 7.5% replacement)	Decrease

If newly developed admixtures are to be used in a concrete, their effect on shrinkage should be evaluated through laboratory studies comparing shrinkage using methods such as ASTM C 157, "Standard Test Method for Length Change of Hardened Hydraulic-Cement, Mortar, and Concrete." Some admixtures are specifically formulated to reduce shrinkage and are discussed by Nmai et al. (1998).

2.3—Effect of environment on drying shrinkage

The environment in which concrete is mixed, placed, and cured and to which it is exposed during its life has a significant effect on the drying of concrete. Low humidity, wind, and high temperatures tend to increase the rate of drying leading to increased rates and magnitudes of drying shrinkage.

2.3.1 *Relative humidity*—Shrinkage is primarily affected by the relative humidity of the air surrounding the concrete. Unrestrained concrete stored in water will tend to swell.

Various mathematical relationships have been used to relate drying shrinkage to relative humidity. The most commonly used formula relating drying shrinkage to relative humidity h, in percent, is shown in Eq. (2-2).

$$\text{shrinkage} \propto 1 - \left(\frac{h}{100}\right)^b \tag{2-2}$$

Typical values for b range from 1 to 4.

Equation (2-2) may not apply to concrete at a relative humidity of less than 50%, as little data exists for this condition. Because of the lack of data, testing may be appropriate for concrete in dry climates and desert regions and for the interior of heated buildings without humidifiers.

2.3.2 *Cyclic relative humidity*—Muller and Pristl (1993) found that concrete specimens stored at a constant relative humidity environment of 65% exhibited greater drying shrinkage than specimens stored in an environment that cycled between 40 and 90% relative humidity, with an average relative humidity of 65%. Their results are shown in Fig. 2.5.

2.3.3 *Temperature*—The effect of elevated temperature alone on concrete shrinkage is less pronounced than the effect of a reduction of relative humidity.

The 1990 CEB-FIP Model Code (1990) presents equations to adjust the time rate of shrinkage and the ultimate shrinkage for concrete exposed to elevated long-term temperatures. For a typical structural concrete, the 1990 CEB-FIP Model Code predicts an increase in time rate of shrinkage of approximately 6% and an increase in ultimate shrinkage of approximately 15% for an increase of temperature from 23 to 60 °C (70 to 140 °F) at a constant relative humidity.

2.4—Effect of design and construction on drying shrinkage

There are many factors at the construction site that can affect the drying shrinkage of concrete. These factors, which are listed in Sections 2.4.1 through 2.4.3, are of importance when it is necessary to minimize concrete cracking due to restrained shrinkage.

2.4.1 *Period of curing*—Extended periods of moist curing will usually reduce the amount of drying shrinkage occurring

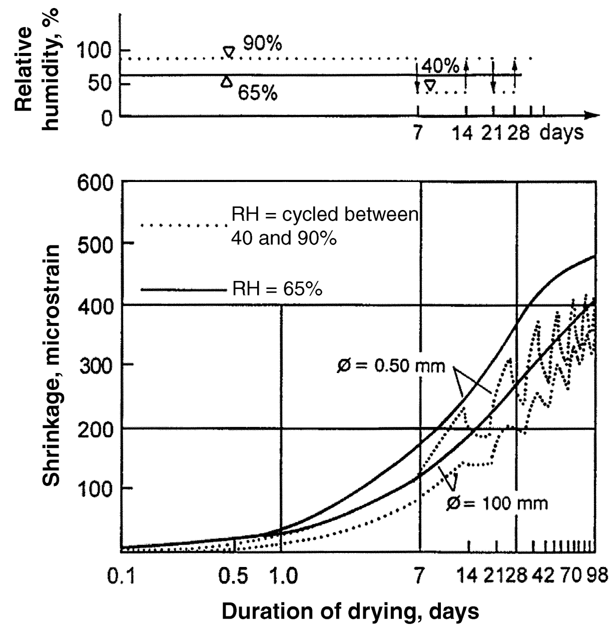

Fig. 2.5—Development of shrinkage strains of long cylindrical concrete specimens with diameters of 50 and 100 mm (2 and 4 in.) at variable (relative humidity cycled between 40 and 90%) and a constant (relative humidity = 65%) ambient humidities (Muller and Pristl 1993). Also shown is the relative humidity used for the test specimens at various times after initiation of drying.

in a concrete mixture by 10 to 20%. This effect varies for concrete with different w/c. Work by Perenchio (1997) relating the period of moist curing and drying shrinkage for concrete with various w/c, showed that periods of curing greater than 4 to 8 days and less than 35 to 50 days may increase the drying shrinkage (Fig. 2.6).

2.4.2 *Heat and steam curing*—Heat and steam curing can significantly reduce drying shrinkage of concrete by as much as 30% (Klieger 1960).

2.4.3 *Size and shape of specimen*—Due to the slower rate of drying of the larger members, thick concrete members shrink at a slower rate than thin concrete members. The rate of shrinkage is generally assumed to be inversely proportional to the ratio of the volume of the specimen to its drying surface area, squared, as shown in Eq. (2-3).

$$\text{shrinkage} \propto \frac{1}{\left(\frac{V}{S}\right)^2} \tag{2-3}$$

where V = volume, and S = surface area.

Shrinkage results from Hansen and Mattock for concrete members with different volume to surface area ratios are shown in Fig. 2.7 (Hansen and Mattock 1966).

The shape of the shrinkage specimen affects the distance moisture has to travel to the air drying environment. It also affects stress concentrations within the drying concrete obtained from nonuniform shrinkage occurring through the cross section of the specimen or member. McDonald and Roper (1993) showed that the influence of specimen size was closely related to stresses developed within the specimen due to

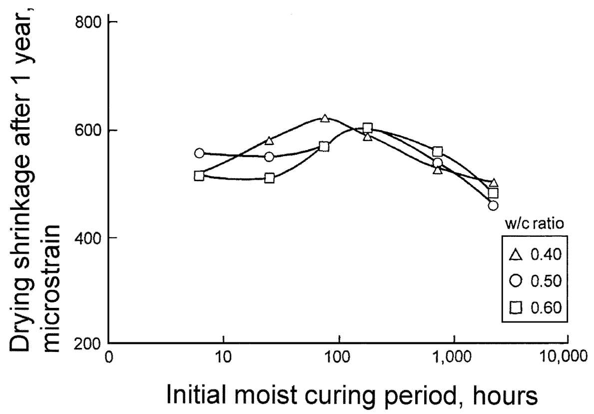

Fig. 2.6—Effect of curing period on drying shrinkage after 1 year for specimens with different w/c *(Perenchio 1997).*

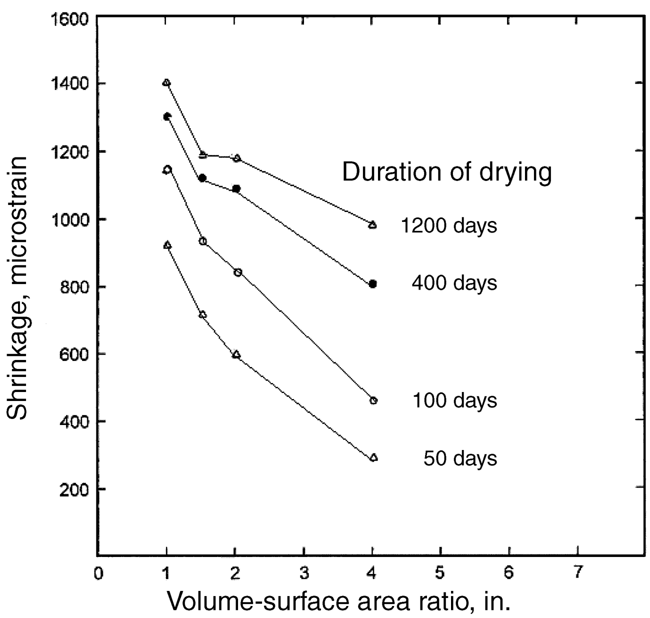

Fig. 2.7—Shrinkage strain at different ages versus volume-surface area ratio (Hansen and Mattock 1966).

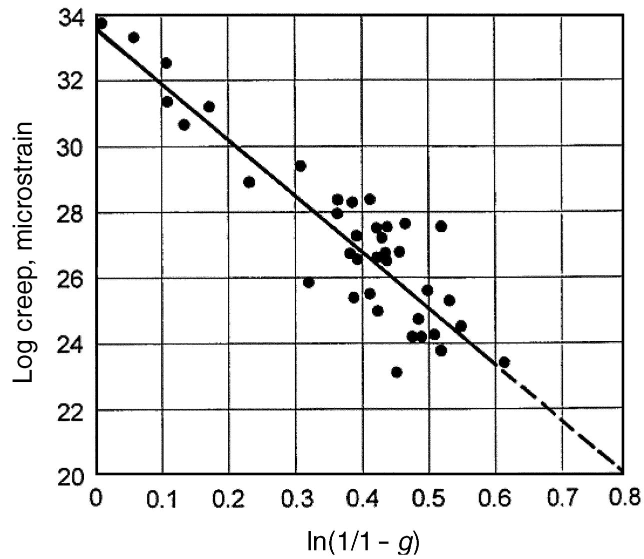

Fig 3.1—Relationship between basic creep and aggregate content, where g *is the aggregate content (Gvozdev 1966).*

humidity gradients during drying. Pickett (1946) and Browne (1967) measured humidity gradients and shrinkage strains in thick concrete test specimens.

CHAPTER 3—FACTORS AFFECTING CREEP

3.1—Introduction

Many factors affect the creep of concrete. These factors are described as follows.

3.2—Effect of mixture proportions on creep

The basic and drying creep of a given concrete are governed by the properties of the cement paste and the quantity and properties of aggregate within a given mixture. Mixture proportions affecting creep are discussed in Sections 3.2.1 through 3.2.7.

3.2.1 *Quantity of aggregate*—Figure 3.1 shows the relation between basic creep and aggregate content (Gvozdev 1966). For the majority of concrete mixtures, the variation of aggregate content is small, but an increase in aggregate volume can decrease creep.

3.2.2 *Size and grading of aggregate*—It was previously believed that the grading, size, and shape of the aggregate were factors affecting basic and drying creep, however, it is now believed that their effects are primarily related to changes in the overall aggregate volume. Aggregate size affects the bond between the paste and the aggregate, and also affects stress concentrations and microcracking.

3.2.3 *Properties of aggregate*—The elastic properties of the aggregate significantly influence basic and drying creep. Dimensional changes in the cement paste can deform softer aggregates easier than stiffer aggregates. For this reason, concrete with low elastic modulus aggregates tends to have higher creep; however, this is not always the case. Aggregates with higher porosity also tend to have higher creep than materials with lower porosity. Work by Troxell, Raphael, and Davis (1958) on the effect of aggregate type on creep is shown in Fig. 3.2.

3.2.4 *Lightweight aggregate*—Lightweight aggregate concrete tends to have a greater basic and drying creep than concrete made with normalweight aggregate. This is primarily due to the lower modulus of elasticity of these aggregates. Additional details are found in ACI 213R.

3.2.5 *Water content, cement content, and slump*—Generally, for the same cement content, concrete with a high water content will have greater basic and drying creep than those with a low water content. Direct comparison of concrete containing different cement contents is difficult, because creep is largely dependent on the applied stress level relative to the concrete strength at the time of loading. Increasing either the water alone or the water and cement content of a mixture will increase the slump. Therefore, it is difficult to determine whether an increase in slump will increase or decrease the creep of a concrete. For this reason, slump alone is not an indicator of creep.

Table 3.1—Effect of various admixtures on basic and total creep

Ingredient	Creep at constant stress-strength ratio	
	Basic	Total*
Water-reducing and high-range water-reducing admixtures	Increase by 20% at same *w/c*	Increase by 20% at same *w/c*
Ground slag	Decrease with increase of replacement	No change
Fly ash	Decrease with increase of replacement	Decrease for replacement levels greater than 10%
Silica fume (less than 7.5% replacement)	Increase	Increase

*Total creep = basic creep + drying creep.

3.2.6 *Air content*—Increasing the air content will increase basic and drying creep; however, quantification of the effects are complicated by the effect of air content on strength and elastic properties of the resulting concrete.

3.2.7 *Admixtures*—The effect of mineral and supplementary cementitious materials is complex; however, Brooks (1989) developed Table 3.1. The effects of new classes or types of admixtures should be evaluated through laboratory studies using tests such as ASTM C 512.

3.3—Effect of environment on creep

The environment in which concrete is cast and to which it is exposed and loaded during its life has a significant effect on the drying creep of concrete.

3.3.1 *Relative humidity*—Drying creep is significantly affected by the relative humidity of the surrounding air. Concrete in water or environments in which drying cannot occur may have only one quarter of the creep of drying concrete. The effect of relative humidity on creep is shown in Fig. 3.3 (Troxell, Raphael, and Davis 1958).

3.3.2 *Cyclic relative humidity*—Muller and Pristl (1993) found that concrete specimens stored at a constant relative humidity environment of 65% exhibited slightly lower drying creep than concrete specimens stored in an environment that cycled between 40 and 90% relative humidity. The effect of cyclic relative humidity is shown in Fig. 3.4.

3.3.3 *Temperature*—The effect of temperature on basic and drying creep of concrete should be examined based on two general categories: first for those structures designed to continually operate at elevated temperatures, and second for the prediction and analysis of structures accidentally exposed to transient high temperatures.

The most common example of structures in the first category is equipment foundations in manufacturing processes that employ high temperatures. In general, foundation elements are insensitive to creep effects, even at high temperatures, due to the low applied load. Nuclear reactor vessels that typically operate in the range of 60 to 82 °C (140 to 180 °F) and at higher load levels are prone to the effects of elevated temperature. Nasser and Neville (1968) found that the rate of creep increases up to approximately 70 °C (160 °F) for a concrete with a *w/c* of 0.6, and is approximately 3.5 times higher than at 23 °C (70 °F). Figure 3.5 shows the relationship between creep and time under load for concretes stored at various temperatures (Arthananari and Yu 1967).

Aggregate Type	Typical Modulus of Elasticity, E_a	
	GPa	psi
Sandstone	19.7	2.85×10^6
Basalt	24.6	3.57×10^6
Granite	20.1	2.91×10^6
Gravel	26.9	3.90×10^6
Quartz	26.0	3.77×10^6
Limestone	25.0	3.63×10^6

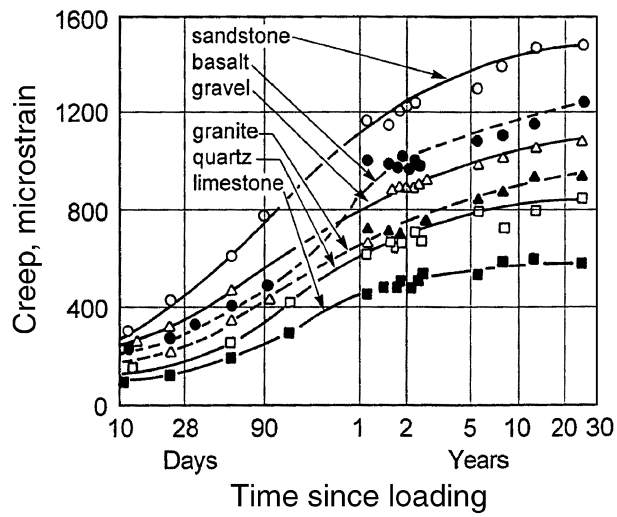

Fig. 3.2—Elastic modulus of aggregate and creep of concrete of fixed proportions but made with different aggregates loaded at an age of 28 days and stored in air at 21°C (70 °F) and a relative humidity of 50% (Troxell, Raphael, and Davis 1958).

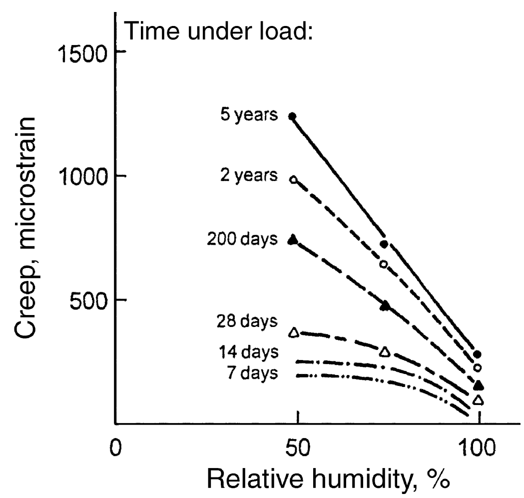

Fig. 3.3—Effect of relative humidity on creep (Troxell, Raphael, and Davis 1958).

The 1990 CEB-FIP Model Code (1990) presents equations to adjust both the time rate of creep and the creep coefficient for concrete exposed to long-term temperatures up to 80 °C (176 °F). The equations presented in the CEB-FIP code are more applicable to sections greater than 300 mm (12 in.) in thickness, where the effects of moisture gradients are more pronounced and thus have greater influence.

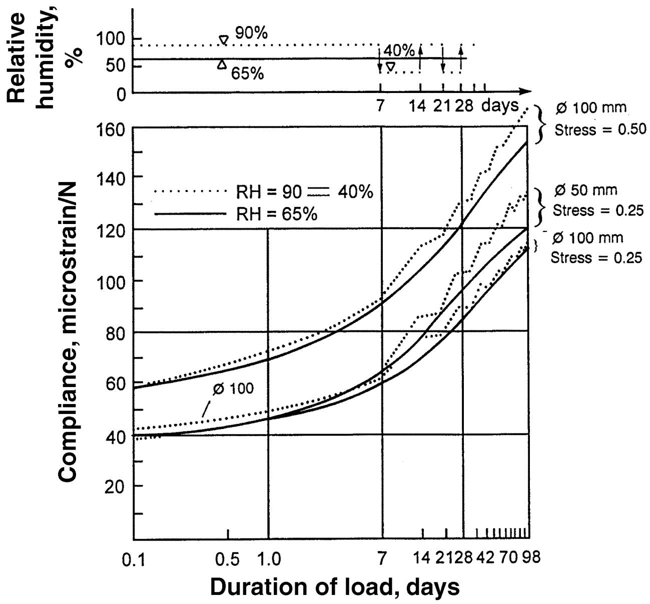

Fig. 3.4—Compliance of cylindrical concrete specimens with diameters of 50 and 100 mm (2 and 4 in.), subjected to stress-strength ratios of 0.25 and 0.50 and exposed to cyclic relative humidities between 40 and 90% and constant humidity of 65%. (Muller and Pristl 1993). Also shown is the relative humidity used for the test specimens at various times after initiation of drying.

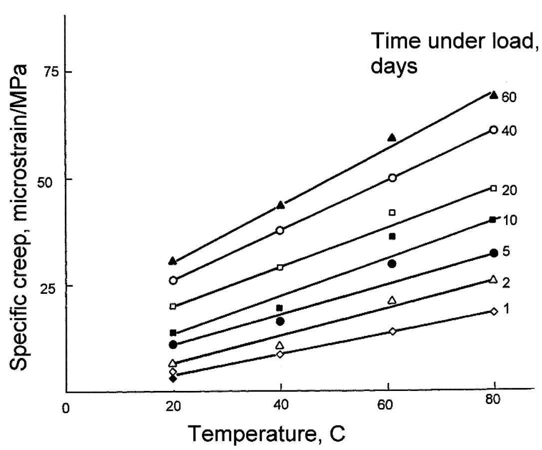

Fig. 3.5—Influence of temperature on the specific creep of concrete under biaxial compression (Arthananari and Yu 1967).

Creep plays an important role in the response of loaded structures to the effects of high temperature from fire. Cruz (1968) investigated the elastic and inelastic properties of concrete exposed to high temperature for 5 h. Concrete exposed to temperatures representative of those developed in building fires experience considerable increase in elastic and inelastic deformations. Factors developed by Cruz for increases in elastic and inelastic deformations over room temperatures are shown in Table 3.2. Further information on concrete exposed to fires may be found in ACI 216R.

3.4—Effect of construction and structural design on creep

There are many factors in design and during construction that can affect the creep of concrete. These factors, which are

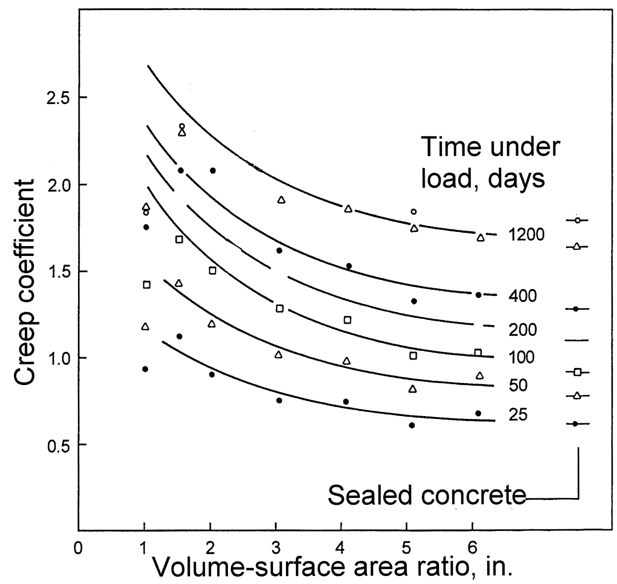

Fig. 3.6—Effect of specimen volume-to-surface area ratio on creep coefficient, shown after different times after loading (days) (Hansen and Mattock 1966).

Table 3.2—Effect of temperature on creep and elastic modulus

Temperature		No. of tests	Ratio of *E* elevated temperature to *E* at 23 °C (75 °F)			Ratio of creep as a multiple of creep at 23 °C (75 °F)
°C	°F		High	Low	Average	
23	75	21	—	—	1.0	1.0
150	300	3	0.87	0.77	0.81	3.3
425	800	4	0.57	0.54	0.56	6.4
480	900	5	0.49	0.42	0.46	14.9
650	1200	5	0.41	0.32	0.36	32.6

discussed in Sections 3.4.1 through 3.4.5, are important when it is necessary to minimize concrete deflections.

3.4.1 *Load*—Basic and drying creep are generally assumed to be linearly related to the applied load for stresses up to $0.4f'_c$; however, Freudenthal and Roff (1958) suggested that basic and drying creep values are linearly related to the applied load for stresses ranging from $0.3f'_c$ to $0.6f'_c$, dependent on the particular concrete.

3.4.2 *Period of curing*—Increasing the period of moist cure before loading will decrease basic and drying creep, as shown in Fig. 1.2. This reduction in creep is due to the combined effect of the reduction of the permeability and increase in the overall concrete strength and modulus of elasticity with time. Drying of the structural element before loading will also decrease the amount of creep.

3.4.3 *Heat or steam curing*—Heat or steam curing significantly reduces the basic and drying creep of concrete as this type of curing increases the strength of the concrete at early ages. This reduction may be as much as 30% (Attiogbe, See, and Daczko 2002).

3.4.4 *Size and shape*—Basic creep (creep without drying) is not affected by member size; however, the rate of creep with drying is significantly affected by the thickness of a concrete member. Thicker concrete members have a lower rate of creep than thin concrete members. This is due to the

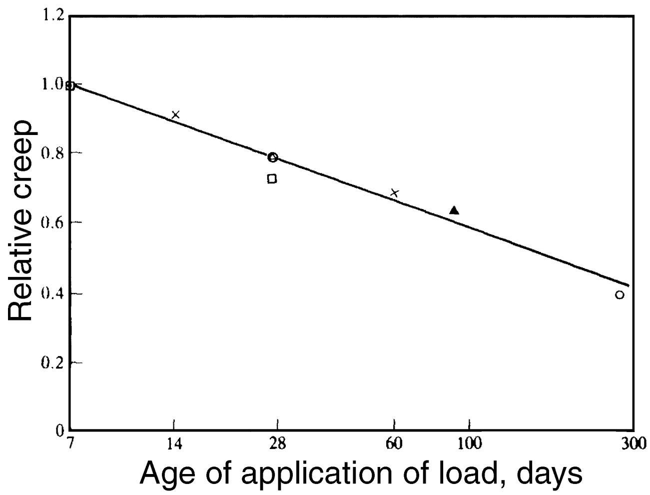

Fig. 3.7 — Effect of loading age on creep relative to creep at loading of 7 days (L'Hermite 1959).

slower rate of drying of the larger members. The rate of creep is generally considered to be inversely proportional to the thickness of the member squared, and the rate decreases with increasing volume-surface area ratio. Results for members of various sizes are shown in Fig. 3.6.

3.4.5 *Loading age*—The age at loading significantly affects the amount of basic and drying creep, with concrete loaded at later ages having lower creep. Results from L'Hermite (1959) are shown in Fig. 3.7.

CHAPTER 4—REFERENCES

4.1—Referenced standards and reports

The latest editions of the standards and reports listed below were used when this document was prepared. Because these documents are revised frequently, the reader is advised to review the latest editions for any changes.

American Concrete Institute

ACI 116R	Cement and Concrete Terminology
ACI 213R	Guide for Structural Lightweight-Aggregate Concrete
ACI 216R	Guide for Determining the Fire Endurance of Concrete Elements

ASTM International

C 150	Standard Specification for Portland Cement
C 157	Standard Test Method for Length Change of Hardened Hydraulic-Cement, Mortar, and Concrete
C 512	Standard Test Method for Creep of Concrete in Compression
C 469	Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

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