3D Concrete Printing Technology
Construction and Building Applications
3D Concrete Printing Technology
Construction and Building Applications

Edited by

JAY G. SANJAYAN
Centre for Sustainable Infrastructure, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia

ALI NAZARI
Centre for Sustainable Infrastructure, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia

BEHZAD NEMATOLLAHI
Centre for Sustainable Infrastructure, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia

Elsevier
Butterworth-Heinemann
An imprint of Elsevier
DEDICATION

3D concrete printing is an entirely new field and putting it into practice in real life requires years of efforts. Not only equipment and facilities are necessary, but trained researchers, industry professionals, and investors are essential to develop this exciting technology. People who are currently developing 3D concrete printing are the pioneers in this field whose perseverance and belief in the technology will definitely be appreciated by the wider community in the not-so-distant future. This book is dedicated to all those who believe in the technology and make serious efforts to make 3D concrete printing a commercially successful technology.
LIST OF CONTRIBUTORS

Ghassan K. Al-Chaar
Construction Engineering Research Laboratory, US Army Engineer Research and Development Center, Champaign, IL, United States

Fatima AlSakka
Civil and Environmental Engineering, American University of Beirut, Beirut, Lebanon

Daniel Avrutis
Centre for Sustainable Infrastructure, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia

Lynette A. Barna
Cold Regions Research and Engineering Laboratory, US Army Engineer Research and Development Center, Hanover, NH, United States

Dale P. Bentz
Materials and Structural Systems Division, Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, United States

Isaiah R. Bentz
Materials and Structural Systems Division, Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, United States

C. Bouyssou
XtreeE, Rungis, France

Jedadiah F. Burroughs
Geotechnical and Structures Laboratory, US Army Engineer Research and Development Center, Vicksburg, MS, United States

Xiangpeng Cao
Shenzhen Mingyuan Building Technology Co., Ltd., Shenzhen, P.R. China

Michael P. Case
Construction Engineering Research Laboratory, US Army Engineer Research and Development Center, Champaign, IL, United States

Jian-Fei Chen
School of Planning, Architecture and Civil Engineering, Queen’s University Belfast, Northern Ireland, United Kingdom

J. Dirrenberger
XtreeE, Rungis, France; Laboratoire PIMM, Arts et Métiers-ParisTech, Cnam, CNRS UMR 8006, Paris, France

R. Duballet
XtreeE, Rungis, France; Laboratoire Navier, UMR 8205, Ecole des Ponts, IFSTTAR, CNRS, UPE, Paris, France
Laurie Edwards
Boral Innovation Factory, Australia

Peng Feng
Department of Civil Engineering, Tsinghua University, Beijing, P.R. China

N. Gaudillière
XtreeE, Rungis, France; Laboratoire GSA, Ecole Nationale Supérieure d’Architecture Paris-Malaquais, Paris, France

Manuel Hambach
Chair of Solid State and Materials Chemistry, University of Augsburg, Augsburg, Germany

Farook Hamzeh
Civil and Environmental Engineering, American University of Beirut, Beirut, Lebanon

Camille Holt
Boral Innovation Factory, Australia

Young Kwang Hwang
School of Civil and Environmental Engineering, College of Engineering, Yonsei University, Seoul, Republic of Korea

Scott Z. Jones
Materials and Structural Systems Division, Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, United States

Ali Kazemian
The Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, United States; Department of Computer Science, University of Southern California, Los Angeles, CA, United States; Contour Crafting Corporation, El Segundo, CA, United States

Louise Keyte
Boral Innovation Factory, Australia

Behrokh Khoshnevis
The Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, United States; Contour Crafting Corporation, El Segundo, CA, United States; Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA, United States

Megan A. Kreiger
Construction Engineering Research Laboratory, US Army Engineer Research and Development Center, Champaign, IL, United States

Mingyang Li
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, Singapore
Zhijian Li
College of Architecture and Civil Engineering, Beijing University of Technology, Beijing, P.R. China; School of Civil Engineering and Transportation, Hebei University of Technology, Tianjin, P.R. China

Zongjin Li
Institute of Applied Physics and Materials Engineering, University of Macau, Macau, P.R. China

Yun Mook Lim
School of Civil and Environmental Engineering, College of Engineering, Yonsei University, Seoul, Republic of Korea

Guowei Ma
School of Civil Engineering and Transportation, Hebei University of Technology, Tianjin, P.R. China; School of Civil, Environmental and Mining Engineering, The University of Western Australia, Crawley, WA, Australia

Zeina Malaeb
Civil and Environmental Engineering, American University of Beirut, Beirut, Lebanon

A. Mallet
XtreeE, Rungis, France

Taylor Marchment
Centre for Sustainable Infrastructure, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia

Viktor Mechtcherine
Technische Universität Dresden, Institute of Construction Materials, Dresden, Germany

Ryan Meier
The Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, United States

Xinmiao Meng
Department of Civil Engineering, Beijing Forestry University, Beijing, P.R. China

Farzad Moghaddam
Boral Innovation Factory, Australia

Young Jun Nam
School of Civil and Environmental Engineering, College of Engineering, Yonsei University, Seoul, Republic of Korea

Ali Nazari
Centre for Sustainable Infrastructure, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia
Dirk Volkmer
Chair of Solid State and Materials Chemistry, University of Augsburg, Augsburg, Germany

Li Wang
School of Civil Engineering and Transportation, Hebei University of Technology, Tianjin, P.R. China

Yiwei Weng
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore Singapore; School of Civil and Environment Engineering, Nanyang Technological University, Singapore, Singapore

Ming Xia
Centre for Sustainable Infrastructure, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia

Lieping Ye
Department of Civil Engineering, Tsinghua University, Beijing, P.R. China

Xiao Yuan
Contour Crafting Corporation, El Segundo, CA, United States

M. Zakeri
XtreeE, Rungis, France
Construction-related spending is $10 trillion globally, equivalent to 13% of GDP. This makes construction one of the largest sectors of the world economy. However, construction has suffered for decades from remarkably poor productivity relative to other sectors. Global labor-productivity growth in construction has averaged only 1% per year over the past two decades (and was flat in most advanced economies). Contrasted with growth of 2.8% in the world economy and 3.6% in manufacturing, this clearly indicates that the construction sector is underperforming. While many sectors including agriculture and manufacturing have increased productivity 10–15 times since the 1950s, the productivity of construction remains stuck at the same level as 80 years ago. Current measurements find that there has been a consistent decline in the industry’s productivity since the late 1960s (McKinsey Global Institute, 2017). Construction remains largely manual, while manufacturing and other industries have made significant progress in the use of digital, sensing, and automation technologies.

In the past few years, many of us have witnessed the wide availability of 3D printers in consumer markets using various types of plastic filaments based on fused deposition modeling technology. 3D printers using metals are becoming commonplace in advanced industries. 3D printing was made famous by the former US President Barak Obama during his 2013 State of the Union Address as a technology that has “the potential to revolutionize the way we make almost everything.” These events have generated significant interest among construction researchers and construction industry innovators in attempting 3D printing using concrete. They envision the 3D printing technology as a way of introducing much-needed automation in construction.

Unlike the conventional approach of casting concrete into a mold (formwork), 3D printing will combine digital technology and new insights from materials technology to allow free-form construction without the use of formwork. Recent advances in numerical control technology, sensing technology, and automatic driving systems with improved functions and accuracy are new enablers for 3D concrete printing. While the technology enthusiasts interested in 3D printing are optimistic, the technology is still in its infancy. The early researchers have identified the key challenges