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Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete

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Reported by ACI Committee 209

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This guide is intended for the prediction of shrinkage and creep in compression in hardened concrete. It may be assumed that predictions apply to concrete under tension and shear. It outlines the problems and limitations in developing prediction equations for shrinkage and compressive creep of hardened concrete. It also presents and compares the prediction capabilities of four different numerical methods. The models presented are valid for hardened concrete moist cured for at least 1 day and loaded after curing or later. The models are intended for concretes with mean compressive cylindrical strengths at 28 days within a range of at least 20 to 70 MPa (3000 to 10,000 psi). This document is addressed to designers who wish to predict shrinkage and creep in concrete without testing. For structures that are sensitive to shrinkage and creep, the accuracy of an individual model's predictions can be improved and their applicable range expanded if the model is calibrated with test data of the actual concrete to be used in the project.

Keywords: creep; drying shrinkage; prediction models; statistical indicators.

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Background

To predict the strength and serviceability of reinforced and prestressed concrete structures, the structural engineer requires an appropriate description of the mechanical properties of the materials, including the prediction of the time-dependant strains of the hardened concrete. The prediction of shrinkage and creep is important to assess the risk of concrete cracking, and deflections due to stripping-reshoring. As discussed in ACI 209.1R, however, the mechanical properties of concrete are significantly affected by the temperature and availability of water during curing, the environmental humidity and temperature after curing, and the composition of the concrete, including the mechanical properties of the aggregates.

Among the time-dependant properties of concrete that are of interest to the structural engineer are the shrinkage due to cement hydration (self-desiccation), loss of moisture to the environment, and the creep under sustained loads. Drying before loading significantly reduces creep, and is a major complication in the prediction of creep, stress relaxation, and strain recovery after unloading. While there is a lot of data on shrinkage and compressive creep, not much data are available for creep recovery, and very limited data are available for relaxation and tensile creep.

Creep under variable stresses and the stress responses under constant or variable imposed strains are commonly determined adopting the principle of superposition. The limitations of this assumption are discussed in Section 1.3.

Further, the experimental results of Gamble and Parrott (1978) indicate that both drying and basic creep are only partially, not fully, recoverable. In general, provided that water migration does not occur as in sealed concrete or the interior of large concrete elements, superposition can be used to calculate both recovery and relaxation.

The use of the compressive creep to the tensile creep in calculation of beam's time-dependant deflections has been successfully applied in the work by Branson (1977), Bažant and Ho (1984), and Carreira and Chu (1986).

The variability of shrinkage and creep test measurements prevents models from closely matching experimental data. The within-batch coefficient of variation for laboratory-measured shrinkage on a single mixture of concrete was approximately 8% (Bažant et al. 1987). Hence, it would be unrealistic to expect results from prediction models to be within plus or minus 20% of the test data for shrinkage. Even larger differences occur for creep predictions. For structures where shrinkage and creep are deemed critical, material testing should be undertaken and long-term behavior extrapolated from the resulting data. For a discussion of testing for shrinkage and creep, refer to Acker (1993), Acker et al. (1998), and Carreira and Burg (2000).

1.2—Scope

This document was developed to address the issues related to the prediction of creep under compression and shrinkage-induced strains in hardened concrete. It may be assumed, however, that predictions apply to concrete under tension and shear. It outlines the problems and limitations in developing prediction equations, presents and compares the prediction capabilities of the ACI 209R-92 (ACI Committee 209 1992), Bažant-Baweja B3 (Bažant and Baweja 1995, 2000), CEB MC90-99 (Muller and Hillsdorf 1990; CEB 1991, 1993, 1999), and GL2000 (Gardner and Lockman 2001) models, and gives an extensive list of references. The models presented are valid for hardened concrete moist cured for at least 1 day and loaded at the end of 1 day of curing or later. The models apply to concretes with mean compressive cylindrical strengths at 28 days within a range of at least 20 to 70 MPa (3000 to 10,000 psi). The prediction models were calibrated with typical composition concretes, but not with concretes containing silica fume, fly ash contents larger than 30%, or natural pozzolans. Models should be calibrated by testing such concretes. This document does not provide information on the evaluation of the effects of creep and shrinkage on the structural performance of concrete structures.

1.3—Basic assumptions for development of prediction models

Various testing conditions have been established to standardize the measurements of shrinkage and creep. The following simplifying assumptions are normally adopted in the development of prediction models.

1.3.1 *Shrinkage and creep are additive*—Two nominally identical sets of specimens are made and subjected to the same curing and environment conditions. One set is not loaded and is used to determine shrinkage, while the other is generally loaded from 20 to 40% of the concrete compressive strength. Load-induced strains are determined by subtracting the measured shrinkage strains on the nonloaded specimens from the strains measured on the loaded specimens. Therefore, it is assumed that the shrinkage and creep are independent of each other.

Tests carried out on sealed specimens, with no moisture movement from or to the specimens, are used to determine autogenous shrinkage and basic creep.

1.3.2 *Linear aging model for creep*—Experimental research indicates that creep may be considered approximately proportional to stress (L'Hermite et al. 1958; Keeton 1965), provided that the applied stress is less than 40% of the concrete compressive strength.

The strain responses to stress increments applied at different times may be added using the superposition principle (McHenry 1943) for increasing and decreasing stresses, provided strain reversals are excluded (for example, as in relaxation) and temperature and moisture content are kept constant (Le Camus 1947; Hanson 1953; Davies 1957; Ross 1958; Neville and Dilger 1970; Neville 1973; Bažant 1975; Gamble and Parrot 1978; RILEM Technical Committee TC-69 1988). Major deviations from the principle of superposition are caused by the neglect of the random scatter of the creep properties, by hygrothermal effects, including water diffusion and time evolution of the distributions of pore moisture content and temperature, and by material damage, including distributed cracking and fracture, and also frictional microslips. A comprehensive summary of the debate on the applicability of the principle of superposition when dealing with the evaluation of creep structural effects can be found in the references (Bažant 1975, 1999, 2000; CEB 1984; RILEM Technical Committee TC-107 1995; Al Manaseer et al. 1999; Jirasek and Bažant 2002; Gardner and Tsuruta 2004; Bažant 2007).

1.3.3 *Separation of creep into basic creep and drying creep*—Basic creep is measured on specimens that are sealed to prevent the ingress or egress of moisture from or to its environment. It is considered a material constitutive property and independent of the specimen size and shape. Drying creep is the strain remaining after subtracting shrinkage, elastic, and basic creep strains from the total measured strain on nominally identical specimens in a drying environment. The measured average creep of a cross section at drying is strongly size-dependant. Any effects of thermal strains have to be removed in all cases or are avoided by testing at constant temperature.

In sealed concrete specimens, there is no moisture movement into or out of the specimens. Low-water-cement-ratio concretes self-desiccate, however, leading to autogenous shrinkage. Normal-strength concretes do not change volume at relative humidity in the range 95 to 99%, whereas samples stored in water swell (L'Hermite et al. 1958).

1.3.4 *Differential shrinkage and creep or shrinkage and creep gradients are neglected*—The shrinkage strains determined according to ASTM C157/C157M are measured along the longitudinal axis of prismatic specimens; however, the majority of reported creep and shrinkage data are based on surface measurements of cylindrical specimens (ASTM C512). Unless finite element analysis (Bažant et al. 1975) or equivalent linear gradients (Carreira and Walser 1980) are used, it is generally assumed that shrinkage and creep strains in a specimen occur uniformly through the specimen cross section. Kristek et al. (2006) concluded that for box girder bridges, the classical creep analysis that assumes the shrinkage and creep properties to be uniform throughout the cross section is inadequate. As concrete ages, differences in strain gradients reduce (Carreira and Walser 1980; Aguilar 2005).

1.3.5 *Stresses induced during curing phase are negligible*—Most test programs consider the measurement of strains from the start of drying. It is assumed that the restrained stresses due to swelling and autogenous shrinkage are negligible because of the large creep strains and stress relaxation of the concrete at early ages. For restrained swelling, this assumption leads to an overestimation of the tensile stresses and, therefore, it may be an appropriate basis for design when predicting deflections or prestress losses. For predicting the effects of restrained autogenous shrinkage or relaxation, however, the opposite occurs. Limited testing information exists for tensile creep.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

a, b = constants used to describe the strength gain development of the concrete, ACI 209R-92 and GL2000 models

a = aggregate content of concrete, kg/m^3 or lb/yd^3, B3 model

$C_o(t,t_o)$ = compliance function for basic creep at concrete age t when loading starts at age t_o, B3 model

$C_d(t,t_o,t_c)$ = compliance function for drying creep at concrete age t when loading and drying starts at ages t_o and t_c, respectively, B3 model

c = cement content of concrete, kg/m^3 or lb/yd^3, ACI 209R-92 and B3 models

$d = 4V/S$ = average thickness of a member, mm or in., ACI 209R-92 model

E = modulus of elasticity, MPa or psi

E_{cm} = mean modulus of elasticity of concrete, MPa or psi

E_{cm28} = mean modulus of elasticity of concrete at 28 days, MPa or psi

E_{cmt} = mean modulus of elasticity of concrete at age t, MPa or psi

E_{cmto} = mean modulus of elasticity of concrete when loading starts at age t_o, MPa or psi

$e = 2V/S$ = effective cross section thickness of member or notional size of member according to B3 or CEB MC90 and CEB MC90-99 models, respectively, in mm or in.; defined as the cross-section divided by the semi-perimeter of the member in contact with the atmosphere, which coincides with the actual thickness in the case of a slab

f_{cm} = concrete mean compressive cylinder strength, MPa or psi

f_{cm28} = concrete mean compressive cylinder strength at 28 days, MPa or psi

f_{cmt} = concrete mean compressive cylinder strength at age t, MPa or psi

f_{cmtc} = concrete mean compressive cylinder strength when drying starts at age t_c, MPa or psi

f_{cmto} = concrete mean compressive cylinder strength when loading starts at age t_o, MPa or psi