ACI 365.1R-17

Report on Service Life Prediction

Reported by ACI Committee 365

American Concrete Institute
Always advancing

First Printing
September 2017
ISBN: 978-1-945487-74-3

Report on Service Life Prediction

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

ACI 365.1R-17

Report on Service Life Prediction

Reported by ACI Committee 365

Evan C. Bentz, Chair

Kyle D. Stanish, Secretary

Muhammed P. A. Basheer
Neal S. Berke
Shrinivas B. Bhide
David N. Bilow
Larry D. Church
Carolyn M. Hansson
R. Doug Hooton
O. Burkan Isgor
Anthony N. Kojundic
Zoubir Lounis
Tracy D. Marcotte
David B. McDonald
Matthew A. Miltenberger
Mohamad Nagi
Dan J. Naus
Karthik H. Obla
Bruce G. Smith
Michael D. A. Thomas
Paul G. Tourney
Wael A. Zatar
Shengjun Zhou
Francois Chapdelaine
David G. Manning
Charles D. Pomeroy
Jesus Rodriguez
Alexander M. Vaysburd
Yash Paul Virmani

Consulting Members
Antonio J. Aldykiewicz Jr.
James P. Archibald

This report presents information to the owner and design professional on the service life prediction of new and existing concrete structures. Key factors controlling the service life of concrete and methodologies for evaluating the condition of the existing concrete structures, including definitions of key physical properties, are also presented. This report assists in the application of available methods and tools to predict the service life of existing structures and provides procedures that can be taken at the design and construction stage to increase the service life of new structures. Techniques for predicting the service life of concrete and the relationship between economics and the service life of structures are discussed. Examples provided discuss which service life techniques are applied to concrete structures or structural components. Needed developments to improve the reliability of service life predictions are also identified.

Keywords: chemical attack; construction; corrosion; design; durability; rehabilitation; repair; service life; sustainability.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 2
1.1—Introduction, p. 2
1.2—Scope, p. 3

CHAPTER 2—DEFINITIONS AND NOTATION, p. 3
2.1—Definitions, p. 3
2.2—Notation, p. 4

CHAPTER 3—ENVIRONMENT, DESIGN, AND CONSTRUCTION CONSIDERATIONS, p. 5
3.1—Introduction, p. 5
3.2—Environmental considerations, p. 5
3.3—Design and structural loading considerations, p. 10
3.4—Interaction of structural load and environmental effects, p. 11
3.5—Construction-related considerations, p. 12

CHAPTER 4—IN-SERVICE INSPECTION, CONDITION ASSESSMENT, AND REMAINING SERVICE LIFE, p. 13
4.1—Introduction, p. 13
4.2—Preliminary condition assessment, p. 14
4.3—Detailed structural assessments, p. 17
4.4—Inspection and maintenance to maintain or predict structural reliability, p. 18

CHAPTER 5—METHODS FOR PREDICTING THE SERVICE LIFE OF CONCRETE STRUCTURES, p. 19
5.1—Introduction, p. 19
5.2—Approaches for predicting service life of new concrete structures, p. 20
5.3—Prediction of remaining service life of existing concrete structures, p. 26
5.4—Predictions for existing structures based on extrapolations, p. 27

ACI 365.1R-17 supersedes ACI 365.1R-00 and was adopted and published September 2017.

5.5—Multi-species approaches, p. 27
5.6—Summary, p. 28

CHAPTER 6—ECONOMIC CONSIDERATIONS, p. 28
6.1—Introduction, p. 28
6.2—Life cycle cost analysis, p. 29
6.3—Governing parameters in LCC analysis, p. 31
6.4—Service life prediction and LCCA of concrete structures, p. 32
6.5—Example, p. 32

CHAPTER 7—EXAMPLES OF SERVICE LIFE TECHNIQUES, p. 33
7.1—Introduction, p. 33
7.2—Example 1: Relationship of amount of steel corrosion to time of spalling, p. 34
7.3—Example 2: Use of multiple inputs to calculate life of structure, p. 35
7.4—Example 3: When to repair or rehabilitate, p. 36
7.5—Example 4: Use of reaction rate to calculate life of sewer pipe, p. 38
7.6—Example 5: Estimating service life and maintenance demands of diaphragm wall exposed to saline groundwater, p. 38
7.7—Example 6: Application of time-dependent reliability concepts to concrete slab, p. 39
7.8—Example 7: Use of stochastic cumulative damage models to predict service life of concrete structures, p. 40
7.9—Example 8: Probabilistic service life prediction, p. 41
7.10—Example 9: Predicting chloride ingress in a marine environment for concrete with different cementitious materials, p. 42
7.11—Example 10: Multi-ionic finite element transport model (parking structure), p. 43

CHAPTER 8—ONGOING WORK AND NEEDED DEVELOPMENTS, p. 45
8.1—Introduction, p. 45
8.2—Designing for durability, p. 46
8.3—Needed developments, p. 47

CHAPTER 9—REFERENCES, p. 47
Authored documents, p. 49

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Service life concepts for buildings and structures date back to when early builders found that certain materials and designs lasted longer than others (Davey 1961). Since then, service life predictions of structures, equipment, and other components have been generally qualitative and empirical. An understanding of the mechanisms and kinetics of many degradation processes of concrete has formed a basis for making quantitative predictions of the service life of concrete structures and components. In addition to actual or potential structural collapse, other factors can govern the service life of a concrete structure. This document reports on these service life factors for new and existing concrete structures and components.

Historically, three types of service life have been defined (Sommerville 1992):

(1) Technical service life is the time in service until a defined unacceptable state is reached, such as spalling of concrete, unacceptable safety level, or failure of elements. Examples of technical end of service life include:

(a) Structural safety is unacceptable due to material degradation or exceeding the design load-carrying capacity
(b) Severe material degradation, such as extensive corrosion of steel reinforcement
(c) Excessive deflection under service loads due to decreased stiffness

(2) Functional service life is the time in service until the structure no longer fulfills the functional requirements or becomes obsolete due to change in functional requirements. Examples include:

(a) Need for increased clearance, higher axle and wheel loads, or road widening
(b) Aesthetics become unacceptable—for example, excessive corrosion staining
(c) Functional capacity of the structure is no longer sufficient—for example, a football stadium with insufficient seating capacity

(3) Economic service life is the time in service until replacement of the structure or part of it is more economical than keeping it in service. Examples include:

(a) Maintenance requirements exceed available resource limits
(b) Replacement to improve economic opportunities—for example, replacing an existing parking garage with a larger one due to increased demand

Essentially, decisions concerning the end of service life are related to public safety, serviceability, functionality, and economic considerations.

In most cases, the performance, appearance, or capacity of a structure can be upgraded to an acceptable level bearing in mind costs, which are addressed in Chapter 6 of this report.

ACI 562, a performance-based code for the repair of structural concrete buildings, has taken the terms for “durability” and “service life,” and defined “design service life” (refer to Chapter 2 of this report) such that licensed design professionals can design rehabilitation and repair programs for owners, allowing for extension of service life for a given structure. Regardless of the service life concept, the terms “durability” and “service life” are often erroneously interchanged. The distinction between the two terms is that durability is about performance for a given time frame in a given environment, and service life is the amount of time to be expected in a given environment or a specific structure.

Service life evaluation methodologies have application both in the design stage of a structure—where certain parameters are established, such as selection of the water-cementitious materials ratio (*w/cm*), concrete cover, and admixtures—and in the operation phase where inspection and maintenance strategies are developed in support of life cycle cost analyses (LCCA) (Zatar 2014). During the design stage, there is typically a design service life that is anticipated. This is either implicitly established or explicitly considered. The implicit design life relies on code minimums to achieve satisfactory performance for a typical life of a concrete structure. Explicitly considering a design service life allows the owner more control over the long-term expectations for the performance of the structure, although code minimums still need to be met.

Service life design includes the architectural and structural design, selection and design of materials, maintenance plans, and quality assurance and quality control plans for a future structure (RILEM 1986). Service life can be predicted based on mixture proportioning, including selection of concrete constituents; known material properties; expected service environment; structural detailing, such as concrete cover; construction methods; projected loading history; and the definition of end-of-life. This allows concrete structures to have a reasonable assurance of meeting the specified design service life (Jubb 1992; Clifton and Knab 1989; Sommerville 2003). The acceptance of advanced materials, such as high-performance concrete, can depend on life cycle cost (LCC) analyses that consider predictions of their increased service life.

Methodologies are being developed that predict the service life of existing concrete structures (Ahmad 2003; Zatar 2014). To make these predictions, information is required on the present condition of concrete and reinforcement, rates of degradation, past and future loading, and definition of the end-of-life (Clifton 1991). Based on remaining life predictions, economic decisions can be made on whether a structure should be repaired, rehabilitated, or replaced. Service life evaluations have also been used to establish inspection frequencies to minimize expected expenditures (Mori and Ellingwood 1994a,b). For rehabilitation and repair programs, this methodology becomes complicated and is not yet well understood, as estimating the service life of a repaired component or structure depends on the type and quality of repair (ACI 546R) as well as the performance of the initial structure, and the materials and systems can vary from traditional concrete and its deterioration mechanisms.

Service life comparisons can also be performed by defining a study period over which alternative durability approaches are considered. Parameters of interest—for example, structural capacity, functionality or initial/repair costs—can then be monitored over the study period so that either a certain level of performance is maintained or the value is optimized over the entire study period.

1.1.1 *Service life and sustainability*—Service life calculation and performance estimation tools should be an integral part of sustainability design for concrete structures (Schokker 2010; ASTM E2921). Several techniques presented in this report for determining the expected service life are also effective methods for green building design. The key sustainability criteria of carbon dioxide (CO_2) emission, embodied energy, and other parameters are greatly impacted by the expected service life of a structure. The overall impact of construction activities is reduced the longer materials last and the more maintenance repair events are minimized. Sustainable design of concrete structures is thereby dependent on using appropriate methods for predicting service life.

Model building codes and sustainability codes in Europe, Canada, and many other parts of the world have established minimum service life performance criteria for buildings. In the United States, the codes have only recently included sustainability requirements that are primarily energy- and water-related, leaving the owners, designers, and contractors responsible for establishing the service life criteria. Sustainable design or green building design takes a holistic approach to the observation of the entire life cycle of the facility. Green design principles, when combined with service life design, can provide justifications for exceeding design code minimums. Often, the appropriate selection of construction materials and techniques can result in a service life of more than 75 years with normal maintenance.

1.2—Scope

This report begins with an overview of important factors controlling the service life of concrete, including past and current design of structures; concrete materials issues; field practices involved with placing, consolidating, and curing of concrete; and in-service stresses induced by degradation processes and mechanical loads. Methodologies used to evaluate the structural condition of concrete structures and the condition and properties of in-service concrete materials are presented. Methods are reviewed for predicting the service life of concrete, including comparative methods, use of accelerated aging (degradation) tests, application of mathematical modeling and simulation, and application of reliability and stochastic concepts.

This is followed by a discussion of relationships between economics and the life of structures, such as when it is more economical to replace a structure than to repair or rehabilitate. Examples are described in which service life prediction techniques are applicable to concrete structures or structural components. Finally, needed developments to improve the reliability of service life predictions are presented.

CHAPTER 2—DEFINITIONS AND NOTATION

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=CT13. Definitions provided herein complement that source.

design service life (of a building, component, or material)—is the period of time after installation or repair during which the performance satisfies the specified requirements if routinely maintained but without being subjected to an overload or extreme event.

durability—the ability of a material or structure to resist weathering action, chemical attack, abrasion, and other conditions of service, and maintain serviceability over a specified time or service life.

service life—an estimate of the remaining useful life of a structure based on the current rate of deterioration or distress, assuming continued exposure to given service conditions without repairs.

2.2—Notation

A = annual capital invested (6.2.2)
A = alkalinity of concrete (7.5)
A_d = amount of accumulative deterioration
A_{df} = amount of damage at failure
B = linear strain caused by a concentration of sulfate reacted in a specific volume of concrete
C = concentration of dissolved material (5.2.4.3)
C = cementitious material content (7.2)
C = average rate of corrosion of concrete by acid (7.5)
C_0 = concentration of reacted sulfate in the form of ettringite (5.2.4.2)
C_0 = initial design and construction costs (6.2.1)
C_0 = surface chloride concentration (7.4.1)
Cl^- = chloride content in concrete
C_s = solution potential of water (5.2.4.3)
C_s = chloride concentration at surface (7.6.2)
C_s = CO_2 concentration at surface (7.9)
C_{ss} = concentration of chloride in soil
C_t = time-dependent chloride concentration
$C(x,t)$= chloride concentration as a function of depth and time
c = concrete cover
c_b = bound chloride ion concentration
c_f = free chloride ion concentration
c_i = chloride ion concentration at the depth of reinforcement (5.2.4.1)
c_i = concentration of species i in solution (5.5)
$c_i(t_i)$= i-th expenditure at time t_i
c_s = sulfate concentration in bulk solution
c_0 = chloride ion concentration at outside surface of concrete
D = apparent diffusion coefficient (5.2.4.1)
D_{28} = 28-day diffusion coefficient
D_c = apparent diffusion coefficient (7.9)
D_i = intrinsic diffusion coefficient of sulfate ions
D_i^0 = diffusion coefficient of species i in free water
D_{MK}= diffusion coefficient for metakaolin concrete
D_n = code-specified dead load
D_{PC} = diffusion coefficient for portland-cement concrete
DR = discount rate (6.2.1)
DR = deterioration rate (7.4.1)
D_{SF} = diffusion coefficient for silica fume concrete
D_T = diffusion coefficient at temperature T
D_{UFFA}= diffusion coefficient for ultra-fine fly ash concrete
D_{ULT}= ultimate diffusion coefficient
$D(i)$ = damage state
$[DS]$= concentration of dissolved sulfide in waste streams
d = diameter of reinforcing bar (7.2)
d = design cover (7.4.1)
d_c = concrete cover
$d_{c,meas}$= measured concrete cover
d_{in} = initial diameter of steel reinforcing bars
E = Young's modulus (5.2.4.2)
E = electric field (5.5)
EFSL= effective functional service life
F = Faraday constant (5.5)
F = future value
$F_0(t)$= service life distribution at the in-service stress level
$F_i(t)$= life distribution at the i-th elevated stress level
H = humidity
ID = noticeable initial surface damage resulting for initiation of corrosion
i_{corr} = corrosion rate
j = fraction of dissolved sulfide preset as H_2S, as a function of pH
j_i = flux of an ion i in solution
j_i^{adv} = flux of an ion i in solution due to advection
j_i^{diff} = flux of an ion i in solution due to diffusion
K = experimentally obtained dissolution-rate constant
K_c = transport coefficient for concrete
K_p = transport coefficient for pasts
k = acceleration factor (5.2.3.1)
k = carbonation coefficient (7.3)
k = acid efficiency coefficient (7.5)
k_e,k_c,k_t = functions that consider the influence of the environment, including results obtained under accelerated and natural conditions
k_f = coefficient related to environmental conditions
L = thickness of concrete element (5.2.4.1)
L = depth of concrete cover (7.3)
L = amount of reinforcement at or below a given cover depth (7.4.1)
L = wall thickness (7.6.1)
L_n = code-specified live load
M = mass loss in time t from an area A (5.2.4.3)
M = applied bending moment of the roofing panel (7.3)
M = resistance number (7.6.1)
m = change in chloride apparent diffusion coefficient (decay coefficient)
N = number of freezing-and-thawing cycles damaging a laboratory specimen (5.2.3.2)
N = NaCl mass of mixing water (7.2)
n = number of years (5.2.5.2)
n = time order (5.4)
o = oxygen concentration
P = freezing-and-thawing resistance index obtained by the Deutscher Beton Verein (DBV) freeze-salt test (5.2.3.2)
P = principal or capital, present value (6.2.1)
p_f = probability of failure
p_i = time transformation function
p_o = target failure probability
p_s = saturated vapor pressure
Q_{cr} = amount of corrosion to cause cracking of the concrete cover
Q_{nyear}= cumulative amount of corrosion
q = corrosion rate (7.2)
q = rate of water transfer (7.6.1)
R = ideal gas constant
$R_{ACC,O}^{-1}$= inverse effective carbonation resistance of dry concrete, determined at a certain point of time t_0 on specimens with the accelerated carbonation test
R_{AT} = rate of degradation in accelerated tests
R_b = compressive strength of concrete
R_s = strength of steel reinforcement
R_d = overall rate of degradation

R_{LT} = rate of degradation in long-term, in-service testing
R_n = nominal or code resistance
R_s = discounted residual value at the end of the life cycle
r = interest rate per year
r = corrosion rate in air
r_{cb} = corrosion rate without chlorides
r_{cl} = corrosion rate with chlorides
S_i = random intensity
s = energy gradient of waste stream
T = temperature (7.2)
T = life cycle (6.2.1)
T = target service life (7.9)
T_{cor} = time to cracking
T_{det} = time after significant corrosion occurrence to deterioration
T_i = time to initiate corrosion
T_m = time to maintenance
T_{rehab}= time to rehabilitation
T_{spall}= time for the spall to occur
t = time
t_1 = service life of a structure
t^* = lifetime of a specimen in an accelerated test
t_1 = service life of a structure
t_{co} = time of waterproofing failure
t_{crack}= contact added to time-to-corrosion to determine service life
t_{yf} = time-to-failure
v = velocity
W = water content per unit volume of concrete (7.2)
W = weather function that considers the effect of meso-climatic conditions (7.9)
X = depth
X_{spall}= thickness of the reaction zone causing the spalling
x = distance from concrete surface to steel reinforcement (5.2.4.1)
x = distance between air exposed side and evaporation zone (7.6.1)
$x_c(T)$= carbonation depth at time T
z = depth of penetration (Eq. (7.6.1a))
z = depth of penetration by capillary suction (Eq. (7.6.1b))
z_i = valence number of the ion
α = parameter based on normal distribution (7.4.1)
α_0 = roughness factor of fracture path
β = statistical parameter
Δd_c = uncertainty in measured concrete cover
Δu = difference in moisture content between the saturated and nonsaturated concrete
ε_t = error term considering the inaccuracies which occur from the accelerated carbonation test method
ε_{xc} = error term that represents the nonuniform carbonation process
λ = mean rate of occurrence
θ = kinetic order of dissolution process
θ_i = initial diameter of the steel reinforcement
$\theta(t)$ = steel diameter at time t
γ_i = activity coefficient of ion i
σ = standard deviation
ρ = density of concrete
τ = duration (7.7)
τ = fracture surface energy of concrete (5.2.4.2)
ν = Poisson's ratio
ψ = electrochemical potential
Φ_{sw} = flux of hydrogen sulfide gas to the pipe wall
ϕ = relative humidity on the air-exposed side

CHAPTER 3—ENVIRONMENT, DESIGN, AND CONSTRUCTION CONSIDERATIONS

3.1—Introduction

Reinforced concrete structures continue to be designed in accordance with national or international consensus codes and standards such as ACI 318, Eurocode 2 (CEN 2006), and the Fédération Internationale du Béton Model Code MC 2010 (*fib* 2013). The codes are developed and based on knowledge acquired in research and testing laboratories and supplemented by field experience. Although present design procedures for concrete are dominated by analytical determinations based on strength principles, designs are increasingly being refined to address durability requirements. Examples include designs that consider resistance to chloride ingress and freezing-and-thawing resistance. Inherent with design calculations and construction documents developed in conformance with these codes is a certain level of durability, such as requirements for concrete cover to protect embedded steel reinforcement under aggressive environmental conditions. Although most reinforced concrete structures have initially met their functional and performance code requirements, numerous examples are available where structures, such as pavements, parking structures, marine structures or bridges, have not exhibited the desired durability or service life. In addition to material selection and proportioning to meet concrete strength requirements, a conscious effort is needed to design and detail concrete structures for long-term durability (Sommerville 1986; Richardson 2003; Bijen 2003). A more holistic approach is necessary for designing concrete structures based on service life considerations. This chapter addresses environmental and structural loading considerations, environmental and structural interaction, and design and construction influences on the service life of structures. Only a brief introduction is provided; refer to ACI 201.2R and ACI 222R for a more in-depth review.

3.2—Environmental considerations

Design of reinforced concrete structures to provide adequate durability is a complicated process. Service life depends on structural design and detailing, mixture proportioning, concrete production and placement, construction methods, and maintenance. Also, loading, environmental exposure, and changes in use are important. Because water or some other liquid is involved in almost every form of concrete degradation, concrete penetrability is important and is composed of three parts:

1. Absorption is the process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body;

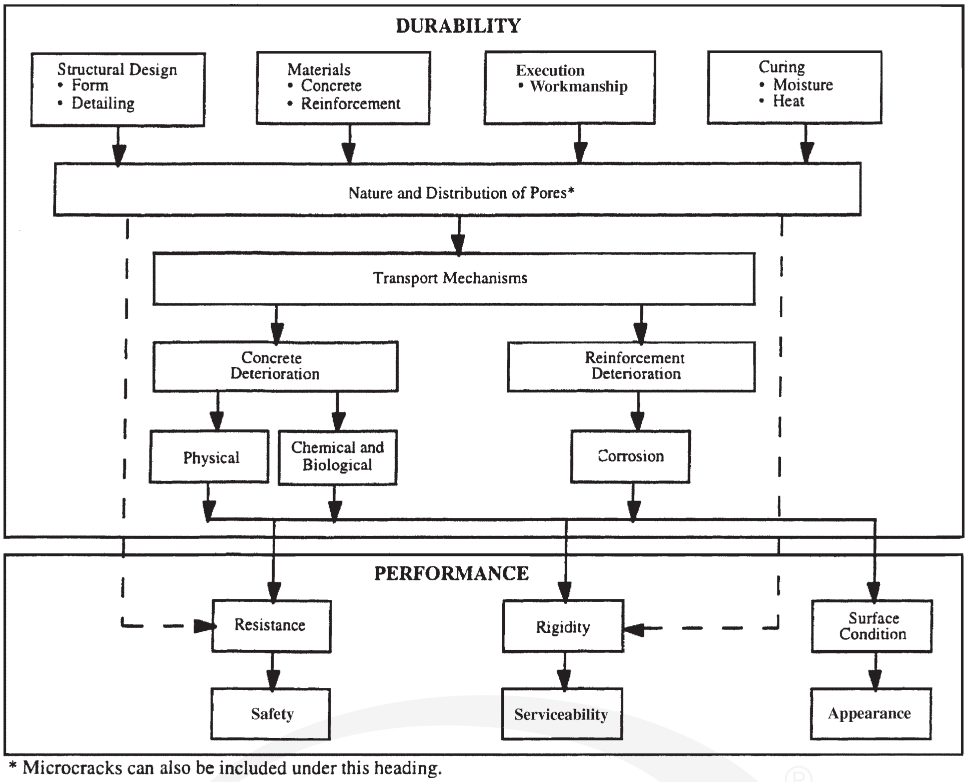

Fig. 3.2—Relationships between the concepts of concrete durability and performance (CEB 1992).

also, the increase in mass of a porous solid body resulting from the penetration of a liquid into its permeable pores

2. Permeability is the ease with which a liquid can flow through a solid under pressure

3. Diffusion is the movement of one medium through another due to concentration gradients

Penetrability is used as a general term encompassing all transport mechanisms. Additional information on the types of transport processes important with respect to the various aspects of concrete durability, such as simple diffusion, diffusion plus reaction, imbibition (capillary suction), and permeation, is available elsewhere (Lawrence 1991; Pommersheim and Clifton 1990; Kropp and Hilsdorf 1995; Nilsson et al. 1997; European Union-Brite EuRam III 2000; Bijen 2003).

The process of chemical and physical deterioration of concrete with time or reduction in durability is generally dependent on the presence and transport of deleterious substances through concrete and the magnitude, frequency, and effect of applied loads. Concrete durability and performance are related concepts, as shown in Fig. 3.2 (CEB 1992).

Figure 3.2 shows that the combined transportation of heat, moisture, and chemicals, both within the concrete and in exchange with the surrounding environment, and the parameters controlling the transport mechanisms constitute the principal elements of durability. The rate, extent, and effect of fluid transport are largely dependent on the concrete pore structure, which is the size distribution and tortuosity, presence of cracks, and microclimate at the concrete surface. The primary mode of transport in uncracked concrete is through the bulk cement paste pore structure and transition zone, which is the interfacial region between the particles of aggregate and hydrated cement paste. The physical-chemical phenomena associated with liquid movement through porous solids is controlled by the solid's permeability. Although the coefficient of permeability of concrete depends primarily on the water-cementitious materials ratio (*w/cm*), paste fraction, and maximum aggregate size, it is also influenced by age, consolidation, curing temperature, drying, and the addition of chemical or supplementary cementitious materials (SCMs). Concrete is generally more permeable than cement paste due to the presence of microcracks in the transition zone between the cement paste and aggregate (Mehta 1986; Collepardi 2006). Table 3.2a presents a series of different concrete mixtures, made using 3/4 in. (19 mm) maximum size crushed limestone aggregate for which sample transport-related properties were measured as shown in Table 3.2b. The results presented are for this testing method, and would be somewhat different if another testing method had been used.

Two additional factors considered for construction of durable concrete structures are the environmental exposure condition and the specific design recommendations pertaining to the expected form of aggressive chemical or physical attack. An example is designing a structure to minimize the accumulation of water. Exposure conditions or severity are generally handled through a specification that addresses the concrete mixture such as its strength, *w/cm*, and cement content, and details such as concrete cover, as dictated by the anticipated exposure. The following paragraphs are summary descriptions of the primary chemical