ACI 224R-01

Control of Cracking in Concrete Structures

Reported by ACI Committee 224

Florian Barth
Chairman

Robert J. Frosch*
Secretary

Mohamed Abou-Zeid	David W. Fowler*	Edward G. Nawy*
John H. Allen	Grant T. Halvorsen	Randall W. Poston*
James P. Barlow	Will Hansen*	Royce J. Rhoads
Merle E. Brander*	M. Nadim Hassoun	Andrew Scanlon
Kathy Carlson	Harvey Haynes*	Ernest K. Schrader*
David Darwin*	Paul Hedli	Wimal Suaris*
Fouad H. Fouad*	Tony C. Liu	Zenon A. Zielinski

*Members of ACI 224 who assisted in revisions to this report.

The principal causes of cracking and recommended crack-control procedures are presented. The current state of knowledge in microcracking and fracture of concrete is reviewed. The control of cracking due to drying shrinkage and crack control in flexural members, overlays, and mass concrete construction are covered in detail. Long-term effects on cracking are considered and crack-control procedures used in construction are presented. Information is presented to assist in the development of practical and effective crack-control programs for concrete structures. Extensive references are provided.

Keywords: aggregates; anchorage (structural); bridge decks; cement-aggregate reactions; concrete construction; concrete pavements; concrete slabs; cooling; corrosion; crack propagation; cracking (fracturing); crack width and spacing; drying shrinkage; shrinkage-compensating concrete; heat of hydration; mass concrete; microcracking; polymer-modified concrete; prestressed concrete; reinforced concrete; restraint; shrinkage; temperature; tensile stresses; thermal expansion; volume change.

CONTENTS

ACI 224R-01 supersedes ACI 224R-90 and became effective May 16, 2001.

CHAPTER 1—INTRODUCTION

Cracks in concrete structures can indicate major structural problems and detract from the appearance of monolithic construction. There are many specific causes of cracking.

This report presents the principal causes of cracking and a detailed discussion of crack-control procedures. The report consists of eight chapters designed to help the engineer and the contractor in developing crack-control measures.

This report is an update of previous committee reports (ACI Committee 224 1972, 1980, 1990). ACI Bibliography No. 9 supplemented the original ACI 224R (1971). The Committee has also prepared reports on the causes, evaluation, and repair of cracking, ACI 224.1R; cracking of concrete in direct tension, ACI 224.2R; and joints in concrete construction, ACI 224.3R.

In this revision of the report, Chapter 2 on crack mechanisms has been revised extensively to reflect the interest and attention given to aspects of fracture mechanics of concrete during the 1980s. Chapter 3 on drying shrinkage has been rewritten. Chapter 4 has been revised to include updated information on crack-width predictive equations, cracking in partially prestressed members, anchorage zone cracking, and flexural cracking in deep flexural members. Chapter 6 on concrete overlays has been reorganized and revised in modest detail to account for updated information on fiber reinforcement and on polymer-modified concrete. Chapter 7 on mass concrete has been revised to consider structural consequences more extensively.

CHAPTER 2—CRACK MECHANISMS IN CONCRETE

2.1—Introduction

Cracking plays an important role in concrete's response to load in both tension and compression. The earliest studies of the microscopic behavior of concrete involved the response of concrete to compressive stress. That early work showed that the stress-strain response of concrete is closely associated with the formation of microcracks, that is, cracks that form at coarse-aggregate boundaries (bond cracks) and propagate through the surrounding mortar (mortar cracks) (Hsu, Slate, Sturman, and Winter 1963; Shah and Winter 1966; Slate and Matheus 1967; Shah and Chandra 1970; Shah and Slate 1968; Meyers, Slate, and Winter 1969; Darwin and Slate 1970), as shown in Fig. 2.1.

During early microcracking studies, concrete was considered to be made up of two linear, elastic brittle materials; cement paste and aggregate; and microcracks were considered to be the major cause of concrete's nonlinear stress-strain behavior in compression (Hsu, Slate, Sturman, and Winter 1963; Shah and Winter 1966). This picture began to change in the 1970s. Cement paste is a nonlinear softening material, as is the mortar constituent of concrete. The compressive nonlinearity of concrete is highly dependent upon the response of these two materials (Spooner 1972; Spooner and Dougill 1975; Spooner, Pomeroy, and Dougill 1976; Maher and Darwin 1977; Cook and Chindaprasirt 1980; Maher and Darwin 1982) and less dependent upon bond and mortar microcracking than originally thought. Research indicates, however, that a significant portion of the nonlinear deformation of cement paste and mortar results from the formation of microcracks that are several orders of magnitude smaller than those observed in the original studies (Attiogbe and Darwin 1987, 1988). These smaller microcracks have a surface density that is two to three orders of magnitude higher than the density of bond and mortar microcracks in concrete at the same compressive strain, and their discovery represents a significant step towards understanding the behavior of concrete and its constituent materials in compression.

The effect of macroscopic cracks on the performance and failure characteristics of concrete has also received considerable attention. For many years, concrete has been considered a brittle material in tension. Many attempts have been made to use principles of fracture mechanics to model the fracture of concrete containing macroscopic cracks.

The field of fracture mechanics was developed by Griffith (1920) to explain the failure of brittle materials. Linear elastic fracture mechanics (LEFM) predicts the rapid propagation of a microcrack through a homogeneous, isotropic, linear-elastic material. The theory uses the stress-intensity factor K that

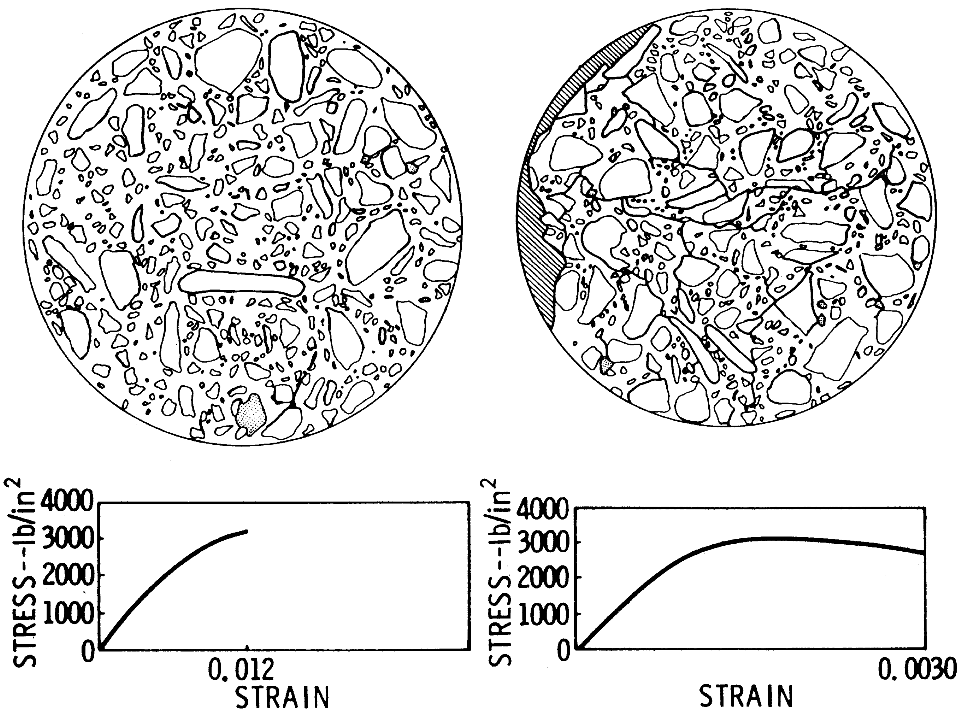

Fig. 2.1—Cracking maps and stress-strain curves for concrete loaded in uniaxial compression (Shah and Slate 1968).

represents the stress field ahead of a sharp crack in a structural member which is a function of the crack geometry and stress. K is further designated with subscripts, I, II, and III, depending upon the nature of the deformation at the crack tip. For a crack at which the deformation is perpendicular to the crack plane, K is designated as K_I, and failure occurs when K_I reaches a critical value K_{Ic}, known as the critical stress-intensity factor. K_{Ic} is a measure of the fracture toughness of the material, which is simply a measure of the resistance to crack propagation. Often the region around the crack tip undergoes nonlinear deformation, such as yielding in metals, as the crack grows. This region is referred to as the plastic zone in metals, or more generally as the fracture process zone. To properly measure K_{Ic} for a material, the test specimen should be large enough so that the fracture process zone is small compared with the specimen dimensions. For LEFM to be applicable, the value of K_{Ic} must be a material property, independent of the specimen geometry (as are other material properties, such as yield strength or compressive strength).

Initial attempts to measure K_{Ic} in concrete were unsuccessful because K_{Ic} depended on the size and geometry of the test specimens (Wittmann 1986). As a result of the heterogeneity inherent in cement paste, mortar, and concrete, these materials exhibit a significant fracture-process zone and the critical load is preceded by a substantial amount of slow crack growth. This precritical crack growth has been studied experimentally by several researchers (John and Shah 1986; Swartz and Go 1984; Bascoul, Kharchi, and Maso 1987; Maji and Shah 1987; Castro-Montero, Shah, and Miller 1990). This research has provided an improved understanding of the fracture process zone and has led to the development of more rational fracture criteria for concrete.

This chapter is divided into two sections. The first section on compressive microcracking presents the current knowledge of the response of concrete and its constituent materials under compressive loading and the role played by the various types of microcracks in this process. The second section discusses the applicability of both linear and nonlinear fracture mechanics models to concrete. A more comprehensive treatment of the fracture of concrete can be found in ACI 446.1R.

2.2—Compressive microcracking

During early microcracking research, a picture developed that closely linked the formation and propagation of microcracks to the load-deformation behavior of concrete. Before loading, volume changes in cement paste cause interfacial cracks to form at the mortar-coarse aggregate boundary (Hsu 1963; Slate and Matheus 1967). Under short-term compressive loads, no additional cracks form until the load reaches about 30% of the compressive strength of the concrete (Hsu, Slate, Sturman, and Winter 1963). Above this value, additional bond cracks are initiated throughout the matrix. Bond cracking increases until the load reaches about 70% of the compressive strength, at which time the microcracks begin to propagate through the mortar. Mortar cracking continues at an accelerated rate, forming continuous cracks parallel to the direction of compressive load, until the concrete is no longer able to sustain the load. The onset of mortar cracking is related to the sustained, or long-term, compressive strength. Derucher (1978) obtained a somewhat different picture of the microscopic behavior of concrete using the scanning electron microscope (SEM). He subjected dried concrete specimens to eccentric compressive loading within the SEM. He observed that microcracks that exist

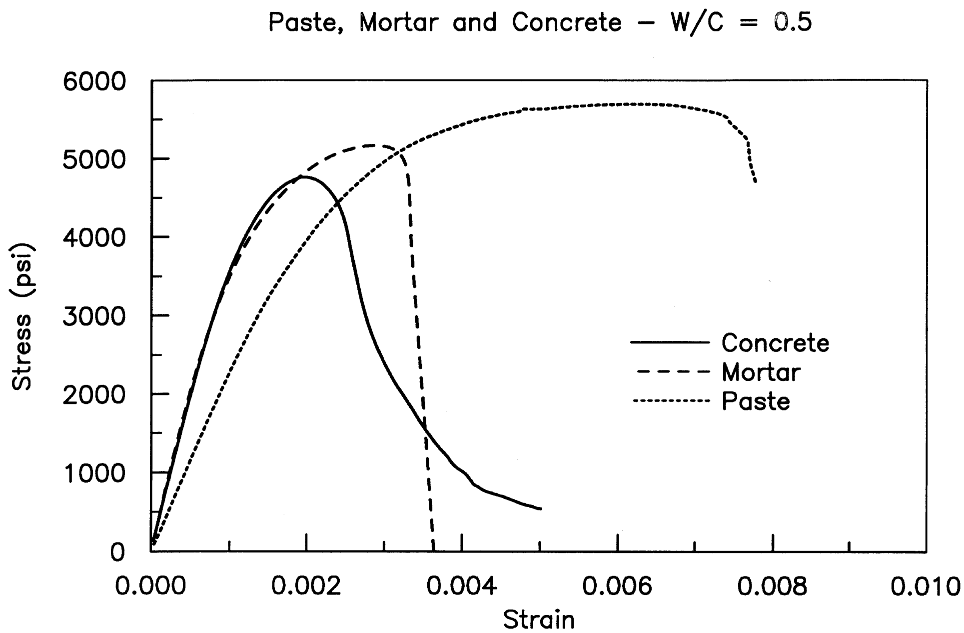

Fig. 2.2—Stress-strain curves for cement paste, mortar, and concrete; w/c *= 0.5 (Martin, Darwin, and Terry 1991).*

before loading are in the form of bond cracks, with extensions into the surrounding mortar perpendicular to the bond cracks. Under increasing compression, these bond cracks widen but do not propagate at loads as low as 15% of the strength. At about 20% of ultimate, the bond cracks begin to propagate, and at about 30%, they begin to bridge between one another. The bridging is almost complete at 45% of the compressive strength. At 75% of ultimate, mortar cracks start to join one another and continue to do so until failure.

In general, microcracking that occurs before loading has little effect on the strength of compressive strength of the concrete.

In studies of high-strength concrete, Carrasquillo, Slate, and Nilson (1981) concluded that it was more appropriate to classify cracks as simple (bond or mortar) and combined (bond and mortar) and that the formation of combined cracks consisting of more than one mortar crack signaled unstable crack growth. They observed that the higher the concrete strength, the higher the strain (relative to the strain at peak stress) at which this unstable crack growth is observed. They observed less total cracking in high-strength concrete than normal-strength concrete at all stages of loading.

Work by Meyers, Slate, and Winter (1969), Shah and Chandra (1970), and Ngab, Slate, and Nilson (1981) demonstrated that microcracks increase under sustained and cyclic loading. Their work indicated that the total amount of microcracking is a function of the total compressive strain in the concrete and is independent of the method in which the strain is applied. Suaris and Fernando (1987) also showed that the failure of concrete under constant amplitude cyclic loading is closely connected with microcrack growth. Sturman, Shah, and Winter (1965) found that the total degree of microcracking is decreased and the total strain capacity in compression is increased when concrete is subjected to a strain gradient.

Since the early work established the existence of bond and mortar microcracks, it has been popular to attribute most, if not all, of the nonlinearity of concrete to the formation of these microscopic cracks (Hsu, Slate, Sturman, and Winter 1963; Shah and Winter 1966; Testa and Stubbs 1977; Carrasquillo, Slate, and Nixon 1981). A cause and effect relationship, however, has never been established (Darwin 1978). Studies by Spooner (1972), Spooner and Dougill (1975), Spooner, Pomeroy, and Dougill (1976), and Maher and Darwin (1982) indicate that the degree of microcracking can be taken as an indication of the level of damage rather than as the controlling factor in the concrete's behavior.

Experimental work by Spooner (1972), Spooner and Dougill (1975), Spooner, Pomeroy, and Dougill (1976), and Martin, Darwin, and Terry (1991) indicates that the nonlinear compressive behavior of concrete is strongly influenced by the nonlinear behavior of cement paste. As illustrated in Fig. 2.2, cement paste under compression is not an elastic, brittle material as stated in the past, but a nonlinear material with a relatively high strain capacity. The nonlinear behavior of cement paste can be tied to damage sustained by the paste, even at very low stresses.

Using a cyclic loading procedure, Spooner (1972), Spooner and Dougill (1975), and Spooner, Pomeroy, and Dougill (1976) demonstrated that both paste and concrete undergo measurable damage at strains (0.0004) at which an increase in bond and mortar microcracking cannot be detected. The level of damage can be detected at low loads by using an energy method and by a change in the initial modulus of elasticity for each load cycle. The process of damage is continuous up to failure.

The physical nature of damage that occurs in cement paste, like that in concrete, appears to be related to cracking. This point was first made by Spooner, Pomeroy, and Dougill (1976) based on volumetric strain measurements and then by

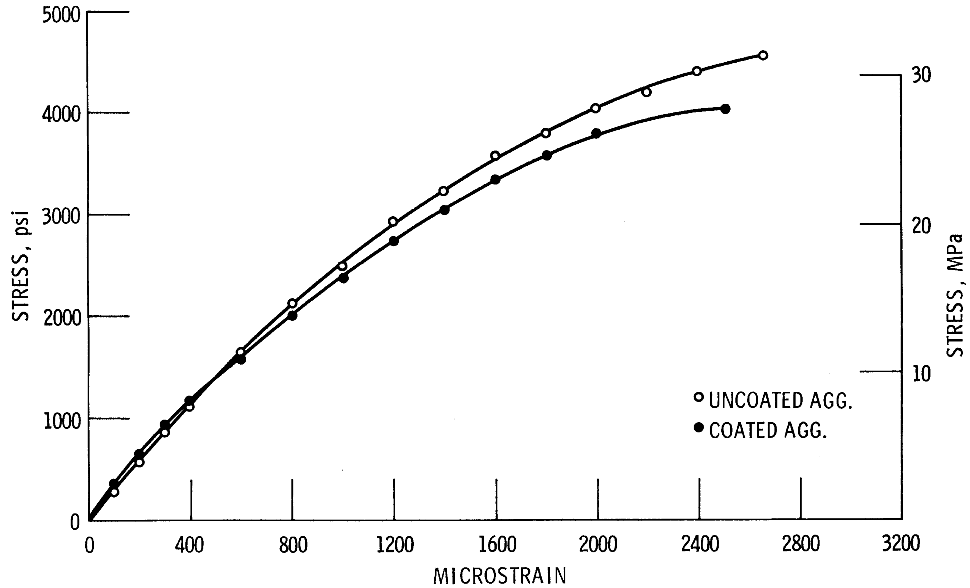

Fig 2.3—Stress-strain curves as influenced by coating aggregates (Darwin and Slate 1970).

Yoshimoto et al. (1972) and Yoshimoto, Ogino, and Kawakami (1976) who reported the formation of "hair-shaped" and "void-shaped" cracks in paste under flexure and compressive loading. The relationship between nonlinear deformation and cracking in cement paste is now firmly established by the work of Attiogbe and Darwin (1987, 1988).

Studies of the stress-strain behavior of concrete under cyclic compressive load (Karsan and Jirsa 1969; Shah and Chandra 1970) indicated the concrete undergoes rapid deterioration once the peak stress exceeds 70% of the short-term compressive strength of the concrete. In their study of cyclic creep, Neville and Hirst (1978) found that heat is generated even when specimens are cycled below this level. They attributed the heat to sliding at the interfacial boundary. The work of Neville and Hirst, along with the work of Spooner, suggests that it can be possible that the heat measured is due to some microscopic sliding within the paste.

Several studies have attempted to establish the importance of interfacial bond strength on the behavior of concrete in compression. Two studies seemed to indicate a very large effect, thus emphasizing the importance of interfacial strength on concrete behavior in compression (Shah and Chandra 1970; Nepper-Christensen and Nielsen 1969). These studies used relatively thick, soft coatings on coarse aggregate to reduce the bond strength. Because these soft coatings isolated the aggregate from the surrounding mortar, the effect was more like inducing a large number of voids in the concrete matrix.

Two other studies (Darwin and Slate 1970; Perry and Gillott 1977) that did not isolate the coarse aggregate from the mortar indicated that interfacial strength plays only a minor role in controlling the compressive stress-strain behavior of concrete. Darwin and Slate (1970) used a thin coating of polystyrene on natural coarse aggregate. They found that a large reduction in interfacial bond strength causes no change in the initial stiffness of concrete under short-term compressive loads and results in about a 10% reduction in the compressive strength, compared with similar concrete made with aggregate with normal interfacial strength (Fig. 2.3). Darwin and Slate also monitored microcracking. In every case, however, the average amount of mortar cracking was slightly greater for specimens made with coated aggregate. This small yet consistent difference may explain the differences in the stress-strain curves. Perry and Gillott (1977) used glass spheres with different degrees of surface roughness as coarse aggregate. Their results also indicate that reducing the interfacial strength of the aggregate decreases the compressive strength by about 10%.

Work by Carino (1977), using polymer-impregnated concrete, corroborated these last two studies. Carino found that polymer impregnation did not increase the interfacial bond strength but did increase the compressive strength of concrete. He attributed the increase in strength to the polymer's effect on mortar strength, therefore downgrading the importance of interfacial bond.

The importance of mortar in controlling the stress-strain behavior of concrete is illustrated by the finite-element work of Buyukozturk (1970) and Maher and Darwin (1976, 1977). Buyukozturk (1970) used a finite-element representation of a physical model of concrete. The model treated mortar (in compression) and aggregate (in compression and tension) as linear elastic materials while allowing cracks to form in the mortar and at mortar aggregate boundaries. Buyukozturk simulated the overall crack patterns under uniaxial loading. His finite-element model, however, could not duplicate the full nonlinear behavior of the physical model using the formation of interfacial bond cracks and mortar cracks as the only nonlinear effects. Maher and Darwin (1976, 1977) have shown that a very close representation of the actual stress-strain behavior can be obtained using a nonlinear representation for the mortar constituent of the physical model.