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Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures

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This report reviews the methods for predicting creep, shrinkage and temperature effects in concrete structures. It presents the designer with a unified and digested approach to the problem of volume changes in concrete. The individual chapters have been written in such a way that they can be used almost independently from the rest of the report.

The report is generally consistent with ACI 318 and includes material indicated in the Code, but not specifically defined therein.

Keywords: beams (supports); buckling; camber; composite construction (concrete to concrete); compressive strength; concretes; concrete slabs; cracking (fracturing); creep properties; curing; deflection; flat concrete plates; flexural strength; girders; lightweight-aggregate concretes; modulus of elasticity; moments of inertia; precast concrete; prestressed concrete: prestress loss; reinforced concrete: shoring; shrinkage; strains; stress relaxation; structural design; temperature; thermal expansion; two-way slabs: volume change; warpage.

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CHAPTER 1-GENERAL

1.1-Scope

This report presents a unified approach to predicting the effect of moisture changes, sustained loading, and temperature on reinforced and prestressed concrete structures. Material response, factors affecting the structural response, and the response of structures in which the time change of stress is either negligible or significant are discussed.

Simplified methods are used to predict the material response and to analyze the structural response under service conditions. While these methods yield reasonably good results, a close correlation between the predicted deflections, cambers, prestress losses, etc., and the measurements from field structures should not be expected. The degree of correlation can be improved if the prediction of the material response is based on test data for the actual materials used, under environmental and loading conditions similar to those expected in the field structures.

These direct solution methods predict the response behavior at an arbitrary time step with a computational effort corresponding to that of an elastic solution. They have been reasonably well substantiated for laboratory conditions and are intended for structures designed using the ACI 318 Code. They are not intended for the analysis of creep recovery due to unloading, and they apply primarily to an isothermal and relatively uniform environment .

Special structures, such as nuclear reactor vessels and containments, bridges or shells of record spans, or large ocean structures, may require further considerations which are not within the scope of this report. For structures in which considerable extrapolation of the state-of-the-art in design and construction techniques is achieved, long-term tests on models may be essential to provide a sound basis for analyzing serviceability response. Reference 109 describes models and modeling techniques of concrete structures. For mass-produced concrete members, actual size tests and service inspection data will result in more accurate predictions. In every case, using test data to supplement the procedures in this report will ...n of service performance.

1.2-Nature of the problem

Simplified methods for analyzing service performance are justified because the prediction and control of time-dependent deformations and their effects on concrete structures are exceedingly complex when compared with the methods for analysis and design of strength performance. Methods for predicting service performance involve a relatively large number of significant factors that are difficult to accurately evaluate. Factors such as the nonhomogeneous nature of concrete properties caused by the stages of construction, the histories of water content, temperature and loading on the structure and their effect on the material response are difficult to quantify even for structures that have been in service for years.

The problem is essentially a statistical one because most of the contributing factors and actual results are inherently random variables with coefficients of variations of the order of 15 to 20 percent at best. However, as in the case of strength analysis and design, the methods for predicting serviceability are primarily deterministic in nature. In some cases, and in spite of the simplifying assumptions, lengthy procedures are required to account for the most pertinent factors.

According to a survey by ACI Committee 209, most designers would be willing to check the deformations of their structures if a satisfactory correlation between computed results and the behavior of actual structures could be shown. Such correlations have been established for laboratory structures, but not for actual structures. Since concrete characteristics are strongly dependent on environmental conditions, load history, etc., a poorer correlation is normally found between laboratory and field service performances than between laboratory and field strength performances.

With the above limitations in mind, systematic design procedures are presented which lend themselves to a computer solution by providing continuous time functions for predicting the initial and time-dependent average response (including ultimate values in time) of structural members of different weight concretes.

The procedures in this report for predicting time-dependent material response and structural service performance represent a simplified approach for design purposes. They are not definitive or based on statistical results by any means. Probabilisitic methods are needed to accurately estimate the variability of all factors involved.

1.3-Definitions of terms

The following terms are defined for general use in this report. It should be noted that separability of creep and shrinkage is considered to be strictly a matter of definition and convenience. The time-dependent deformations of concrete, either under load or in an unloaded specimen, should be considered as two aspects of a single complex physical phenomenon.[88]

1.3.1 *Shrinkage*

Shrinkage, after harden[...] with time of concrete volume. The decrease is clue to changes in the moisture content of the concrete and physico-chemical changes, which occur without stress attributable to actions external to the concrete. The converse of shrinkage is swellage which denotes volumetric increase due to moisture gain in the hardened concrete. Shrinkage is conveniently expressed as a dimensionless strain (in./in. or m/m) under steady conditions of relative humidity and temperature.

The above definition includes drying shrinkage, autogenous shrinkage, and carbonation shrinkage.

a) Drying shrinkage is due to moisture loss in the concrete
b) Autogenous shrinkage is caused by the hydration of cement
c) Carbonation shrinkage results as the various cement hydration products are carbonated in the presence of CO,

Recommended values in Chapter 2 for shrinkage strain $(\epsilon_{sh})_t$ are consistent with the above definitions.

1.3.2 *Creep*

The time-dependent increase of strain in hardened concrete subjected to sustained stress is defined as creep. It is obtained by subtracting from the total measured strain in a loaded specimen, the sum of the initial instantaneous (usually considered elastic) strain due to the sustained stress, the shrinkage, and the eventual thermal strain in an identical load-free specimen which is subjected to the same history of relative humidity and temperature conditions. Creep is conveniently designated at a constant stress under conditions of steady relative humidity and temperature, assuming the strain at loading (nominal elastic strain) as the instantaneous strain at any time.

The above definition treats the initial instantaneous strain, the creep strain, and the shrinkage as additive, even though they affect each other. An instantaneous change in stress is most likely to produce both elastic and inelastic instantaneous changes in strain, as well as short-time creep strains (10 to 100 minutes of duration) which are conventionally included in the so-called instantaneous strain. Much controversy about the best form of "practical creep equations" stems from the fact that no clear separation exists between the instantaneous strain (elastic and inelastic strains) and the creep strain. Also, the creep definition lumps together the basic creep and the drying creep.

a) Basic creep occurs under conditions of no moisture movement to or from the environment
b) Drying creep is the additional creep caused by drying

In considering the effects of creep, the use of either a unit strain, δ_t (creep per unit stress), or creep coefficient, [...]al strain), yields the same results, since the concrete initial modulus of elasticity, E_{ci}, must be included, that is:

$$v_t = \delta_t E_{ci} \quad (1\text{-}1)$$

This is seen from the relations:

$$\begin{aligned} \text{Creep strain} &= \sigma\,\delta_t \\ &= \epsilon_i\, v_t, \text{ and} \\ E_{ci} &= \sigma/\epsilon_i \end{aligned}$$

where, σ is the applied constant stress and ϵ_i is the instantaneous strain.

The choice of either of δ_t or v_t is a matter of convenience depending on whether it is desired to apply the creep factor to stress or strain. The use of v_t is usually more convenient for calculation of deflections and prestressing losses.

1.3.3-*Relaxation*

Relaxation is the gradual reduction of stress with time under sustained strain. A sustained strain produces an initial stress at time of application and a deferred negative (deductive) stress increasing with time at a decreasing rate.[89]

1.3.4-*Modulus of elasticity*

The static modulus of elasticity (secant modulus) is the linearized instantaneous (1 to 5 minutes) stress-strain relationship. It is determined as the slope of the secant drawn from the origin to a point corresponding to 0.45 f_c' on the stress-strain curve, or as in ASTM C 469.

1.3.5-*Contraction and expansion*

Concrete contraction or expansion is the algebraic sum of volume changes occurring as the result of thermal variations caused by heat of hydration of cement and by ambient temperature change. The net volume change is a function of the constituents in the concrete.

CHAPTER 2-MATERIAL RESPONSE

2.1-Introduction

The procedures used to predict the effects of time-dependent concrete volume changes in Chapters 3,4, and 5 depend on the prediction of the material response parameters; i.e., strength, elastic modulus, creep, shrinkage and coefficient of thermal expansion.

The equations recommended in this chapter are simplified expressions representing average laboratory data obtained under steady environmental and loading conditions. They may be used if specific material response parameters are not available for local materials and environmental conditions.

Experimental determination of the response parameters using the standard referenced throughout this report and listed in Section 2.10 is recommended if an accurate prediction of structural service response is desired. No prediction method can yield better results than testing actual materials under environmental and loading conditions similar to those expected in the field. It is difficult to test for most of the variables involved in one specific structure. Therefore, data from standard test conditions used in connection with the equations recommended in this chapter may be used to obtain a more accurate prediction of the material response in the structure than the one given by the parameters recommended in this chapter.

Occasionally, it is more desirable to use material parameters corresponding to a given probability or to use upper and lower bound parameters based on the expected loading and envionmental conditions. This prediction will provide a range of expected variations in the response rather than an average response. However, probabilistic methods are not within the scope of this report.

The importance of considering appropriate water content, temperature. and loading histories in predicting concrete response parameters cannot be overemphasized. The differences between field measurements and the predicted deformations or stresses are mostly due to the lack of correlation between the assumed and the actual histories for water content, temperature, and loading.

2.2-Strength and elastic properties

2.2.1-*Concrete compressive strength versus time*

A study of concrete strength versus time for the data of References 1-6 indicates an appropriate general equation in the form of Eq. (2-1) for predicting compressive strength at any time.[6,7]

$$(f_c')_t = \frac{t}{a + \beta t}(f_c')_{28} \quad (2\text{-}1)$$

where a in days and β are constants, $(f_c')_{28}$ = 28-day strength and t in days is the age of concrete.

Compressive strength is determined in accordance with ASTM C 39 from 6 x 12 in. (152 x 305 mm) standard cylindrical specimens, made and cured in accordance with ASTM C 192.

Equation (2-1) can be transformed into

$$(f_c')_t = \frac{t}{a/\beta + t}(f_c')_u \quad \textbf{(2-2)}$$

where a/β is age of concrete in days at which one half of the ultimate (in time) compressive strength of concrete, $(f_c')_u$ is reached.[92]

The ranges of a and β in Eqs. (2-1) and (2-2) for the normal weight, sand lightweight, and all lighweight concretes (using both moist and steam curing, and Types I and III cement) given in References 6 and 7 (some 88 specimens) are: a = 0.05 to 9.25, β = 0.67 to 0.98.

The coastants a and β are functions of both the type of cement used and the type of curing employed. The use of normal weight, sand lighweight, or all-lightweight aggregate does not appear to affect these constants significantly. Typical values recommended in References 7 are given in Table 2.2.1. Values for the time-ratio, $(f_c')_t/(f_c')_{28}$ or $(f_c')_t/(f_c')_t/(f_c')_u$ in Eqs. (2-1) and (2-2) are given also in Table 2.2.1.

"Moist cured conditions" refer to those in ASTM C 132 and C 511. Temperatures other than 73.4 ± 3 F (23 ± 1.7 C) and relative humidities less than 35 percent may result in values different than those predicted when using the constant on Table 2.2.1 for moist curing. The effect of concrete temperature on the compressive and flexural strength development of normal weight concr etes made with different types of cement with and without accelerating admixtures at various temperatures between 25 F (-3.9 C) and 120 F (48.9 (C) were studied in Reference 90.

Constants in Table 2.2.1 are not applicable to concretes, such as mass concrete, containing Type II or Type V cements or containing blends of portland cement and pozzolanic materials. In those cases, strength gains are slower and may continue over periods well beyond one year age.

"Steam cured" means curing with saturated steam at atmospheric pressure at temperatures below 212 F (100 C).

Experimental data from References 1-6 are compared in Reference 7 and all these data fall within about 20 percent of the average values given by Eqs. (2-l) and (2-2) for constants a and β in Table 2.2.1. The temperature and cycle employed in steam curing may substantially affect the strength-time ratio in the early days following curing.[107]

2.2.2 *Modulus of rupture, direct tensile strength and modulus of elasticity*

Eqs. (2-3), (2-4),and (2-5) are considered satisfactory in most cases for computing average values for modulus of rupture, f_r, direct tensile strength, f_t', and secant modulus of elasticity at $0.4(f_c')_t, E_{ct}$ respectively of different weight concretes.[1,4-12]

$$f_r = g_r\,[w(f_c')_t]^{1/2} \qquad (2\text{-}3)$$

$$f_t' = g_t\,[w(f_c')_t]^{1/2} \qquad (2\text{-}4)$$

$$E_{ct} = g_{ct}\,[w^3(f_c')_t]^{1/2} \qquad (2\text{-}5)$$

For the unit weight of concrete, w in pcf and the compressive strength, $(f_c')_t$ in psi

g_r = 0.60 to 1.00 (a conservative value of $g_r = 0.60$ may be used, although a value $g_r = 0.60$ to 0.70 is more realistic in most cases)
g_t = ⅓
g_{ct} = 33

For w in Kg/m^3 and $(f_c')_t$ in MPa

g_r = 0.012 to 0.021 (a conservative value of $g_r =$ 0.012 may be used, although a value of $g_r =$ 0.013 to 0.014 is more realistic in most cases)
g_t = 0.0069
g_{ct} = 0.043

The modulus of rupture depends on the shape of the tension zone and loading conditions Eq.(2-3) corresponds to a 6 x 6 in. (150 x 150 mm) cross section as in ASTM C 78, Where much of the tension zone is remote from the neutral axis as in the case of large box girders or large I-beams, the modulus of rupture approaches the direct tensile strength.

Eq. (2-5) was developed by Pauw[11] and is used in Subsection 8.5.1 of Reference 27. The static modulus of elasticity is determined experimentally in accordance with ASTM C 649.

The modulus of elasticity of concrete, as commonly understood is not the truly instantaneous modulus, but a modulus which corresponds to loads of one to five minutes duration.[86]

2.3—Theory for predicting creep and shrinkage of concrete

The principal variables that affect creep and shrinkage are discussed in detail in References 3, 6, 13-16, and are summarized in Table 2.2.2. The design approach presented[6,7] for predicting creep and shrinkage: refers to "standard conditions" and correction factors for other than Standard conditions. This approach has also been used in References 3, 7, 17, and 83.

Based largely on information from References 3-6, 13, 15, 18-21, the following general procedure is suggested for predicting creep and shrinkage of concrete at any time.[7]

$$v_t = \frac{t^{\psi}}{d + t^{\psi}}\, v_u \qquad (2\text{-}6)$$

$$(\epsilon_{sh})_t = \frac{t^{\alpha}}{f + t^{\alpha}}\, (\epsilon_{sh})_u \qquad (2\text{-}7)$$

where d and f (in days), ψ and α are considered constants for a given member shape and size which define the time-ratio part, v_u is the ultimate creep coefficient defined as ratio of creep strain to initial strain, $(\epsilon_{sh})_u$ is the ultimate shrinkage strain, and t is the time after loading in Eq. (2-6) and time from the end of the initial curing in Eq. (2-7).

When ψ and α are equal to 1.0, these equations are the familiar hyperbolic equations of Ross[15] and Lorman[21] in slightly different form.

The form of these equations is thought to be convenient for design purposes, in which the concept of the ultimate (in time) value is modified by the time-ratio to yield the desired result. The increase in creep after, say, 100 to 200 days is usually more pronounced than shrinkage. In percent of the ultimate value, shrinkage usually increases more rapidly during the first few months. Appropriate powers of t in Eqs. (2-6) and (2-7) were found in References 6 and 7 to be 1.0 for shrinkage (flatter [...] creep (steeper curve for