Report on Application of Nanotechnology and Nanomaterials in Concrete

Reported by ACI Committees 236 and 241

ACI 241R-17

American Concrete Institute
Always advancing

American Concrete Institute
Always advancing

First Printing
January 2017
ISBN: 978-1-945487-50-7

Report on Application of Nanotechnology and Nanomaterials in Concrete

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at http://concrete.org/Publications/DocumentErrata.aspx. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided "as is" without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised ACI Manual of Concrete Practice (MCP).

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 241R-17

Report on Application of Nanotechnology and Nanomaterials in Concrete

Reported by ACI Committees 236 and 241

ACI Committee 241

Konstantin Sobolev, Chair

Mahmoud M. Reda Taha, Secretary

Aali R. Alizadeh
Muhammed P. A. Basheer
Jon S. Belkowitz
Haroldo de Mayo Bernardes
Jeremy Betts
Paul W. Brown
Samir E. Chidiac
Vyatcheslav R. Falikman
Liberato Ferrara
Ismael Flores-Vivian
Brian H. Green
William S. Hart
Aulis Kappi
Shiho Kawashima
Maria S. Konsta-Gdoutos
Konstantin Kovler
Kimberly E. Kurtis
David A. Lange
Berengere Lebental
Samuel J. Lines
Viktor Mechtcherine
Anol Kanti Mukhopadhyay
Jose F. Munoz
Scott Muzenski
Moncef L. Nehdi
Narayanan Neithalath
Kamran M. Nemati
Jan Olek
H. Celik Ozyildirim
Alva Peled
Amirpasha Peyvandi
Amal Puthur-Jayapalan
Laila Raki
Todd S. Rushing
Aly Said
Florence Sanchez
Surendra P. Shah
Lin Shen
Mohammed Sonebi
Dietmar Stephan
Valeria Strokova
Peter Stynoski
Zhihui Sun
Jussara Tanesi
Kejin Wang
Kay Wille
Brett Anthony Williams
Erik E. Wotring
Ardavan Yazdanbakhsh
Min-Hong Zhang
Igor Zhernovsky
Consulting Member
Mohamadreza Moini

Committee 236

The following voting members from Committee 236 drafted and voted on the initial report.

Maria G. Juenger, Chair
Zachary C. Grasley*, Secretary

Voting Members
Emmanuel K. Attiogbe
Muhammed P. A. Basheer*
Jeremy Betts*
Joseph J. Biernacki
Andrew J. Boyd
Paul W. Brown*
Van K. Bui
Jeffrey W. Bullard
Frederic Chapdelaine
Samir E. Chidiac*
Peter A. Claisse*
Neil J. Crockett
Matthew D. D'Ambrosia
Christopher C. Ferraro
Mette Geiker
R. Doug Hooton
Jason H. Ideker
O. Burkan Isgor
Ara A. Jeknavorian
Aulis Kappi*
Kamal H. Khayat
Eric P. Koehler
Konstantin Kovler*
Kimberly E. Kurtis*
David A. Lange*
Tyler Ley
Jacques Marchand
Benjamin J. Mohr
Paramita Mondal*
Anol Kanti Mukhopadhyay*
Moncef L. Nehdi*
Narayanan Neithalath*
Kamran M. Nemati*
Michelle R. Nokken
Jan Olek*
Sulapha Peethamparan*
Vincent Picandet
Aleksandra Radlinska
Laila Raki*
Prasad R. Rangaraju*
Mahmoud M. Reda Taha*
Kyle Austin Riding
David A. Rothstein
Della M. Roy
Aly Said*
Florence Sanchez*
Gaurav N. Sant*
Yixin Shao
Caijun Shi
Kenneth Snyder
Konstantin Sobolev†
Mohammed Sonebi*
Jussara Tanesi*
Peter C. Taylor*
Michael D. A. Thomas
David Trejo
Wilasa Vichit-Vadakan
Kejin Wang*
Zhaozhou Zhang

Subcommittee Members
Aali Alizadeh*
Mohamed Bassuoni*
Jon Belkowitz*
Haroldo de Mayo Bernardes*
Chul-Woo Chung*
Deborah D. L. Chung*
Vyatcheslav Falikman*
Liberato Ferrara*
Ismael Flores-Vivian*
Nishant Garg*
Brian Green*
William S. Hart*
Payam Hosseini*
Maria S. Konsta *
Berengere Lebental*
Samuel Lines*
Viktor Mechtcherine*
Jose Munoz*
H Celik Ozyildirim*
Bekir Pekmezci*
Alva Peled*
Amal Puthur-Jayapalan*
Todd S. Rushing*
Joan Schoepfer*
Surendra P. Shah*
Lin Shen*
Caijun Shi*
Valeria Strokova*
Peter Stynoski*
Zhihui Sun*
Jacqueline N. Villa Prenger*
Brett Williams*
Min-Hong Zhang*
Igor Zhernovsky*

Consulting Members
Barbara Lothenbach
Weiping Ma
Frank Winnefeld

*Members of 236D subcommittee who drafted this report.
†Chair of 236D subcommittee who drafted this report.

Members of Committees 236 and 241 thank J. Beaudoin, M. Rahman, J. Kim, L. Brown, C. Gay, and T. Sato for their contributions to this report.

ACI 241R-17 was adopted and published January2017.

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.

CONTENTS

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