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Report on Application of Nanotechnology and Nanomaterials in Concrete

Reported by ACI Committees 236 and 241

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This report presents information on nanotechnology of concrete, including recent developments related to investigation of nanostructure and nanodesign of cement-based materials, the effects of nanoparticles, field applications, and health and environmental safety concerns related to the use of nanomaterials.

Keywords: biomimicry; carbon nanofibers; carbon nanotubes; nanobinder; nanoclay; nanoindentation; nanoparticles; nanosilica; nanotechnology; nanotitanium dioxide; superhydrophobic concrete.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Nanotechnology is a multidisciplinary field of science and engineering focused on understanding and controlling matter at dimensions between 1 and 100 nanometers, where unique phenomena enable novel applications.

Nanotechnology was first introduced by Feynman (1960) and is rapidly becoming an interdisciplinary field; many developments have emerged in physics, chemistry, biology, and engineering in the study of various materials or substances at the nanoscale.

There are two main approaches in nanotechnology: 1) the top-down approach, in which larger structures are reduced in size to the nanoscale while maintaining their original properties without atomic-level control (for example, miniaturization in the domain of electronics), or deconstructed from larger structures into smaller, composite parts (top part of Fig. 1.1a); and 2) the bottom-up approach, also called molecular nanotechnology or molecular manufacturing, introduced by Drexler et al. (1991), in which materials are engineered from atoms, or molecular components, through a process of assembly or self-assembly (bottom part of Fig. 1.1a). While most contemporary technologies, including concrete, rely on the top-down approach, molecular nanotechnology holds great promise for advancement in materials and manufacturing, electronics, medicine and healthcare, energy, biotechnology, information technology, and national security.

Nanoscience and nanoengineering are commonly-used terms that describe nanotechnology applications in concrete (Sobolev and Ferrada-Gutiérrez 2005a; Scrivener and Kirkpatrick 2008; Scrivener 2009; Raki et al. 2009; Garboczi 2009). To date, nanotechnology applications and advances in the fields of construction and building materials have been inconsistent (Bartos 2009; Sanchez and Sobolev 2010; Sobolev and Sanchez 2012). Implementing nanotechnology into concrete on a commercial scale remains limited. Some research developments, however, have been successfully converted into marketable products. The main advances have been in nanoscience of cementitious and pozzolanic materials, providing an increase in the knowledge and understanding of basic phenomena in cement at the nanoscale (Scrivener and Kirkpatrick 2008; Scrivener 2009). Examples include structure and mechanical properties of the main hydrate phases, origins of cement cohesion, cement hydration, interfaces in concrete, and mechanisms of degradation. Recent innovations in instrumentation for observing and measuring at the nanoscale are providing a wealth of new and unprecedented information about concrete. This information is crucial for a better understanding of mechanisms and factors influencing performance requirements, as well as predicting the service life of concrete and providing new insights for improvement. Important summaries and compilations of nanotechnology in construction can be found in Sobolev and Ferrada-Gutiérrez (2005a), Bartos et al. (2006), de Miguel et al. (2006), Scrivener and Kirkpatrick (2008), Sobolev and Shah (2008), Sobolev et al. (2008b), Sanchez

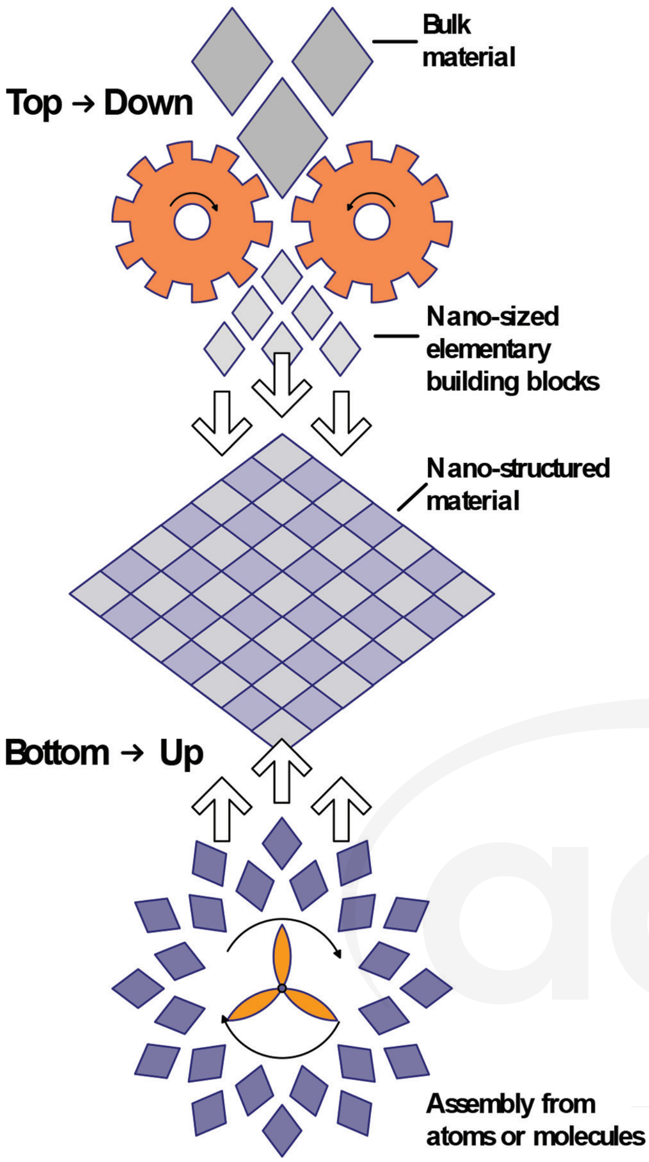

Fig. 1.1a—Illustration of the top-down and bottom-up approaches in nanotechnology (Sobolev and Ferrada-Gutiérrez 2005a).

and Sobolev (2010), Sobolev and Sanchez (2012), and Birgisson et al. (2012).

Concrete, the most ubiquitous construction material, is a "nanostructured, multiphase, porous composite material, composed of amorphous phases, nanometer- to micrometer-size crystals, and bound and free water" (Sanchez and Sobolev 2010). The properties of concrete exist at multiple length scales, nano to micro to macro (Fig. 1.1b). The properties of each scale derive from those of the next-smaller scale (Jennings et al. 2008; Sanchez et al. 2009). The amorphous phase, calcium-silicate-hydrate (C-S-H), is the phase that holds concrete together (Chong and Garboczi 2002), and is itself a nanostructured material (Fig. 1.1c).

Viewed from the bottom-up, concrete at the nanoscale is a composite of molecular assemblages, surfaces such as aggregates and fibers, and chemical bonds that interact through local chemical reactions, intermolecular forces, and intra-phase diffusion. Properties characterizing this scale include surface properties and chemical bond properties such as type, length, strength/energy, and density. Structures of the amorphous and crystalline phases and the interphase boundaries originate from this scale. Properties and processes at the nanoscale define interactions that occur between particles and phases at the microscale, the effects of working loads, and the surrounding environment at the macroscale. Processes occurring at the nanoscale ultimately affect the engineering properties and performance of the bulk material (Garboczi and Bentz 1996, 1998; Xi et al. 2000; Jennings et al. 2008; Scrivener and Kirkpatrick 2008; Sanchez et al. 2009).

1.2—Scope

This report provides information for those involved in concrete design and construction so they are familiar with the factors involved in the effective use of nanomaterials and nanotechnology. This document is not intended as a primary reference source for researchers. Rather, it is aimed at engineers and architects who wish to gain further understanding of the effects of nanomaterials and nanoadditives being used or proposed for application in concrete.

Application of available technology is demonstrated for a range of nanoconcrete structures to show that technological risks are at a known and acceptable level and high industry standards maintained. An overview reports on the main developments in the fields of nanotechnology and nanoscience that are related to concrete, along with their implications and key findings. Factors affecting performance of fresh and hardened concrete are discussed to enable those involved in the evaluation and formulation of concrete mixtures to determine the effects of these factors.

The potential of nanotechnology to improve concrete performance can lead to the development of novel, sustainable, advanced cement-based composites with unique mechanical, thermal, and electrical properties. New developments have already taken place in nanoengineering and nanomodification of concrete. Current challenges, including proper dispersion, compatibility of the nanomaterials in cement, processing, manufacturing, safety, handling issues, and cost all need to be solved before the complete potential of nanotechnology can be realized in concrete applications. Additionally, introduction of these novel materials into the construction practice requires an evaluation and understanding of their potential impact on the environment and human health.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = aluminum oxide (Al_2O_3)
A_i = area of indentation impression, μm^2
C = calcium oxide (CaO)
$CaCO_3$ = calcium carbonate
CH = calcium hydroxide
C/S = the molar or mass ratio of calcium oxide (CaO) to silicon dioxide (SiO_2)
C-S-H = amorphous calcium silicate hydrate phase

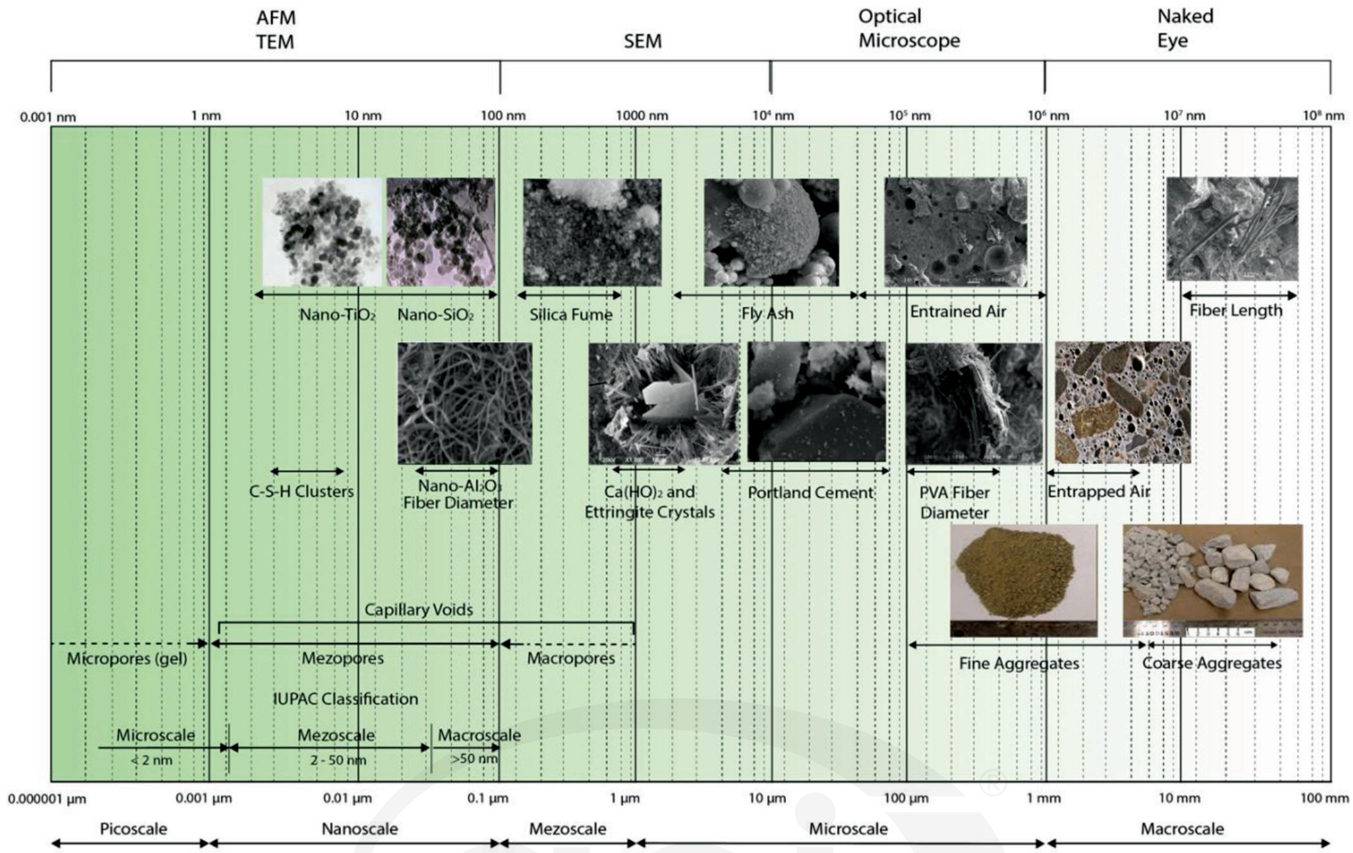

Fig. 1.1b—The multiple length scales related to concrete technology (Sobolev 2016).

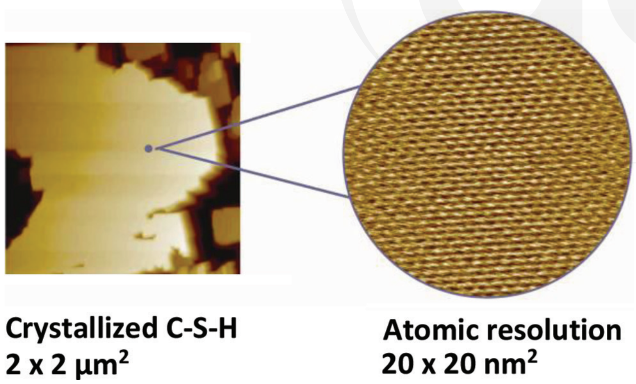

Fig. 1.1c—Nanoscale structure of C-S-H crystallized on calcite substrate as revealed by atomic force microscope (AFM) (Sobolev and Ferrada-Gutiérrez 2005a).

C_3A = tricalcium aluminate
C_3S = tricalcium silicate, alite
E = Young's modulus, GPa
E' = storage modulus, GPa
E_i = Young's elastic modulus of the indenter, GPa (for diamond, E_i = 1141 GPa)
E_r = reduced modulus of concrete, GPa
F = iron oxide or ferric oxide (Fe_2O_3)
H = concrete hardness, Pa
h_a = displacement of surface at perimeter, nm
h_e = elastic impression depth, nm
h_p = contact indentation depth, nm
h_r = residual impression depth, nm
h_t = total impression depth, nm
k = stiffness of probe cantilever ($k = 3EI/L^3$), N/m
k^* = contact stiffness, N/m
$MgAl_2O_4$ = magnesium aluminum oxide
m% = percent by mass
NO_x = nitrogen oxide
P = load, N
P_t = maximum indentation load, mN
S = silica dioxide (SiO_2)
S_c = contact stiffness or compliance
tanδ = internal friction
TiO_2 = titanium dioxide
vol% = percent by volume
$ZnFe_2O_4$ = zinc iron oxide
β = coefficient for Berkovich indenter (= 1.034)
β-C_2S = β-dicalcium silicate, belite
λ^* = eigenvalue
Θ = contact angle, degrees
ν_c = Poisson's ratio of concrete
ν_I = Poisson's ratio of indenter

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology" (https://www.concrete.org/portals/0/files/pdf/ACI_Concrete_Terminology.pdf). Definitions provided herein complement that resource.