

Materials and Quality Considerations for High-Strength Concrete in Moderate to High Seismic Applications

Reported by ACI Innovation Task Group 4 and Other Contributors



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Materials and Quality Considerations for High-Strength Concrete in Moderate to High-Seismic Applications

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This document addresses materials and quality considerations when using cast-in-place, normalweight, high-strength concrete in structures that must be designed for moderate to high seismic applications.

The term “high-strength concrete,” as defined by ACI Committee 363, refers to concrete having a specified compressive strength for design of 8000 psi (55 MPa) or greater. The lower 6000 psi (41 MPa) threshold, however, was chosen for the ITG-4 document series because it deals with a specialized application of high-strength concrete in areas of moderate to high seismicity.

An accompanying standard, ITG-4.1, is written in mandatory language in a format that can be adopted by local jurisdictions, and will allow building officials to approve the use of high-strength concrete on projects that are being constructed under the provisions of ACI 301 and 318. ITG 4.2R is the supporting document for that standard.

ITG 4 has also developed another nonmandatory language document: ITG-4.3R. It addresses structural design and detailing considerations.

Keywords: curing; high-strength concrete; mixture proportioning; placement; preconstruction meeting; production; project specification; quality control; seismic design; supplementary cementitious materials; temperature; trial batches.

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CHAPTER 1—INTRODUCTION

1.1—Background

The origin of ACI's Innovation Task Group (ITG) 4, High-Strength Concrete for Seismic Applications, can be traced back to an International Conference of Building Officials (ICBO) (now International Code Council [ICC])

Evaluation Report titled "Seismic Design Utilizing High-Strength Concrete (ER-5536)" (ICC Evaluation Service, Inc. 2004). Evaluation Reports (ERs) are issued by Evaluation Service subsidiaries of model code groups. An ER essentially states that, although a particular method, process, or product is not specifically addressed by a particular edition of a certain model code, it is in compliance with the requirements of that particular edition of that model code.

ER-5536, first issued in April 2001, was generated for the seismic design of moment-resisting frame elements using high-strength concrete. High-strength concrete was defined as "normalweight concrete with a design compressive strength greater than 6000 psi (41.3 MPa) and up to a maximum of 12,000 psi (82.7 MPa)." It was based on research carried out at the University of Southern California and the University of California at San Diego to support building construction in Southern California using concrete with compressive strengths greater than 6000 psi (41 MPa). ER-5536 is available on the ICC website (<http://www.icc-es.org/>).

The Portland Cement Association (PCA) performed a review of the aforementioned document,* which brought up several concerns that focused on inconsistencies between the ER and existing industry documents in two primary areas: material and structural aspects. Irrespective of those concerns, it was evident that the ER had been created because quality assurance and design provisions are needed by local jurisdictions in cities such as Los Angeles to allow the use of high-strength concrete in a safe manner. ACI has assumed a proactive role in the development of such provisions with the goal of creating a document that can be adopted nationwide.

Within ACI, Committee 363, High Strength Concrete, was considered the best choice to develop the section addressing materials quality considerations aspects of the document, while ACI Committee 318-H, Structural Concrete Building Code—Seismic Provisions, was considered the logical choice to address seismic detailing aspects. Because ACI Committee 318-H is a subcommittee of a code-writing body, the development of a technical document of this kind is not part of its intended mission. Also, producing a document by a technical committee is typically a lengthy process. Based on these limitations, a request was made to form an Innovation Task Group (ITG) that would have the advantage of completing the desired product within a shorter timeline. In response to the request, the Technical Activities Committee (TAC) of ACI approved the formation of ITG 4. Following the approval by TAC, David Darwin, then Chair of the TAC Technology Transfer Committee (TTTC), established the mission of the ITG. The mission is to develop an ACI document that addresses the application of high-strength concrete in structures located in areas of moderate and high seismicity. The document is intended to cover structural design, material properties, construction procedures, and quality-control measures. It is to be written or contain example language in a format that will allow building officials to approve the use of high-strength concrete in projects that are being constructed under the provisions of ACI 301 and 318.

*Unpublished report available from PCA, Skokie, Ill., Aug. 2001.

The concept of “areas of moderate and high seismicity” goes back to the days when U.S. seismic codes used to divide the country into seismic zones, which were regions in which seismic ground motion on rock, corresponding to a certain probability of occurrence, was within certain ranges. Given that public safety is a primary code objective and that not all buildings in a given seismic zone are equally crucial to public safety, a new mechanism for triggering seismic design requirements and restrictions, called the seismic performance category (SPC), was developed. The SPC classification included not only the seismicity at the site, but also the occupancy of the structure. Recognizing that building performance during a seismic event depends not only on the severity of subsurface rock motion, but also on the type of soil upon which a structure is founded, seismic design criteria in more recent seismic codes are based on seismic design categories (SDCs). The SDC is a function of location, building occupancy, and soil type. The TTTC-established mission of ITG 4 is interpreted to mean that the task group is to address the application of high-strength concrete in structures:

- Located in Seismic Zones 2, 3, or 4 of the “Uniform Building Code”;
- Assigned to SPCs C, D, or E of the “BOCA/National Building Code” (1993 and subsequent editions) or the “Standard Building Code” (1994 or subsequent editions); or
- SDCs C, D, E, or F of the “International Building Code” or the National Fire Protection Association (NFPA) 5000 “Building Construction and Safety Code.”

SPC or SDC C is also referred to as the “intermediate” SPCs or SDCs. Similarly, SPCs D and E or SDCs D, E, and F are referred to as “high” SPCs or SDCs. The terminology, “moderate to high seismic applications,” however, is used throughout the ITG 4 documents.

When TAC approved the formation of ITG 4, the approval was to “create a nonmandatory standard on the use of high-strength concrete in moderate to high seismic applications.” After some discussion at the TTTC meeting that followed, a concern was raised that a nonmandatory standard might not be able to fully satisfy the goals of the ITG, specifically providing a document that could be implemented with the approval of a building official.

1.2—Scope

The ITG 4 document series addresses the material and design considerations when using cast-in-place normalweight concretes having specified compressive strengths of 6000 psi (41 MPa) or greater in structures that must be designed for moderate to high seismic applications. Irrespective of seismic zone, SPC, or SDC, the ITG-4 document series is also applicable to cast-in-place normalweight high-strength concrete in intermediate or special moment frames and intermediate or special structural walls as defined in ACI 318.

The term “high-strength concrete,” as defined by ACI Committee 363, refers to concrete having a specified compressive strength for design of 8000 psi (55 MPa) or greater. The lower 6000 psi (41 MPa) threshold was chosen for the ITG-4 documents because they deal with a specialized

application of high-strength concrete application in areas of moderate to high seismicity.

Even though high-strength concrete is defined based on a threshold compressive strength, the concept of “high strength” is relative. The limit at which concrete is considered to be “high-strength” depends largely on the location in which it is being used. For example, in some regions, structures are routinely designed with concrete having specified compressive strengths of 12,000 psi (83 MPa) or higher, whereas in other regions, concrete with a much lower specified compressive strength is considered high-strength concrete. Essentially, the strength threshold at which concrete is considered “high-strength” depends on regional factors, such as the characteristics and availability of raw materials, production capabilities, testing capabilities, and lastly, experience on the part of the concrete supplier.

Although for the purpose of this document 6000 psi (42 MPa) was selected as the threshold compressive strength, this is not intended to imply that any drastic change in material properties or in production techniques occurs at this particular compressive strength. In reality, the changes in material properties that take place occur gradually with respect to compressive strength.

The ITG-4 series consists of three documents. ITG-4.1 deals with materials and quality considerations and is an ACI Reference Specification that the licensed design professional can make applicable to any construction project by citing it in the Project Specifications. The licensed design professional is expected to supplement the provisions of ITG-4.1 as needed by specifying individual project requirements. The requirements of ITG-4.1 are in addition to those of ACI 301 and 318. It is expected that an authority having jurisdiction will approve the use of high-strength concrete on a project when the Project Specifications include the mandatory requirements of ITG-4.1 in their entirety. ITG-4.2R (this document) is the support document upon which the requirements of ITG-4.1 are based. ITG-4.3R is on structural design and detailing. Certain modifications to ACI 318 requirements are proposed in the last chapter of ITG-4.3R. These modifications are expected to be considered by ACI Committee 318 for inclusion in ACI 318-08.

CHAPTER 2—PREAMBLE

From a materials perspective, there are few differences between the requisite properties of high-strength concrete used in seismic applications and those of high-strength concrete used in nonseismic applications; therefore, the information presented in ITG-4.2R is generally applicable to all high-strength concrete. When special considerations are warranted due to seismic applications, they are addressed specifically.

The information in **Chapters 3 through 16** of this document is presented in a format similar to that of a committee report. **Chapter 17** contains a summary of the information presented and recommendations that an authority may choose to adopt as the basis for a specification. ITG-4.1 is a mandatory-language version of the recommendations in **Chapter 17** of ITG-4.2R.

CHAPTER 3—GLOSSARY OF TERMS

The terminology used in this document is in substantial agreement with ACI 116R and 318. When the definitions of a term in ACI 116R and 318 differ, the ACI 318 definition is adopted.

admixture—material other than water, aggregate, or hydraulic cement, used as an ingredient of concrete and added to concrete before or during mixing to modify its properties.

aggregate—granular material, such as sand, gravel, crushed stone, and iron blast-furnace slag, used with a cementing medium to form a hydraulic cement concrete or mortar.

alkali-aggregate reaction (AAR)—chemical reaction in either mortar or concrete between alkalies (sodium and potassium) from portland cement or other sources and certain constituents of some aggregates; under certain conditions, deleterious expansion of concrete or mortar may result.

alkali-silica reaction (ASR)—the reaction between the alkalies (sodium and potassium) in portland cement and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

bleeding—the autogenous flow of mixing water within, or its emergence from, newly placed concrete or mortar; caused by the settlement of the solid materials within the mass; also called water gain.

cementitious materials—materials that have cementing value when used in concrete, either by themselves, such as portland cement, blended hydraulic cements, and expansive cement, or in combination with fly ash, other raw or calcined natural pozzolans, silica fume, and/or ground-granulated blast-furnace slag.

concrete, compressive strength of—the measured maximum resistance of a concrete or mortar specimen to axial compressive loading; expressed as force per unit cross-sectional area; or the specified resistance used in design calculations.

concrete, high-strength—concrete that has a specified compressive strength of 6000 psi (41 MPa) or greater.

concrete, hydraulic-cement—mixture of portland cement or any other hydraulic cement, fine aggregate, coarse aggregate, and water, with or without admixtures.

concrete, specified compressive strength of (f'_c)—compressive strength of concrete used in design.

consistency—the relative mobility or ability of freshly mixed concrete or mortar to flow; the usual measurements are slump or spread for concrete, flow for mortar or grout, and penetration resistance for neat cementitious paste.

creep—time-dependent increase in deformation due to sustained load; determined in accordance with ASTM C 512.

creep coefficient—strain due to creep divided by the initial elastic strain.

curing—provision of moisture and appropriate temperatures for sufficient time for the concrete to develop the required properties.

delayed ettringite formation (DEF)—a form of internal sulfate attack caused by the suppression of normal ettringite

formation during early hydration, particularly from excessively high concrete temperatures at early ages.

density—mass per unit volume.

ettringite—a naturally occurring mineral, calcium trisulfate aluminate hydrate, with the chemical composition $\text{Ca}_6\text{Al}_2\text{S}_3\text{O}_{18}\cdot 32\text{H}_2\text{O}$, normal product of cement hydration; also formed by sulfate attack on mortar or concrete.

evaporation retardant—long-chain organic material such as cetyl alcohol that, when spread on a water film on the surface of concrete, retards the evaporation of bleed water.

false set—the rapid development of rigidity in a freshly mixed portland cement paste, mortar, or concrete without the evolution of much heat, in which rigidity can be dispelled and plasticity regained by further mixing without addition of water.

flash set—the rapid development of rigidity in a freshly mixed portland cement paste, mortar, or concrete, characteristically with the evolution of considerable heat, in which rigidity cannot be dispelled nor can the plasticity be regained by further mixing without the addition of water.

flowing concrete—concrete that maintains a slump greater than 7-1/2 in. (190 mm) while remaining cohesive.

mass concrete—a volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and temperature gradients from hydration of the cementitious materials and attendant volume change.

modulus of elasticity—ratio of normal stress to corresponding strain for tensile or compressive stress below the proportional limit of the material, determined in accordance with ASTM C 469.

modulus of rupture (f_r)—a measure of the load-carrying capacity of a beam and sometimes referred to as rupture modulus or rupture strength; it is calculated for apparent tensile stress in the extreme tension fiber of a test specimen subject to bending under the load that produces rupture. It is determined in accordance with ASTM C 78 (third-point loading) or ASTM C 293 (center-point loading).

normal-strength concrete—structural concrete that is below the strength threshold defining high-strength concrete.

Poisson's ratio—the absolute value of the ratio of transverse (lateral) strain to the corresponding axial (longitudinal) strain resulting from uniformly distributed axial stress below the proportional limit of the material; the value will average approximately 0.20 for concrete and 0.25 for most metals.

pozzolan—a siliceous or siliceous and aluminous material that in itself possesses little or no cementitious value but that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties.

quality assurance (QA)—all the planned and systematic activities implemented within the quality assurance and control system and demonstrated as needed, to provide adequate confidence that an entity will fulfill requirements for quality. There are both internal and external purposes for quality assurance. Internal quality assurance, within an organization, provides confidence to management. External quality assurance, in contractual or other situations, provides confidence to the owner or others (such as building officials or government agencies).

quality control (QC)—actions taken by a concrete producer or contractor to provide and document control over what is being done and what is being provided so that the applicable standards of good practice and the contract documents for the work are followed.

rheology—the science dealing with flow of materials, including studies of deformation of hardened concrete, the handling and placing of freshly mixed concrete, and the behavior of slurries, pastes, and the like.

sand equivalent test—a rapid field-correlation test to indicate the relative proportion of plastic fines and dust to sand size particles in granular soil and fine aggregate that pass a No. 4 (4.75 mm) sieve.

segregation—the differential concentration of the components of mixed concrete, such as aggregate, resulting in nonuniform proportions in the mass.

self-consolidating concrete—fresh concrete that can flow around reinforcement and consolidate within formwork under its own weight without vibration, and that exhibits no defect due to segregation or bleeding.

shrinkage—decrease in either length or volume. (Note: may be restricted to the effects of moisture content or chemical changes).

slump—a measure of consistency of freshly mixed concrete, mortar, or stucco equal to the subsidence measured to the nearest 1/4 in. (6 mm) of the molded specimen immediately after removal of the slump cone, determined in accordance with ASTM C 143.

specific creep—strain due to creep, caused by stresses within the elastic range, divided by the applied stress.

splitting tensile strength (f_{ct})—tensile strength of concrete determined by applying a diametrical compressive force along the length of a cylindrical concrete specimen, in accordance with ASTM C 496.

spread—the distance of lateral flow that concrete travels using the slump flow test method.

sulfate attack—either a chemical reaction, a physical reaction, or both, between sulfates usually in soil or ground-water and concrete or mortar; the chemical reaction is primarily with calcium aluminate hydrates in the cement-paste matrix, often causing deterioration.

sulfate resistance—ability of concrete or mortar to withstand sulfate attack.

supplementary cementitious material—cementitious materials (such as ground-granulated blast-furnace slag, fly ash, metakaolin, or silica fume) other than cements used in concrete and masonry construction.

workability—a property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogeneous condition.

CHAPTER 4—PROPERTIES OF HIGH-STRENGTH CONCRETE

As with all concrete, the properties of high-strength concrete can be classified into three basic categories: mechanical, durability, and constructibility. Mechanical and durability properties are measured in the hardened state, whereas constructibility properties pertain to both the plastic

(fresh) and the hardened state. For concrete to be used successfully, consideration should be given to all essential concrete properties, not just a few.

Concrete is a composite material consisting of a filler and a binder. In hydraulic-cement concrete, aggregates act as the filler, which are bound together by a paste that usually consists of cementitious materials, water, hydration products, and admixtures.

As the strength of concrete increases, the material properties change. Although property changes occur gradually with increasing strength, the material properties of high-strength concrete can be quite different from those of normal-strength concrete. The fundamental difference between normal-strength and high-strength concrete is the relative difference in the mechanical properties of the paste versus the aggregate. Upon failure in axial compression in normal-strength concrete, fracturing is more likely to occur through the paste and along the surface of the aggregate, whereas in high-strength concrete, fracturing is more likely to pass through the aggregate.

4.1—Mechanical properties

Important mechanical properties related to high-strength concrete in seismic applications include the relationship between stress and strain in axial compression, the modulus of elasticity, and the compressive strength. Depending on the intended seismic performance of the structural system, special considerations may need to be given to ensure that the mechanical properties of the concrete are compatible with the structural design assumptions.

Other important mechanical properties of high-strength concrete include creep, modulus of rupture, splitting tensile strength, Poisson's ratio, and shrinkage. A brief discussion of each property is provided. For further information, refer to ACI 363R.

4.1.1 Axial stress versus strain—Axial stress versus strain curves for concrete with compressive strength up to 14,000 psi (96 MPa) are shown in Fig. 4.1. As compressive strength increases, the shape of the ascending portion of the axial stress-versus-strain curve becomes steeper and more linear. The strain at maximum stress increases, and the slope of the descending part becomes steeper as concrete strength increases.

For a given imposed axial strain, high-strength concrete exhibits less internal microcracking than normal-strength concrete (Carrasquillo et al. 1981b). As Fig. 4.2 shows, the relative increase in lateral strains is less for high-strength concrete (Ahmad and Shah 1982a). The lower relative lateral expansion within the inelastic range means that the effects of triaxial stresses may be different for high-strength concrete. For example, the influence of hoop reinforcement was observed to be different for high-strength concrete, and it was reported that the effectiveness of spiral reinforcement is less for high-strength concrete (Ahmad and Shah 1982b).

4.1.2 Modulus of elasticity—The modulus of elasticity can significantly influence the behavior of a high-strength concrete structure, and is therefore a very important mechanical property. In calculations for seismic design of reinforced concrete structures, calculated drift and other properties are affected by the modulus of elasticity of the concrete used in

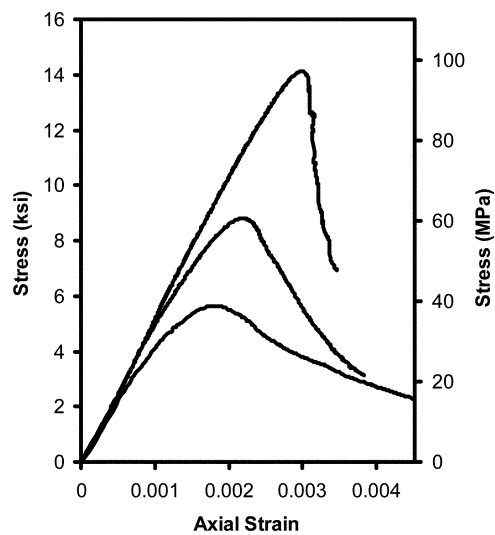


Fig. 4.1—Compressive stress-strain curves for plain normal-density concrete (Jansen et al. 1995).

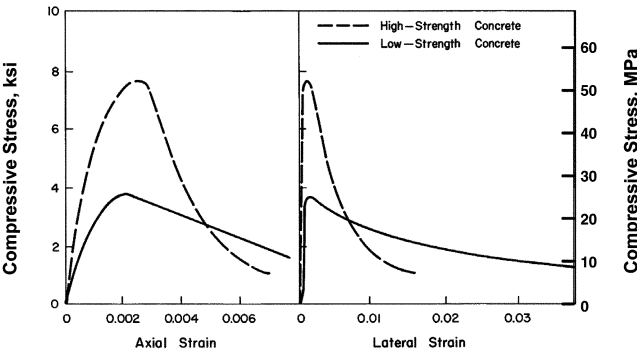


Fig. 4.2—Axial stress versus axial strain and lateral strain for plain normal-density concrete (adapted from Ahmad and Shah [1982a]).

structural members. The modulus of elasticity can be influenced by several mixture properties, including the compressive strength of the concrete, coarse aggregate content, and the mechanical properties of the coarse aggregate. Many investigators (Ahmad 1981; Burg and Ost 1994; Iravani 1996; Kaar et al. 1978; Nedderman 1973; Teychenne et al. 1978) have reported values for the modulus of elasticity of high-strength concrete on the order of 4.5 to 7.5×10^6 psi (31 to 52 GPa), depending on the method of determination used, raw materials, and mixture proportioning. Figure 4.3 compares the modulus of elasticity calculated using several reported empirical equations and the expression given in Section 8.5 of ACI 318-05. The ACI 318-05 equation was developed from results of what are now considered normal-strength concrete, and has been used for high-strength concrete. The equation used in Fig. 4.3 is based on a dry unit weight of 145 lb/ft^3 (2346 kg/m^3). No single empirical expression presented in this section estimates the modulus of elasticity for concrete with compressive strength over 6000 psi (41 MPa) with a high degree of accuracy for the data set given in Fig. 4.3. As widely reported, curing conditions, which affect the development of compressive strength in normal- and high-

Table 4.1—Empirical equations for modulus of elasticity based on curing condition (Myers and Carrasquillo 1999)

Curing regime	Empirical equation, psi	
	With zero intercept	Without zero intercept
ASTM moist-cured cylinders	$E_c = 56,300f_c'^{0.50}$	$E_c = 38,200f_c'^{0.50} + 2,110,000$
Member-cured cylinders*	$E_c = 55,050f_c'^{0.50}$	$E_c = 39,900f_c'^{0.50} + 1,730,000$
Match-cured cylinders†	$E_c = 55,000f_c'^{0.50}$	$E_c = 17,200f_c'^{0.50} + 4,250,000$

*Member-cured cylinders were placed next to the beams as they cured.
†Match-cured cylinders were subjected to identical curing temperatures as the interior of the beams as measured by thermocouples.
Note: $1 \text{ ksi} = 1000 \text{ psi} = 6.895 \text{ MPa}$.

strength concrete, also affect other mechanical properties, including the modulus of elasticity. Table 4.1 illustrates the differences found in expressions for the modulus of elasticity based on curing regime, with and without a zero intercept, as reported by Myers and Carrasquillo (1999).

Due to the significant influence of the mixture proportions, aggregate type, aggregate content, and other raw materials, the modulus of elasticity should be determined based on the specific concrete mixture proposed for use.

The modulus of elasticity should be determined as early as possible during the design phase, either through an evaluation program involving field trials or based on previously documented field performance data.

4.1.3 Creep—Parrott (1969) reported that the total strain observed in sealed high-strength concrete under a sustained loading of 30% of the ultimate strength was the same as that of normal-strength concrete when expressed as a ratio of the short-term strain. Under drying conditions, this ratio was 25% lower than that for normal-strength concrete. The total long-term strains of drying and sealed high-strength concrete were 15 and 65% lower, respectively, than for a corresponding lower-strength concrete at a similar relative stress level. Ngab et al. (1980) found little difference between the creep of high-strength concrete under drying and sealed conditions. Creep of high-strength concrete is reported to decrease significantly when made with high-range water-reducing admixtures (Nagataki and Yonekura 1978). Specific creep was less for high-strength concrete than for normal-strength concrete loaded at the same age (Russell and Corley 1978; Ngab et al. 1980; Gross and Burns 1999). An example is shown in Fig. 4.4. Because high-strength concrete is generally subjected to higher stress, the total creep is often about the same regardless of compressive strength. As in the case of normal-strength concrete, creep decreases as the age at loading increases (Ngab et al. 1980), specific creep increases with increased water-cement ratio (w/c) (Perenchio and Klieger 1978), and there is a linear relationship with the applied stress. This linearity extends to a higher stress-strength ratio than for lower-strength concrete. No problems due to creep were found in columns cast with high-strength concrete (Pfeifer et al. 1971). Gross and Burns (1999) reported that creep was largely dependent on the amount of mixing water and suggested that the lower

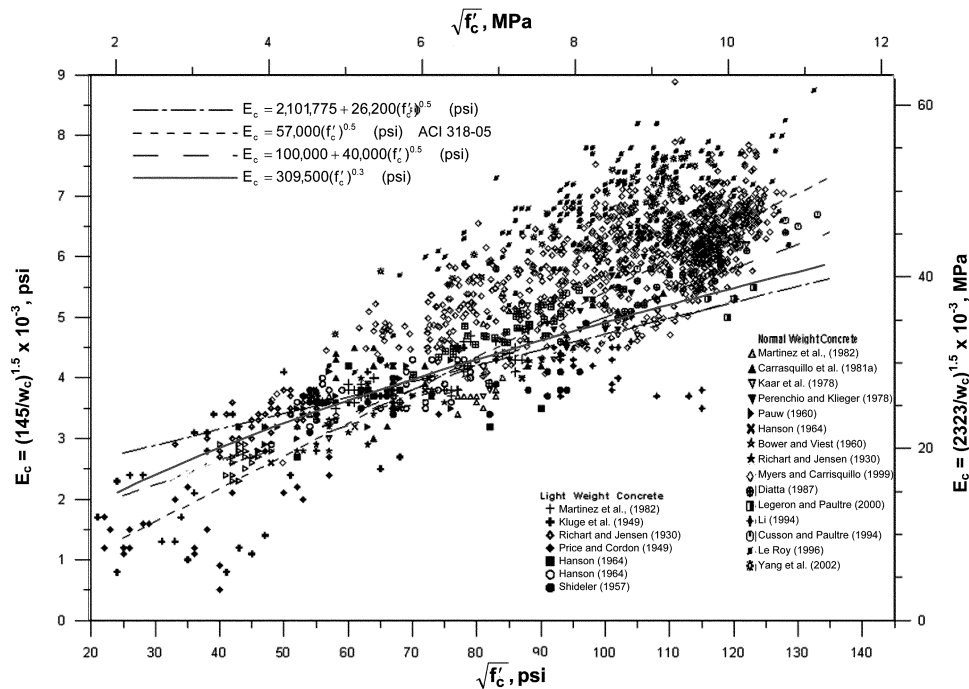


Fig. 4.3—Modulus of elasticity versus concrete strength (incorporating lower and higher strength concrete data) (adapted from ACI 363R).

creep values observed in instrumented high-strength concrete girders may result in less prestress losses compared with values determined using a method to predict the creep of normal-strength concrete girders. Mokhtarzadeh and French (2000a) reported that higher curing temperatures result in higher specific creep. They also determined that the general ACI 209R equation was suitable for predicting the creep coefficient of high-strength concrete at any time, while others reported contradictory results (Gross and Burns 1999).

4.1.4 Modulus of rupture—ACI 318-05 references Eq. (4-1) to calculate the modulus of rupture f_r of normalweight concrete. Equation (4-2) was recommended (Ahmad and Shah 1982a) for the prediction of the modulus of rupture of normalweight concrete as a function of the compressive strength (Fig. 4.5)

$$f_r = 7.5(f'_c)^{0.5} \quad (\text{psi}) \quad (4-1)$$

$$f_r = 0.62(f'_c)^{0.5} \quad (\text{MPa})$$

$$f_r = 11.7(f'_c)^{0.5} \quad (\text{psi}) \quad \text{for } 3000 \text{ psi} < f'_c < 12,000 \text{ psi} \quad (4-2)$$

$$f_r = 0.94(f'_c)^{0.5} \quad (\text{MPa}) \quad \text{for } 21 \text{ MPa} < f'_c < 83 \text{ MPa}$$

Considering data from samples that were either moist or steam cured, Mokhtarzadeh and French (2000b) recommended Eq. (4-3), which includes the effects of various curing regimes

$$f_r = 0.71(f'_c)^{0.79} \quad (\text{psi}) \quad (4-3)$$

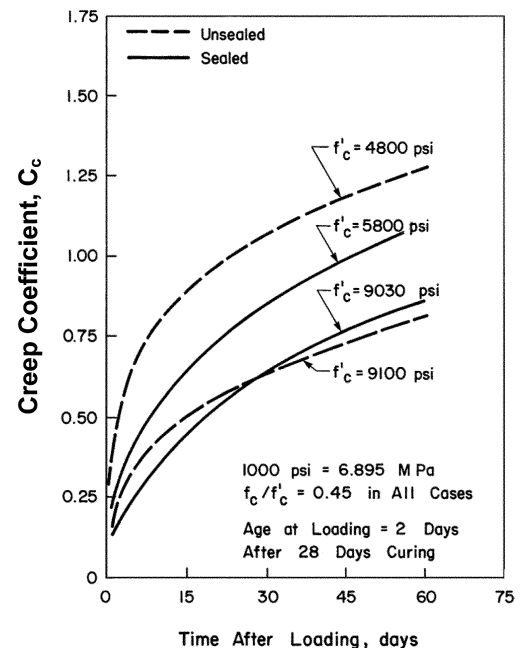


Fig. 4.4—Relationship between creep coefficient and time for sealed and unsealed concrete specimens (Kaplan 1959a).

$$f_r = 0.25(f'_c)^{0.79} \quad (\text{MPa})$$

4.1.5 Splitting tensile strength—Dewar (1964) studied the relationship between the indirect tensile strength (cylinder splitting strength f_{ct}) and the compressive strength of concretes having compressive strengths of up to 12,000 psi (83.8 MPa) at 28 days. He concluded that for relatively low