Report on Service Life Prediction

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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

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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