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Guide to Durable Concrete

Reported by ACI Committee 201

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Reported by ACI Committee 201

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This guide describes specific types of concrete deterioration. Each chapter contains a discussion of the mechanisms involved and the recommended requirements for individual components of concrete, quality considerations for concrete mixtures, construction procedures, and influences of the exposure environment, which are all important considerations to ensure concrete durability.

This guide was developed for conventional concrete but is generally applicable to specialty concretes; however, specialty concretes, such as roller-compacted or pervious concrete, may have unique durability-related issues that deserve further attention that are not addressed herein.

Keywords: abrasion resistance; alkali-aggregate reaction; chemical attack; curing; deterioration; durability; freezing and thawing; physical salt attack, sulfate attack.

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Concrete is the most widely used construction material in the world. The design, detailing, and execution of concrete to resist weathering action, chemical attack, abrasion, and other processes of deterioration over its intended service life will determine its durability. Durable concrete will retain its original form, quality, and serviceability when exposed to its environment. Properly designed, proportioned, transported, placed, finished, and cured concrete is capable of providing decades of service with little or no maintenance. Yet certain conditions or environments exist that can lead to concrete deterioration. Deterioration mechanisms are either chemical or physical in nature and may originate from within the concrete, or may be the result of the external environmental exposure. Chemical and physical attacking mechanisms often work synergistically. Depending on the nature of the attack, distress may be concentrated in the paste, aggregate, or reinforcing components of the concrete, or a combination thereof.

The various factors influencing durability and a particular mechanism of deterioration should be considered in the context of the environmental exposure of the concrete. In addition, consideration should be given to the microclimate to which the specific structural element is to be exposed. The type and severity of deterioration of a given structure may be affected by its proximity to sources of deleterious agents or agents that facilitate distress, exposure to wind, precipitation, or temperature. For instance, exterior girders in a bridge structure may be exposed to a more aggressive environment than interior girders.

The concept of service life is increasingly used for the design of new structures. To produce concrete suitable for a particular application, required service life, design requirements, and expected exposure environments, both macro and micro, should be determined before defining the necessary materials and mixture proportions.

The use of good materials and proper mixture proportioning will not, by itself, ensure durable concrete. Appropriate placement practices and workmanship are essential to the production of durable concrete. Fresh concrete can be consolidated and molded to the shape desired to serve its intended purpose. During this stage, a number of properties significantly influencing the durability of the hardened concrete are established. Pore structure development, air-void system formation, material uniformity, and potential for cracking are established at early ages and are important to the ultimate durability of concrete. As such, durable concrete requires the application of good quality control during construction. Inspection and testing by trained and certified personnel can help ensure the use of durable mixtures and proper practices.

1.2—Scope

This guide discusses the important mechanisms of concrete deterioration and gives recommendations on how to mitigate or minimize such damage. This guide also addresses durability by first discussing the importance of mass transport and then addressing specific modes of attack in separate chapters. These include freezing and thawing, alkali-aggregate reaction (AAR), sulfate attack, aggressive chemical attack, physical salt attack, corrosion of metals and other embedded materials, abrasion, or a combination of these. Fire resistance of concrete and cracking are not addressed directly. Fire resistance is covered in ACI 216.1 and cracking is covered in ACI 224R and ACI 224.1R. While cracking does impact the durability of concrete in severe exposures, the different causes of cracking and their specific impacts are not discussed. Cracking is only mentioned in general terms regarding its impact on fluid ingress.

CHAPTER 2—DEFINITIONS

2.1—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," https://www.concrete.org/store/productdetail.aspx?ItemID=CT16. Definitions provided herein complement that source.

advective transport—transfer of heat or matter via the bulk motion of a fluid.

alkali loading (or content)—total amount of equivalent alkalis (Na_2O_e) in a concrete mixture expressed as mass per volume.

calcium sulfoaluminate cement—product obtained by pulverizing clinker containing mainly ye′elimite [$Ca_4(AlO_2)_6SO_4$] that is often used in expansive cements and ultra-high-early-strength cements.

diffusion—movement of species, such as ions, gas, or vapor, from an area of higher concentration to an area of lower concentration, independent of the bulk motion of a fluid.

electrical migration—transport of electrons or ions due to an electric potential gradient.

ice lens—layer of ice, generally parallel to the exposed surface of the concrete, that can produce internal damage and also lead to scaling or delamination.

leaching—dissolution and removal of soluble components such as calcium hydroxide from concrete.

permeability—the ability of a given concrete to permit liquids or gases to pass through.

permeation—flow of a liquid, gas, or vapor within a solid under the action of a pressure gradient.

physical salt attack—mechanism in which concrete or mortar is damaged as a result of salt crystallization pressure.

reactive silica—form of silica, often amorphous or crypto-crystalline, that dissolves when in contact with concrete pore solution having a sufficiently high concentration of hydroxyl ions.

salt weathering—form of deterioration most commonly observed in arid climates where exposure to soluble salts and cyclic variations in temperature and relative humidity can lead to salt crystallization.

thaumasite—silicate mineral, colorless to white prismatic hexagonal crystals typically as acicular radiating groups, with the chemical formula $\{[Ca_3Si(OH)_6 \cdot 12(H_2O)](SO_4)(CO_3)\}$.

CHAPTER 3—MASS TRANSPORT

3.1—Introduction

Concrete is a multiphase porous medium consisting of a multiscale porous cement paste matrix with aggregate inclusions. Liquid and gas may be present in any pores and microcracks. As such, it is susceptible to the ingress and movement of substances (fluids or ions) from its environment within and through its pore system. This chapter discusses the transport of gases, liquids, and ions in solution through concrete (Lichtner et al. 1996; Baer 1988; Hearn et al. 2006; Hall and Hoff 2012). Methods for improving the durability of concrete and some of the common test methods used to measure the transport properties, along with their advantages and limitations with regard to assessing concrete durability, are also discussed. It is recognized that the rate of ingress of fluids and ions will increase by the presence of cracks. However, the specific influences of different types of cracks and crack widths are not discussed herein.

The ingress of gases, liquids, or ions in solution through concrete may initiate chemical processes, physical processes, or both, that affect the durability of the concrete under a given set of service conditions. Water itself may be harmful because of its ability to leach calcium hydroxide (CH) from the hardened cement paste and because of osmotic pressures generated as water flows to sites of higher alkalinity (Powers et al. 1954; Powers 1975; Helmuth 1960b,c). In addition, water may also be acidic or carry harmful dissolved chemicals, such as chlorides or sulfates, into the concrete. The ingress of gases such as oxygen and carbon dioxide through the concrete pores can contribute to the corrosion of steel reinforcement.

Different substances may interact with components of the concrete in different ways; therefore, transport of a substance through concrete is unique to that substance. For example, water can hydrate previously unhydrated cement particles or leach calcium. Chloride ions may be bound by the hydration products of cement or supplementary cementitious materials (SCMs). The size of the molecules or ions that are transported through the concrete, viscosity of the fluid, valence of the ions, and other ionic species present also affect the transport properties. Thus, permeability and diffusivity must be expressed in terms of the substance that is migrating through the concrete. In general, concrete with transport properties that limit the rate of ingress of external agents is not immune to chemical deterioration, but the effects are mainly near the exposed surfaces, so the concrete tends to be more durable.

3.2—Transport processes in nonreactive porous media

This section provides a brief overview of the transport processes of fluids (gases and liquids) and ions in solution within a nonreactive porous medium. This is a simplifying assumption because concrete changes chemically and physically with time in response to its environment. Physical changes, chemical changes, or both, in the internal structure of the porous medium resulting from interactions with the migrating fluids or ions are not discussed herein. The transport pathways described here include:

a) Transport by permeation
b) Advective transport
c) Hydrodynamic dispersion
d) Diffusion within the pores
e) Transport due to electrostatic interactions or electrical migration

Martín-Pérez et al. (2001) modeled transport related to corrosion of reinforcement in concrete based on chloride transport, moisture diffusion, heat transfer, and oxygen transport using a two-dimensional finite element model. They used a modified version of Fick's second law.

Johannesson (2003) developed a theoretical model for diffusion of different types of ions in concrete pore solution. The model incorporates diffusion caused by concentration gradients of ions (for example, due to drying), internal electrical potential, convection, effects of changes in moisture content, and mass exchange of ions between solution and solid hydration phases.

Chung and Consolazio (2005) developed a finite difference model to simulate heat and mass transport in rapid heating conditions, such as fires in reinforced concrete structures. The model accounts for the interference between liquid and gas phases, slip-flow effects in steam flow, and the interference of steel reinforcement in moisture movement in concrete.

3.2.1 *Transport by permeation*—Permeation is the flow of a fluid under the action of a pressure gradient. Permeability is the property that characterizes the ease with which fluid passes through a porous material under a pressure gradient. For a steady laminar flow through a saturated porous medium, the fluid flow is related to the hydraulic pressure gradient according to Darcy's law.

$$dq/dt = K_1 A \Delta h/l \tag{3.2.1}$$

where dq/dt is the flow (expressed as a rate); K_1 is the permeability coefficient; A is the cross-sectional area; Δh is the hydraulic head; and l is the thickness of the specimen. The permeability coefficient K_1 is the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions. Darcy's law indicates that for a given cross-sectional area and permeability coefficient, the flow is proportional to the hydraulic gradient $\Delta h/l$. Under service conditions, flow is three-dimensional and the concrete may not be saturated. In concrete, the permeability coefficient may change with increased hydration, cracking, or changes in the pore structure due to various physical and chemical processes.

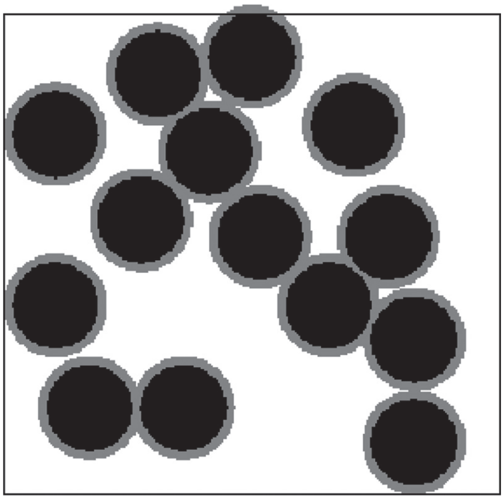

Fig. 3.2.1–Graphical representation of a simple percolation theory model used to model the permeability of concrete.

Permeability coefficients of plastic portland cement pastes of 0.5 water-cement ratio (w/c), calculated from measurements of bleeding, ranged from 5 to 8 × 10^{-7} m/s for four cements with different chemical composition but the same specific surface (180 m^2/kg by the Wagner turbidimeter). The permeability coefficient of mature paste (for example, at greater than 28 days of age) is between 1 millionth and one 10 millionth of that of fresh paste. It ranges from 1 × 10^{-15} to 1.2 × 10^{-12} m/s for w/c ranging from 0.3 to 0.7 (Powers et al. 1954).

To understand the effects of microstructure on the permeability of concrete, Bentz et al. (1999) at the National Institute of Standards and Technology (NIST) used percolation theory. One useful application of percolation theory is the examination of the time needed for a material to progress through a complex maze (Stauffer and Aharony 1992). This maze consists of areas that can allow free movement, as well as areas that impede the transport of a fluid to different degrees. These models can be made in two and three dimensions and can include the effects of cracks. Lu et al. (2012) were able to use a three-dimensional version of the NIST model to predict chloride ingress into cracked concrete.

Work has also been done by NIST that models changes in the properties of these systems with time. This allows the change in the microstructure of the concrete to be examined with time and observe the effects on the ability of a fluid to move through the system.

A graphical representation of a simple percolation theory model has been used by Bentz (2000) to model the transport of a fluid through concrete in two dimensions, as shown in Fig. 3.2.1. Very dense areas are used for aggregates. Moderately dense material is used for the cement paste and low-density material is used to model the interfacial transition zone (3.3.4).

3.2.2 *Advective transport*—Advective transport refers to the movement of molecules and ions with the bulk solution flow. This transport process is related directly to the velocity

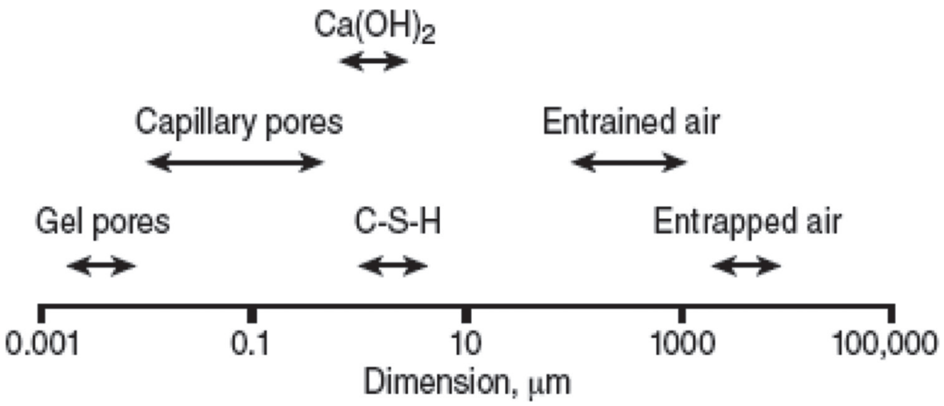

Fig. 3.3.1a—Relative sizes of different types of pores and other microstructural features (adapted from Mehta [1986]).

of fluid flow and concentration of ions in solution. Depending on exposure condition and degree of saturation, the velocity of fluid flow depends on the sorptivity or permeability of concrete, viscosity of the fluid phase, and pressure head of the permeating fluid or rate of evaporation from the exposed surface in the case of wick action (Buenfeld et al. 1995).

3.2.3 *Hydrodynamic dispersion*—Dispersion is the spreading of the ion concentration during advective transport due to variations in the pore fluid velocity. These variations can be a result of the tortuosity of the pore structure, the connectivity of the pore network, or variation in the fluid properties.

3.2.4 *Diffusion within pores*—Diffusion refers to the transport mechanism whereby ions or gases migrate from areas of higher concentration to areas of lower concentration. For the idealized one-dimensional case, Fick's second law describes the non-steady-state diffusion of ions within the pores

$$dc/dt = D_e \cdot d^2c/dx^2 \qquad (3.2.4)$$

where c is the concentration of the ion at distance x from the surface after time t, and D_e is the effective diffusion coefficient or effective diffusivity. The effective diffusivity is a function of the porosity and tortuosity of the porous medium and the molecular diffusivity of the ion of concern. Many factors affect diffusion of ions in concrete. Based on measurements obtained under controlled conditions in the laboratory, diffusion coefficients increase with temperature and water-to-cementitious materials ratio (*w/cm*) and decrease with increasing degree of hydration. Because concrete pore solutions have high ionic strength, electrical charge effects can be significant. Diffusion coefficients can also vary with the species of other ions present in solution. For these and other reasons discussed in 3.4.1.2, the values obtained experimentally using Fick's second law are generally termed "apparent diffusion coefficients". Diffusion coefficients for Na^+ in concrete are on the order of 10^{-11} to 10^{-13} m^2/s, and for Cl^-, on the order of 10^{-11} to 10^{-12} m^2/s (Taylor 1997).

3.2.5 *Transport due to electrostatic interactions or electrical migration*—Migration refers to the transport mechanism due to the charged nature of ions and is the result of the potential difference across the specimen. The electrical coupling between ions in concentrated solutions was demonstrated by Snyder (2001) and Snyder and Marchand (2001). Electrical migration occurs when an external electric field such as in ASTM C1202 (or AASHTO T277) is applied to the medium (Buenfeld et al. 1998). The migration flux J_i of ion i is given by

$$J_i = -D_i C_i \frac{z_i F}{RT} \frac{\partial \varphi}{\partial x} \qquad (3.2.5)$$

where $\partial\varphi/\partial x$ is the potential difference; Z_i is the charge of the ion; F is the Faraday constant; T is the temperature; D_i is the ion diffusivity; R is the gas constant; and C_i is the concentration of the ion in solution.

Further information on ionic transport in concrete can be found in McGrath and Hooton (1996) and for the more complex case of multi-species transport in Truc et al. (2000) and Samson et al. (1999).

3.3—Factors affecting mass transport in concrete

3.3.1 *Porosity and pore size distribution*—Porosity is defined as the volume of voids as a fraction that is usually expressed as a percent of the total volume

$$\text{porosity (\%)} = (\text{volume of voids/total volume}) \times 100\% \qquad (3.3.1)$$

Figure 3.3.1a shows the size ranges for the various types of pores in concrete. Pores in concrete range in size from nanometers to millimeters. The capillary pores, also ranging in size from tens of nanometers to millimeters, have the most significant effect on the transport properties. Transport properties, however, depend more on the connectivity of the pores than on either the porosity or size of the pores. Figure 3.3.1b shows two hypothetical porous materials with approximately the same porosity. In one material, the pores are discontinuous, as would be the case with entrained air bubbles, whereas in the other the pores are continuous. The latter material would allow for more rapid rates of transport than the former.

3.3.2 *Water-cement ratio* (w/c)—The initial porosity of a cement paste is determined by the *w/c*. As cement hydrates, hydration products fill some of the void space formerly occupied by water. With time, this process results in a continued

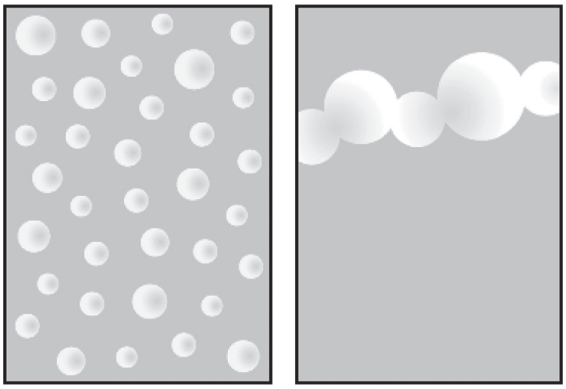

Fig. 3.3.1b—Porosity and permeability are related but distinct. The two hypothetical materials shown have approximately the same porosity (total volume of pores), but different permeabilities. Discrete pores, such as those resulting from air entrainment, have almost no effect on permeability, but interconnected pores increase permeability.

decrease in the porosity of the cement paste. Figure 3.3.2a (Mehta 1986) illustrates the relationship among *w/c*, degree of hydration, and capillary porosity. For a *w/c* of 0.45, the degree of hydration must reach approximately 70 percent to bring the porosity down to 30 percent. For a *w/c* of 0.60, the degree of hydration must reach approximately 100 percent to reach the same porosity. The degree of hydration that could be expected for good curing conditions—for example, moist curing for 5 to 7 days—would range between 70 and 80 percent, depending on cement chemistry and fineness, and on hydration temperatures; a 100 percent degree of hydration is not a practical possibility. Figure 3.3.2b shows the relationship between porosity and permeability. Above a porosity of approximately 30 percent, the coefficient of permeability increases sharply.

Powers (1962b) calculated that for cement paste with a *w/c* of 0.38, all of the capillary pore space was just filled by maximum density gel when all of the cement was hydrated. Sealed, fully hydrated cement pastes made at *w/c* above 0.38 have remaining capillary pore space equal to the excess above 0.38. Partially hydrated mixtures have proportionately less gel and more capillary space. Powers et al. (1959) calculated the time required for capillary pores to become discontinuous with increasing hydration of the cement, as shown in Table 3.3.2. It is notable that mixtures with a *w/c* greater than 0.7 will always have continuous pores. Even for *w/c* of 0.40 to 0.45, extended moist curing or other favorable curing conditions are necessary to achieve the desired low permeability.

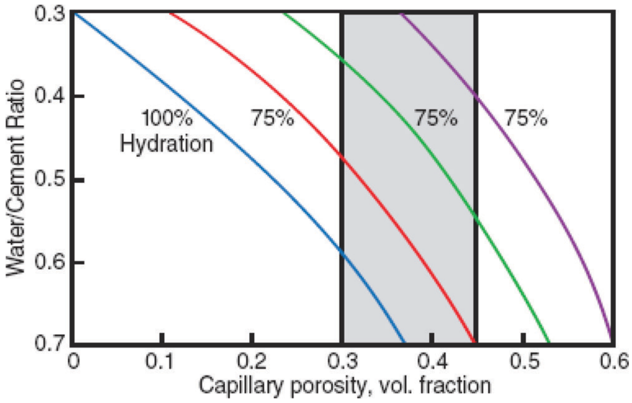

Fig. 3.3.2a—Water-cement ratio versus capillary porosity for cement paste at different degrees of hydration (Mehta 1986) based on equations developed by Powers and Brownyard (1948).

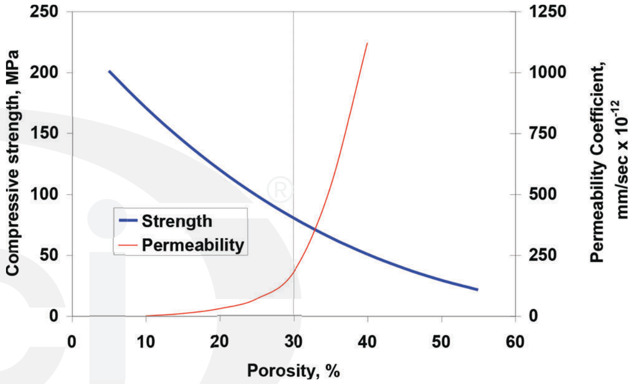

Fig. 3.3.2b—Both compressive strength and permeability are related to the capillary porosity of the cement paste (adapted from Powers [1958]).

Table 3.3.2–Approximate age required to produce maturity at which capillaries become discontinuous for concrete continuously moist-cured (Powers et al. 1959)

w/c by mass	Time required
0.40	3 days
0.45	7 days
0.50	14 days
0.60	6 months
0.70	1 year
Over 0.70	Impossible

3.3.3 *Curing temperature*

3.3.3.1 *At normal temperatures*—Soon after mixing cement with water, a gel layer forms on the surfaces of the cement grains (Taylor 1997). Between 3 and 24 hours after mixing cement with water, approximately 30 percent of the cement reacts. Rapid formation of calcium silicate hydrate (C-S-H) and CH is accompanied by significant evolution of heat. The CH forms massive crystals in the originally water-filled space. The C-S-H forms a thickening layer around the cement grains. As the shells grow outward, they begin to coalesce at about 12 hours, a time coinciding with the maximum rate of heat evolution (Fig. 3.3.3.1) and corresponding approximately to completion of setting (Taylor 1997). In Fig. 3.3.3.1, the first heat peak is associated with the initial hydrolysis of the C_3S and the hydration of the C_3A. The acceleration period begins with the renewed evolution of heat at the beginning of the second peak as the initial hydration products of the C_3S begin to form. Initial

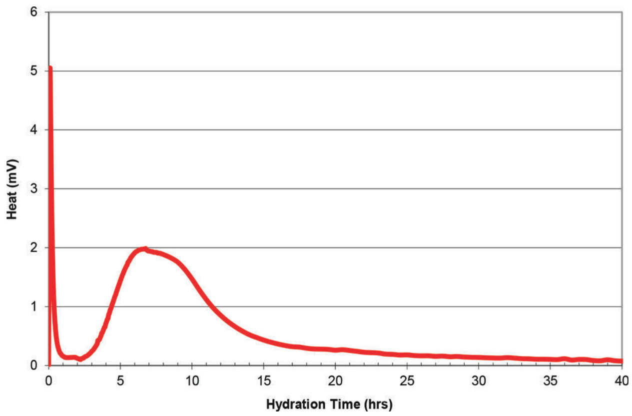

Fig. 3.3.3.1—Heat evolution of Type I/II portland cement paste as measured by conduction calorimetry (Image courtesy of E. Shkolnik.).

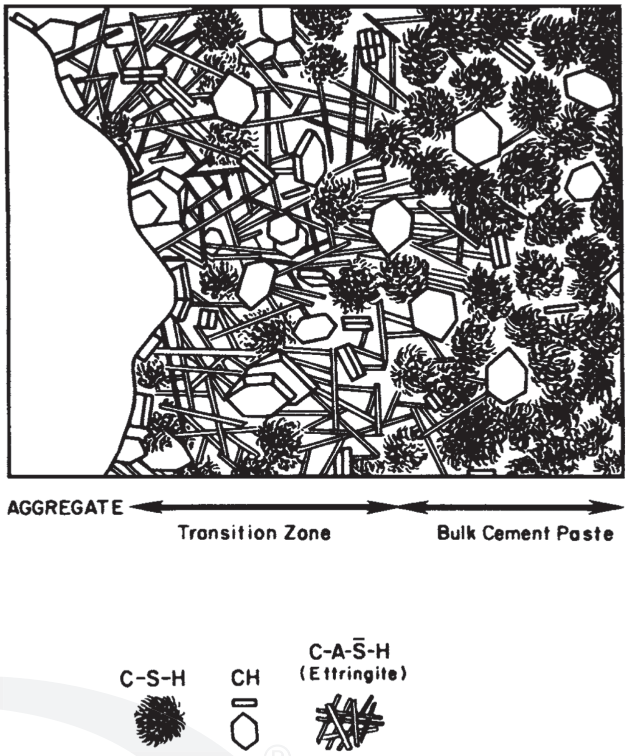

Fig. 3.3.4—Representation of transition zone at paste/aggregate interface in concrete, showing more coarsely crystalline and porous microstructure than in interzonal mass (Mehta 1986).

set coincides with the beginning of the acceleration period. Final set takes place just before the maximum point of the second peak. The shoulder of the second peak is associated with the renewed formation of ettringite (Taylor 1997). Further hydration of the cement continues at a much slower rate, asymptotically approaching 100 percent (Mindess and Young 1981). After the spaces between the hydration shells and the cement grains fill with hydration products, further hydration is slow (Taylor 1997). Capillary pores remaining in mature cement paste increase in size with *w*/*c* and have diameters of 10 nm and higher (Mindess and Young 1981).

3.3.3.2 *At high or low temperatures*—Like most chemical reactions, cement hydration is faster with increasing temperature. Verbeck and Helmuth (1969) postulated that at elevated temperatures, cement hydration products would not have time to diffuse any significant distance from the cement grain, thus forming relatively dense hydration shells around the cement grains. A consequence of the uneven distribution of the solid phases is a coarser pore structure. Goto and Roy (1981) found that the total porosities of pastes hydrated at 140°F (60°C) were greater than those of pastes hydrated at 81°F (27°C). For cement pastes hydrated at low temperatures, on the order of 50°F (10°C), the hydration products are more evenly distributed and the pores fine and discontinuous. For cement pastes hydrated at elevated temperatures, pores are coarser and more interconnected (Kjellsen et al. 1991). Cement pastes containing fly ash, slag cement, or both, are less sensitive to the effects of elevated temperatures, as discussed in 3.3.5.

3.3.4 *Aggregates*—Aggregates generally have fundamentally different transport properties from those of cement paste. For example, the permeability of granite is typically two to three orders of magnitude lower than that of cement paste. The presence of the aggregate in a cement-paste matrix creates an inhomogeneity in the structure of hardened concrete known as the interfacial transition zone between the cement paste and aggregate. Mehta (1986) reported that, compared to the bulk cement paste, the interfacial transition zone has a higher void content, higher contents of CH and ettringite, reduced content of C-S-H, and larger crystals of CH strongly oriented parallel to the aggregate surface (Fig. 3.3.4). Factors contributing to the anomalous nature of the interfacial transition zone include bleeding, which creates pockets of water-filled space beneath aggregate particles; less efficient packing of particles of cementitious materials in the vicinity of a surface, which is called the wall effect; and the one-sided growth effect of dissolved cementitious materials and hydration products diffusing in from the bulk cement paste, but not from the aggregate (Bentz et al. 1995). As the cementitious materials hydrate, the interfacial transition zone fills preferentially with CH and ettringite. Because of the relatively open space, the crystals can grow large. Thus, in most concrete, the interfacial transition zone is the weakest link in terms of mechanical behavior and transport properties. For the latter, the interfacial transition zone can serve as a relatively open channel for fluids and ions, and the CH is vulnerable to leaching and acid attack. For a given *w*/*c* and degree of hydration, water permeability of concrete made with low-permeability aggregates is approximately one to two orders of magnitude lower than that of cement paste due to the interfacial transition zone between aggregate and cement paste (Mehta 1986). It was found that the diffusivity of chloride in the interfacial transition zone is 10 times greater than that in bulk cement paste (Delagrave et al. 1997). The connectivity of pores in the interfacial transition zone may be high, leading to significantly greater rates of transport for some concretes than might be predicted from their mixture proportions. For mixtures with high coarse