Construction and Building Materials 24 (2010) 2060–2071

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

Nanotechnology in concrete – A review

Florence Sanchez [a,*], Konstantin Sobolev [b]

[a] Department of Civil and Environmental Engineering, Vanderbilt University, VU B 35 1831, Nashville, TN 37235, USA
[b] Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee, P.O. Box 784, Milwaukee, WI 53201, USA

ARTICLE INFO

Article history:
Received 3 July 2009
Received in revised form 16 March 2010
Accepted 28 March 2010
Available online 15 May 2010

Keywords:
Concrete
Cement
Nanotechnology
Nanoscience
Nano-engineering
Nanomodification

ABSTRACT

This paper reviews the state of the field of nanotechnology in concrete. Definitions of nanotechnology, including nanoscience and nano-engineering in concrete, are provided. The impact of recent advances in instrumentation and computational materials science and their use in concrete research is discussed. Recent progress in nano-engineering and nanomodification of cement-based materials is presented.

Contents

1. Introduction

Since nanotechnology was introduced by Nobel laureate Richard P. Feynman during his now famous 1959 lecture "*There's Plenty of Room at the Bottom*," [1] there have been many revolutionary developments in physics, chemistry, and biology that have demonstrated Feynman's ideas of manipulating matter at an extremely small scale, the level of molecules and atoms, i.e., the nanoscale.

While the meaning of "nanotechnology" varies from field to field and country to country and is widely used as a "catch all" description for anything very small, nanotechnology is commonly

* Corresponding author. Tel.: +1 615 322 5135; fax: +1 615 322 3365.
E-mail address: florence.sanchez@vanderbilt.edu (F. Sanchez).

0950-0618/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2010.03.014

defined as the understanding, control, and restructuring of matter on the order of nanometers (i.e., less than 100 nm) to create materials with fundamentally new properties and functions [2]. Nanotechnology encompasses two main approaches: (i) the "top-down" approach, in which larger structures are reduced in size to the nanoscale while maintaining their original properties without atomic-level control (e.g., miniaturization in the domain of electronics) or deconstructed from larger structures into their smaller, composite parts and (ii) the "bottom-up" approach, also called "molecular nanotechnology" or "molecular manufacturing," introduced by Drexler et al. [3], in which materials are engineered from atoms or molecular components through a process of assembly or self-assembly (Fig. 1). While most contemporary technologies rely on the "top-down" approach, molecular nanotechnology holds great promise for breakthroughs in materials and manufacturing, electronics, medicine and healthcare, energy, biotechnology, information technology, and national security.

To date, nanotechnology applications and advances in the construction and building materials fields have been uneven [4]. Exploitation of nanotechnology in concrete on a commercial scale remains limited with few results successfully converted into marketable products. The main advances have been in the nanoscience of cementitious materials [5,6] with an increase in the knowledge and understanding of basic phenomena in cement at the nanoscale (e.g., structure and mechanical properties of the main hydrate phases, origins of cement cohesion, cement hydration, interfaces in concrete, and mechanisms of degradation). Recent strides in instrumentation for observation and measurement at the nanoscale are providing a wealth of new and unprecedented information about concrete, some of which is confounding previous conventional thinking. Important earlier summaries and compilations of nanotechnology in construction can be found in [5,7–11]. This paper reviews the main developments in the field of nanotechnology and nanoscience research in concrete, along with their implications and key findings. The paper is divided into three main sections: (i) definitions of nanotechnology in concrete, (ii) advances in instrumentation and computational materials science, and (iii) nano-engineering of cement-based materials.

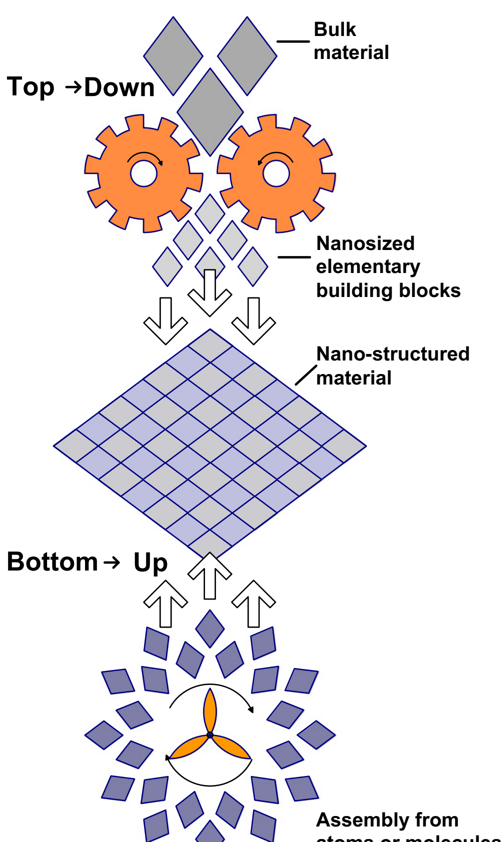

Fig. 1. Illustration of the "top-down" and "bottom-up" approaches in nanotechnology. Adapted from [108].

2. Nanotechnology and concrete: definitions

2.1. Concrete: a complex, nano-structured material

Concrete, the most ubiquitous material in the world, is a nano-structured, multi-phase, composite material that ages over time. It is composed of an amorphous phase, nanometer to micrometer size crystals, and bound water. The properties of concrete exist in, and the degradation mechanisms occur across, multiple length scales (nano to micro to macro) where the properties of each scale derive from those of the next smaller scale [12–14]. The amorphous phase, calcium–silicate–hydrate (C–S–H) is the "glue" that holds concrete together [15] and is itself a nanomaterial (Fig. 2).

Viewed from the bottom-up, concrete at the nanoscale is a composite of molecular assemblages, surfaces (aggregates, fibers), and chemical bonds that interact through local chemical reactions, intermolecular forces, and intraphase diffusion. Properties characterizing this scale are molecular structure; surface functional groups; and bond length, strength (energy), and density. The structure of the amorphous and crystalline phases and of the interphase boundaries originates from this scale. The properties and processes at the nanoscale define the interactions that occur between particles and phases at the microscale and 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 [5,12,13,16–18].

2.2. Definition of nanotechnology in concrete

The nanoscience and nano-engineering, sometimes called nanomodification, of concrete are terms that have come into common usage and describe two main avenues of application of nanotechnology in concrete research [5,6,19,20]. *Nanoscience* deals with the measurement and characterization of the nano and microscale structure of cement-based materials to better understand how this structure affects macroscale properties and performance through the use of advanced characterization techniques and atomistic or molecular level modeling. *Nano-engineering* encompasses the techniques of manipulation of the structure at the nanometer scale to develop a new generation of tailored, multifunctional, cementitious composites with superior mechanical performance and durability potentially having a range of novel properties such as: low electrical resistivity, self-sensing capabilities, self-cleaning, self-healing, high ductility, and self-control of cracks. Concrete can be nano-engineered by the incorporation of nanosized building blocks or objects (e.g., nanoparticles and nanotubes) to control material behavior and add novel properties, or by the grafting of molecules onto cement particles, cement phases, aggregates, and additives (including nanosized additives) to provide surface functionality, which can be adjusted to promote specific interfacial interactions.

3. Advances in instrumentation and computational materials science

Advances in the characterization of the nanoscale structure of cement-based materials and in computational materials science have provided scientists and engineers with promising new tools