Report on Early-Age Cracking: Causes, Measurement, and Mitigation

Reported by ACI Committee 231

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Early-age cracking is a challenge for the concrete industry. Materials selection, environmental conditions, and field practices all have considerable influence on the propensity for early-age cracking to occur. This document focuses on thermal- and moisture-related deformations; both are materials-related and contribute to early-age cracking. The document provides detailed reviews on the causes of deformation and cracking, test methods for assessing shrinkage and thermal deformation properties, and mitigation strategies for reducing early-age cracking.

Keywords: autogenous shrinkage; cracking; early-age; heat of hydration; measurement; microstructure; mitigation methods; shrinkage; shrinkage cracking; sustainability; thermal cracking; thermal properties.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

ACI Committee 231 defines "early age" as the period after final setting, during which properties are changing rapidly. For a typical Type I portland-cement concrete moist cured at room temperature, this period is approximately 7 days. This document, however, includes discussions of early-age effects beyond 7 days. It is important to understand how concrete properties change with time during early ages and how different properties are interrelated, which may not be the same as for mature concrete. It is also important to understand how these early-age changes influence the properties of concrete at later ages. The temperature history at early ages has a strong effect on whether concrete may develop its potential strength. Poor early-age curing has been demonstrated to detrimentally affect the strength, serviceability, and durability.

Concrete structures change volume due to the thermal- and moisture-related changes. This may be detrimental because substantial stresses may develop when the concrete is restrained from moving freely. This is particularly important at early ages while the concrete has a low tensile strength. Therefore, the assessment and control of early-age cracking should be based on several factors, such as age-dependent material properties, thermal- and moisture-related stresses and strains, material viscoelastic behavior, restraints, and environmental exposure.

Temperature control in concrete during the early stages of hydration is essential for achieving early strength as well as ultimate strength and to eliminate or minimize uncontrolled cracking due to excessive mean peak temperature rise and thermal gradients (ACI 207.1R and 207.2R). Of particular importance in determining the risk of early-age cracking of any concrete member is an assessment of the magnitude of the stresses generated in the concrete as a result of restraint to thermally induced movement. In general, there are two types of restraint: external and internal. External restraints are caused by support conditions, contact with adjacent sections, applied load, reinforcement, and base friction in the case of concrete slabs-on-ground. Internal restraint is a manifestation of the residual stresses that develop as a result of nonlinear thermal and moisture gradients within a cross section.

New methods were developed and older methods rediscovered for evaluating stress and strain development and assessing cracking risk in concrete mixtures under realistic exposure conditions. Categories of evaluation methods discussed in this document include restrained and unrestrained volume change tests, coefficient of thermal expansion tests, and tools for assessing stress development and cracking potential. Some of these evaluation methods have been standardized.

Mitigation methods have focused mainly on reducing the autogenous (moisture-related) component of the early-age stresses or compensating for the early-age shrinkage by employing expansive cement. In the former case, both shrinkage-reducing admixtures (SRAs) and internal curing have been demonstrated to reduce the magnitude of the early-age shrinkage of specimens cured under sealed, isothermal conditions.

The prevention or mitigation of early-age cracking will improve the long-term durability of concrete structures and, therefore, enhance their sustainability by increasing the service life.

1.2—Scope

This document reviews the causes of early-age deformation and cracking. The test methods for quantifying the early-age stress development and hence the risk of cracking due to thermal and moisture conditions are described. Mitigation methods for stress reduction are also discussed.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

C = cement factor (content) for concrete mixture, lb/yd^3 (kg/m^3)
C_f = correction factor accounting for the change in length of the measurement apparatus with temperature, 0.56 × 10^{-6}/°F (1 × 10^{-6}/°C)
CS = chemical shrinkage of cement (mass of water/mass of cement)
D = moisture diffusion coefficient of concrete
dT/dt = temperature change
$d\varepsilon_{hygral}/dt$ = rate of nonthermal deformation due to autogenous shrinkage, drying shrinkage, or both
$E(t)$ = Young's modulus at time t, psi (MPa)
E_c = creep-adjusted modulus of elasticity of concrete, psi (MPa)
$E_c(t)$ = age-dependent elastic modulus of concrete
E_{CON} = elastic modulus of concrete
E_{steel} = modulus of elasticity of steel ring, psi (MPa)
$erfc$ = complementary error function
f = geometry function (Moon and Weiss 2006)
h = humidity (0 to 1)
G = coefficient relating stress to steel ring strain 10.44 × 10^6 psi (72.2 GPa) for the ASTM ring)
$\hat{K}$ = stress amplification factor
K_r = degree of restraint factor
L = length
L_o = measured length of specimen at room temperature, in. (mm)
M_{LWA} = mass of (dry) fine lightweight aggregate needed per unit volume of concrete, lb/yd^3 (kg/m^3)
R = degree of restraint

R' = ideal gas constant [8.314 J/(mol·K)]

R_{IC} = inner radius of concrete ring

R_{IS} = inner radius of steel ring

R_{OC} = outer radius of concrete ring

R_{OS} = outer radius of steel ring

r = radius

S = degree of saturation of aggregate (0 to 1)

T_c = average concrete temperature °F (°C)

T_{min} = minimum concrete temperature on a cold night, °F (°C)

$T_{zero\text{-}stress}$ = concrete zero-stress temperature, °F (°C)

t_{CR} = time to cracking

V_W = molar volume of pore solution

α_{max} = maximum expected degree of hydration of cement (0 to 1)

α_T = coefficient of thermal expansion, strain/°F (strain/°C)

β = coefficient relating shrinkage rate to shrinkage (0.056 day^{-1})

$\Delta\varepsilon$ = strain increment from autogenous and drying shrinkage

Δ_{La} = actual length change of specimen during temperature change, in. (mm)

Δ_{Lm} = measured length change of specimen during temperature change, in. (mm) (increase = positive; decrease = negative)

Δ_{Lf} = length change of the measuring apparatus during temperature change, in. (mm)

ΔT = measured temperature change (average of the four sensors) °F (°C) (increase = positive; decrease = negative)

$\Delta\sigma$ = stress increment, psi (MPa)

$\varepsilon_c(t)$ = creep strain

$\varepsilon_e(t)$ = elastic strain

$\varepsilon_{sh}(t)$ = free shrinkage strain

ε_{hygral} = nonthermal deformation due to autogenous or drying shrinkage

ε_{SH} = free shrinkage at time t

$\varepsilon_{SH\text{-}CONST}$ = shrinkage coefficient

ε_{ST} = deformation of steel

ϕ_{LWA} = desorption of lightweight aggregate from saturation down to 93% RH (mass water/mass dry lightweight aggregate)

$\phi(t)$ = creep coefficient at time t

γ = surface tension

θ = contact angle

ν = Poisson's ratio

ν_c and ν_s = Poisson's ratio of concrete and steel

σ = stress, psi (MPa)

$\sigma_{Elastic\text{-}Max}$ = theoretical maximum elastic stress

$\psi(t)$ = relaxation coefficient at time t

$\Omega(t)$ = aging coefficient to account for the reduced creep coefficient due to a gradually increasing load in restrained specimen; 0.6 to 0.9 for ordinary hardened concrete, and 0.9 to 1.0 for young concrete

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org. Definitions provided herein complement that resource.

early age—the period after final setting, during which properties are changing rapidly. For a typical Type I portland-cement concrete moist cured at room temperature, this period is approximately 7 days.

CHAPTER 3—CAUSES OF EARLY-AGE DEFORMATION AND CRACKING

The two major driving forces for early-age volume change are the thermal deformation due to cement hydration and shrinkage deformation (autogenous shrinkage and drying shrinkage). The hydration reaction leads to a net reduction in the total volume of the hardened paste, which causes self-desiccation of pores and associated shrinkage. The incremental stress development in a hardening concrete structure with thermal and shrinkage deformations being considered is written as

$$\Delta\sigma = (\Delta T \cdot \alpha_T + \Delta\varepsilon) \cdot E \cdot \psi \cdot R \quad (3\text{-}1)$$

3.1—Thermal deformation

Thermal deformation is a dimensional change resulting from a temperature change in concrete. Thermal deformation depends on the coefficient of thermal expansion (α_T), which is a function of the state of internal moisture. This was first experimentally identified in 1950 by Meyers (1950), later found by Zoldners (1971), and more recently validated by Bjontegaard (1999). Both Meyers and Zoldners found that, while the α_T at fully dried or saturated conditions was approximately the same, there was a dramatic increase in the α_T at intermediate relative humidities (RHs). Meyers hypothesized that in the intermediate RH range, there is additional dilation due to changes in the pore water pressure exerted on the solid skeleton. Powers and Brownyard (1947) noted that with changes in temperature, water expands and undergoes a reduction in surface tension. As the surface tension of water goes down, the negative pressure exerted on the pore system goes down (the pressure pushing the solid nanostructure apart increases), causing additional expansion with increases in temperature.

The development of thermal stresses due to a temperature rise for concrete flatwork may be calculated by the simplified expression presented in Eq. (3-2). The magnitude of the thermal stress is directly proportional to the magnitude of the temperature change to which the flatwork is exposed. For an accurate estimate of the thermal stress, creep effects during early ages and throughout the member's life should be accounted for in Eq. (3-2) (Emborg 1989)

$$\text{thermal stress} = \sigma_T = \Delta T \alpha_T E_c K_r \quad (3\text{-}2)$$

It is clear from Eq. (3-2) that the α_T of mixtures is an important factor affecting early-age thermal stress. During early ages, α_T changes very rapidly as the concrete gains