

Baoguo Han · Liqing Zhang
Jinping Ou

Smart and Multifunctional Concrete Toward Sustainable Infrastructures

 Springer

Smart and Multifunctional Concrete Toward Sustainable Infrastructures

Baoguo Han · Liqing Zhang
Jinping Ou

Smart and Multifunctional Concrete Toward Sustainable Infrastructures

 Springer

Baoguo Han
School of Civil Engineering
Dalian University of Technology
Dalian
China

Jinping Ou
School of Civil Engineering
Dalian University of Technology
Dalian
China

Liqing Zhang
School of Civil Engineering
Dalian University of Technology
Dalian
China

and
School of Civil Engineering
Harbin Institute of Technology
Harbin
China

ISBN 978-981-10-4348-2 ISBN 978-981-10-4349-9 (eBook)
DOI 10.1007/978-981-10-4349-9

Library of Congress Control Number: 2017937727

© Springer Nature Singapore Pte Ltd. 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

To the families!

—Baoguo Han, Liqing Zhang, Jinping Ou

Preface

With the rapid consumption of more and more resources, the quality of energy stored in resources decreases to cause the relentless increase in entropy on the earth. Due to material performance, degeneration and external action failures are inevitable during the service of structures. Material and structure system sinks into a crisis of entropy increment, i.e., availability loss. With the advance of science and technology and the upgrading of social demand, materials have been driven to further develop toward material/structure integration, structure/function integration, and multifunctionality/intelligence integration for defusing this crisis. Smart and multifunctional material is an area of technology that is integrated with sensing and actuation functionality, and those functions are combined with control elements. It usually has one or more properties which can be changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields. Depending on the changes in external conditions, smart and multifunctional materials can change either their properties (mechanical, electrical, appearance), structure, composition, or their functions. They therefore possess strong and effective capability to control entropy for adapting external environment and avoiding availability reduction. Many new applications of smart and multifunctional material technology have been found in civil infrastructures, and they represent an emerging research field. These applications include condition/health monitoring, damage assessment, structural control, structural repair and maintenance, integrity assessment and more recently asset management, preservation, and operation of civil infrastructures. The relative technologies possess many potential benefits such as improved infrastructure reliability and longevity, enhanced structural performance and durability, improved safety against natural hazards and vibrations, and reduced life cycle costs in operating and managing civil infrastructures.

Concrete is the most widely used material for infrastructures because it has excellent mechanical strength and is resistant to water, easily formed into various shapes and sizes, and cheap and readily available everywhere. Twice as much concrete is used in infrastructures around the world as the total of all other building materials, including wood, steel, plastic, and aluminum. Production and application

of concrete have significant impact on resources, energy, and environment. Although the production of concrete binder (e.g., cement, asphalt) needs intensive energy, concrete has more excellent ecological profile than other construction materials such as metal, glass, and polymers. Compared with other construction materials, the production of concrete consumes the least amount of materials and energy, produces the least amount of harmful by-products, and causes the least amount of damage to environment. Concrete is a responsible choice for sustainable development. In the foreseeable future, concrete will continue to play an important role in infrastructure construction. However, the development of concrete is encountering enormous problems and challenges. (1) Binder manufacturing has a direct and visible negative impact on the world's resources, energy consumption, and environment. For example, making 1 ton of cement requires about 2 tons of raw material (limestone and shale); consumes about 4 GJ of energy in electricity, process heat, and transport (energy equivalent to 131 cubic meters of natural gas); and produces approximately 1 ton of CO₂, about 3 kg of NO_x (an air contaminant that contributes to ground-level smog), and about 0.4 kg of PM10 (an airborne particulate matter harmful to respiratory tract when inhaled). (2) Increasing attention has been paid to security of infrastructures since concrete is a brittle material and it usually works with cracks. (3) The durability of infrastructures becomes an increasingly important issue. Due to the degeneration of concrete materials, complex interaction between concrete materials and their service environment, absence of advanced design and condition assessment tools, and timely maintenance, many concrete structures are in a state of utter disrepair. It is therefore needed to render the failing infrastructures back to a serviceable and safe state. (4) Concrete belongs to a primary and complex composite in nature. The behaviors of concrete during the life cycle should be able to be controlled through mass, energy, or information exchange with external environment. (5) Multifunctional and smart concrete is required since traditional concrete just serving as structural materials cannot meet the upgrading requirement in terms of safety, longevity, and function of advanced engineering infrastructures. (6) The complex composition and structure of concrete has not been completely understood yet, which limits the utility and predictability of concrete in critical applications, but offers opportunities for formulation of additional control. Smart and multifunctional concrete provides a suite of capabilities to address these unmet needs in the infrastructure field, by developing materials with improved performance, better durability, and reduced environmental impact.

Smart and multifunctional concrete is an intelligent system with properties different from those of conventional concrete, such as self-sensing, self-healing, electrically conductive, thermal, and electromagnetic properties, or the ability to react upon an external stimulus, such as stress and temperature. The “smartness and multifunction” of concrete is achieved through material composition design, special processing, introduction of other functional components, or modification of microstructure. The basic principle of smart and multifunctional concrete is based on biomimetic design, and multiscale and multicomponent compositization. The concept of smart and multifunctional concrete was developed in the late 1980s.

In the past nearly four decades, much work has been done on the development and deployment of smart and multifunctional concrete. This book provide a summary report on current researches on smart and multifunctional concrete to help people working on this particular aspect to their job better.

This book covers theory, techniques, and applications of smart and multifunctional concrete containing its design, fabrication and processing, test and characterization, properties and their control method, mechanisms and models, application in infrastructures, and future development. This book is organized as shown below. The first part provides a general introduction to the smart and multifunctional concrete (Chap. 1). The second part presents some specific smart or multifunctional concrete involving self-compacting concrete (Chap. 2), self-expanding concrete (Chap. 3), self-curing concrete (Chap. 4), self-shaping concrete (Chap. 5), self-sensing concrete (Chap. 6), self-healing concrete (Chap. 7), self-adjusting concrete (Chap. 8), damping concrete (Chap. 9), anti-spalling concrete (Chap. 10), wear resisting concrete (Chap. 11), aircraft arresting concrete (Chap. 12), electrically conductive concrete (Chap. 13), electrothermal concrete (Chap. 14), light-transmitting concrete (Chap. 15), light-emitting concrete (Chap. 16), photocatalytic concrete (Chap. 17), electromagnetic wave shielding/absorbing concrete (Chap. 18), radiation shielding concrete (Chap. 19), hydrophobic/superhydrophobic concrete (Chap. 20), permeable concrete (Chap. 21), nondispersible underwater concrete (Chap. 22), and energy harvesting concrete (Chap. 23). Finally, the third part discusses the future challenges for continued development and deployment of smart and multifunctional concrete (Chap. 24).

Dalian, China
Dalian, China
Dalian/Harbin, China

Baoguo Han
Liqing Zhang
Jinping Ou

Acknowledgements

Many professional colleagues and friends have contributed directly or indirectly to this book, and we thank all these people. This book is funded by National Science Foundation of China (grant Nos. 51578110, 51428801, 51178148 and 50808055), Program for New Century Excellent Talents in University of China (grant No. NCET-11-0798), and the Ministry of Science and Technology of China (grant No. 2011BAK02B01). We also thank Springer for his enthusiastic and hard work to make the publication possible.

Contents

1	General Introduction of Smart and Multifunctional Concrete	1
1.1	Introduction	1
1.2	Definition of Smart and Multifunctional Concrete	3
1.3	Classification of Smart and Multifunctional Concrete	3
1.4	Origin of Smart and Multifunctional Concrete	5
1.5	Philosophical Foundation of Smart and Multifunctional Concrete	5
1.6	Summary	7
	References	8
2	Self-Compacting Concrete	11
2.1	Introduction	11
2.2	Definition and Classification of Self-Compacting Concrete	12
2.3	Principles of Self-Compacting Concrete	13
2.3.1	Raw Material Selection Principles	13
2.3.2	Mix Design Principles	14
2.4	Current Progress of Self-Compacting Concrete	16
2.4.1	Test Methods of Self-Compacting Property	17
2.4.2	Property of Fresh Self-Compacting Concrete	22
2.4.3	Properties of Hardened Self-Compacting Concrete	31
2.5	Applications	31
2.6	Summary	33
	References	33
3	Self-Expanding Concrete	37
3.1	Introduction	37
3.2	Definition and Classification of Self-Expanding Concrete	38
3.3	Principles of Self-Expanding Concrete	38
3.4	Current Progress of Self-Expanding Concrete	42

- 3.5 Applications of Self-Expanding Concrete 46
 - 3.5.1 Applications of Self-Compensating Concrete. 46
 - 3.5.2 Applications of Self-Stressing Concrete. 49
- 3.6 Summary 51
- References. 51
- 4 Self-Curing Concrete. 55**
 - 4.1 Introduction 55
 - 4.2 Definition and Mechanism of Self-Curing Concrete 56
 - 4.3 Current Progress of Self-Curing Concrete. 57
 - 4.3.1 Absorption and Desorption of Self-Curing Water 58
 - 4.3.2 Workability and Durability 61
 - 4.3.3 Mechanical Properties 63
 - 4.4 Application of Self-Curing Concrete. 64
 - 4.5 Summary 65
 - References. 65
- 5 Self-Shaping Concrete. 67**
 - 5.1 Introduction 67
 - 5.2 Definition and Principles of Self-Shaping Concrete 68
 - 5.3 Current Progress of Self-Shaping Concrete. 69
 - 5.3.1 Material and Mix Proportion Design. 69
 - 5.3.2 Mechanical Properties 70
 - 5.3.3 Building Plan Design 72
 - 5.4 Applications of Self-Shaping Concrete 74
 - 5.4.1 Self-Shaping Concrete in Practice 74
 - 5.4.2 Self-Shaping Concrete in Potential 77
 - 5.4.3 Market Prediction 78
 - 5.5 Summary 79
 - References. 79
- 6 Self-Sensing Concrete 81**
 - 6.1 Introduction 81
 - 6.2 Intrinsic Self-Sensing Concrete. 83
 - 6.2.1 Definition and Sensing Mechanism of Intrinsic Self-Sensing Concrete 83
 - 6.2.2 Current Progress of Intrinsic Self-Sensing Concrete 90
 - 6.2.3 Applications of Intrinsic Self-Sensing Concrete. 92
 - 6.3 Non-Intrinsic Self-Sensing Concrete 96
 - 6.3.1 Non-Intrinsic Self-Sensing Concrete Integrated with Electric Resistance Strain Gauges 98
 - 6.3.2 Non-Intrinsic Self-Sensing Concrete Integrated with Optical Fibers 98
 - 6.3.3 Non-Intrinsic Self-Sensing Concrete Integrated with Piezoelectric Materials. 103

6.3.4	Non-Intrinsic Self-Sensing Concrete Integrated with Shape Memory Alloys.	105
6.3.5	Non-Intrinsic Self-Sensing Concrete Integrated with Self-Diagnosing Polymer Composites	106
6.4	Summary	109
	References.	109
7	Self-Healing Concrete	117
7.1	Introduction	117
7.2	Definition and Classification of Self-Healing Concrete	118
7.3	Autogenous Self-Healing Concrete	118
7.3.1	Self-Healing High-Strength/High-Performance Concrete	120
7.3.2	Self-Healing Concrete with Mineral Admixtures	120
7.3.3	Self-Healing Concrete with Fibers	123
7.3.4	Self-Healing Asphalt Concrete.	125
7.4	Autonomous Self-Healing Concrete	127
7.4.1	Self-Healing Based on Vascular Method	128
7.4.2	Self-Healing Based Microcapsule Method	129
7.4.3	Self-Healing Based on Electrodeposition Method	136
7.4.4	Self-Healing Based on Bacterial Method	139
7.4.5	Self-Healing Based on Shape Memory Alloy Method	143
7.4.6	Self-Healing Based on Induction Energy/Microwave Method	146
7.5	Summary	151
	References.	151
8	Self-Adjusting Concrete	157
8.1	Introduction	157
8.2	Definition and Classification of Self-Adjusting Concrete	158
8.3	Moisture Self-Adjusting Concrete.	159
8.3.1	Definition, Classification, and Test of Moisture Self-Adjusting Concrete.	159
8.3.2	Principles of Moisture Self-Adjusting Concrete.	159
8.3.3	Current Progress of Moisture Self-Adjusting Concrete	160
8.3.4	Application of Moisture Self-Adjusting Concrete	161
8.4	Thermal Parameter Self-Adjusting Concrete	161
8.4.1	Definition and Principles of Thermal Parameter Self-Adjusting Concrete.	161
8.4.2	Current Progress of Thermal Parameter Self-Adjusting Concrete.	163
8.4.3	Applications of Thermal Parameter Self-Adjusting Concrete	166

8.5	Hydration Heat Self-Adjusting Concrete	169
8.6	Summary	173
	References.	173
9	Damping Concrete.	177
9.1	Introduction	177
9.2	Definition and Principles of Damping Concrete	178
9.3	Current Progress of Damping Concrete	179
9.3.1	Damping Concrete with Polymers	179
9.3.2	Damping Concrete with Fibers	180
9.3.3	Damping Concrete with Silica Fume.	183
9.3.4	Damping Concrete with Graphite	183
9.3.5	Damping Concrete with Emulsified Asphalt	184
9.3.6	Damping Concrete with Graphene.	186
9.4	Application of Damping Concrete	187
9.5	Summary	188
	References.	189
10	Anti-Spalling Concrete	191
10.1	Introduction	191
10.2	Definition and Principles of Anti-Spalling Concrete	192
10.2.1	Definition and Occurrence Mechanism of Concrete Spalling	192
10.2.2	Principles of Anti-Spalling Concrete	194
10.3	Current Progress of Anti-Spalling Concrete	198
10.3.1	Anti-Spalling Concrete with Polypropylene Fibers	198
10.3.2	Anti-Spalling Concrete with Hybrid Fibers	202
10.3.3	Anti-Spalling Concrete with Air Entraining Agent	212
10.3.4	Anti-Spalling Concrete with Mineral Admixtures	215
10.4	Applications of Anti-Spalling Concrete.	217
10.5	Summary	218
	References.	218
11	Wear-Resisting Concrete.	223
11.1	Introduction	223
11.2	Definition and Principles of Wear-Resisting Concrete	224
11.3	Current Progress and Applications of Abrasion Resisting Concrete	225
11.4	Current Progress and Applications of Erosion and Cavitation Resisting Concrete	229
11.5	Summary	231
	References.	231

12 Aircraft Arresting Concrete 235

 12.1 Introduction 235

 12.2 Definition and Principles of Aircraft Arresting Concrete. 237

 12.3 Current Progress of Aircraft Arresting Concrete 238

 12.4 Application of Aircraft Arresting Concrete 243

 12.5 Summary 244

 References. 245

13 Electrically Conductive Concrete 247

 13.1 Introduction 247

 13.2 Definition and Principles of Electrically Conductive Concrete 248

 13.3 Current Progress of Electrically Conductive Concrete. 250

 13.4 Applications of Electrically Conductive Concrete 250

 13.4.1 Electrically Conductive Concrete Used in Electromagnetic Defense 251

 13.4.2 Electrically Conductive Concrete Used in Cathodic Protection 252

 13.5 Summary 257

 References. 258

14 Electrothermal Concrete 261

 14.1 Introduction 261

 14.2 Definition and Principles of Electrothermal Concrete 262

 14.3 Electrothermal Concrete Filled with Metal Particles and Fibers 264

 14.4 Electrothermal Concrete Filled with Carbon Particles and Fibers 266

 14.5 Summary 270

 References. 270

15 Light-Transmitting Concrete 273

 15.1 Introduction 273

 15.2 Definition and Classification of Light-Transmitting Concrete 274

 15.3 Principles and Manufacture of Light-Transmitting Concrete 275

 15.4 Current Progress of Light-Transmitting Concrete 276

 15.5 Applications of Light-Transmitting Concrete 280

 15.6 Summary 282

 References. 282

16 Light-Emitting Concrete 285

 16.1 Introduction 285

 16.2 Definition and Classification of Light-Emitting Concrete 286

- 16.3 Mechanisms and Properties of Light-Emitting Concrete 286
 - 16.3.1 Mixing Luminous Components into Concrete 286
 - 16.3.2 Modifying the Microstructure of Concrete. 288
 - 16.3.3 Covering the Concrete Surface
 - with Luminous Coat 289
- 16.4 Current Progress of Light-Emitting Concrete 291
- 16.5 Applications of Light-Emitting Concrete 293
 - 16.5.1 Building Environment Decoration 293
 - 16.5.2 Road and Lane Lighting 294
 - 16.5.3 Highway Signs and Safety 295
- 16.6 Summary 296
- References. 297
- 17 Photocatalytic Concrete 299**
 - 17.1 Introduction 299
 - 17.2 Definition and Principles of Photocatalytic Concrete 300
 - 17.3 Current Progress of Photocatalytic Concrete. 303
 - 17.4 Applications of Photocatalytic Concrete 307
 - 17.5 Summary 309
 - References. 310
- 18 Electromagnetic Wave Shielding/Absorbing Concrete 313**
 - 18.1 Introduction 313
 - 18.2 Electromagnetic Wave Shielding Concrete 314
 - 18.2.1 Definition, Mechanism, and Test of Electromagnetic Wave Shielding Concrete 314
 - 18.2.2 Current Progress and Applications of Electromagnetic Wave Shielding Concrete 315
 - 18.3 Electromagnetic Wave Absorbing Concrete 321
 - 18.3.1 Definition, Mechanism, and Test of Electromagnetic Wave Absorbing Concrete. 321
 - 18.3.2 Current Progress and Applications of Electromagnetic Wave Absorbing Concrete. 322
 - 18.4 Summary 326
 - References. 326
- 19 Radiation Shielding Concrete 329**
 - 19.1 Introduction 329
 - 19.2 Definition and Classification of Radiation Shielding Concrete 330
 - 19.3 Current Progress of Radiation Shielding Concrete 331
 - 19.3.1 Binding Materials 331
 - 19.3.2 Aggregates. 331
 - 19.3.3 Admixture 335

19.4	Applications of Radiation Shielding Concrete.	336
19.5	Summary	336
	References.	336
20	Hydrophobic/Superhydrophobic Concrete.	339
20.1	Introduction	339
20.2	Definition and Preparation of Hydrophobic/Superhydrophobic Concrete	340
20.3	Test Methods of Hydrophobic/Superhydrophobic Concrete	342
20.4	Current Progress of Hydrophobic/Superhydrophobic Concrete	343
20.5	Applications of Hydrophobic/Superhydrophobic Concrete	353
20.6	Summary	354
	References.	354
21	Permeable Concrete	359
21.1	Introduction	359
21.2	Definition and Principles of Permeable Concrete	360
21.3	Components of Permeable Concrete	361
	21.3.1 Coarse Aggregates.	361
	21.3.2 Binders	363
21.4	Current Progress of Permeable Concrete.	363
21.5	Applications of Permeable Concrete	365
21.6	Summary	367
	References.	367
22	Non-Dispersible Underwater Concrete.	369
22.1	Introduction	369
22.2	Definition and Classification of Non-Dispersible Underwater Concrete	370
22.3	Principles of Non-Dispersible Underwater Concrete	371
22.4	Current Progress of Non-Dispersible Underwater Concrete.	371
22.5	Applications of Non-Dispersible Underwater Concrete.	376
22.6	Summary	377
	References.	377
23	Energy-Harvesting Concrete.	379
23.1	Introduction	379
23.2	Definition and Principles of Energy-Harvesting Concrete.	380
23.3	Energy-Harvesting Concrete Based on Piezoelectric Effect.	382
23.4	Energy-Harvesting Concrete Based on Pyroelectric Effect	384
23.5	Energy-Harvesting Concrete Based on Thermoelectric Effect	386

23.6 Energy-Harvesting Concrete Based on Photovoltaic Effect 387

23.7 Summary 389

References. 390

24 Future Developments and Challenges of Smart and Multifunctional Concrete. 391

24.1 Introduction 391

24.2 Design of Smart and Multifunctional Concrete. 392

24.3 Fabrication of Smart and Multifunctional Concrete. 394

24.4 Test and Characterization of Smart and Multifunctional Concrete 394

24.5 Properties of Smart and Multifunctional Concrete 394

24.6 Mechanisms and Models of Smart and Multifunctional Concrete 396

24.7 Applications of Smart and Multifunctional Concrete 396

24.8 General Evolution Principles of Smart and Multifunctional Concrete 397

24.9 Summary 398

References. 399

About the Authors

Baoguo Han received his Ph.D. degree in the field of smart materials and structures from the Harbin Institute of Technology, China, in 2005. He is currently a Professor of civil engineering in the Dalian University of Technology, China. His main research interests include smart materials and structures, cement and concrete materials, multifunctional composites, nanotechnology, structural health monitoring, and traffic detection. He is a member of the editorial board of three international journals and has published 1 book, 10 chapters, and more than 100 technical papers. He was invited to the University of Minnesota and has worked as a Visiting Research Scholar there for 3 years. He was also awarded the New Century Excellent Talents in University by the Ministry of Education of China and the First Prize of Natural Science by the Ministry of Education of China. E-mail: hithanbaoguo@163.com, hanbaoguo@dlut.edu.cn.

Liqing Zhang received her M.S. degree in materials science from the Dalian University of Technology, China, in 2015. She is currently pursuing her Ph.D. degree at Dalian University of Technology, China. Her current research interests include cement and concrete composites, smart materials and structures, and nanotechnology. She has published 4 chapters and 10 published journal papers. E-mail: zhangliqingdagong@163.com.

Jinping Ou received his Ph.D. degree from the Harbin Institute of Technology, China, in 1987. He is a Professor at both Harbin Institute of Technology and Dalian University of Technology, China. His main research interests include structural damage, reliability and health monitoring, structural vibration and control, and smart materials and structures. He has published more than 300 technical papers/reports and 4 books. He has been awarded the second-level National Awards of Science and Technology Progress twice and the first-level provincial and ministerial Awards of Science and Technology Progress five times. He has been an Academician of Chinese Academy of Engineering since 2003 and was the President

of the Chinese Society for Vibration Engineering, the Vice-President of the Architectural Society of China, an Executive Board Member at the International Association for Structural Control and Monitoring, as well as the Vice-President and Fellow of the International Society for Structural Health Monitoring of Intelligent Infrastructure. E-mail: oujinping@dlut.edu.cn, oujinping@hit.edu.cn.

Abbreviations

3DP	Three-dimensional printing
AEA	Air entraining agent
AGT	Ambient Glow Technology
AWA	Anti-washout admixture
CAM	Cement asphalt mortar
CB	Carbon black
CC	Contour Crafting
CF	Carbon fiber
CFRC	CF-reinforced concrete
CFRCC	Carbon fiber-reinforced cement composites
CL	Cellulose
CNT	Carbon nanotube
CP	Cathodic protection
CRT	Cathode ray tubes
CRTS	China Rail Track System
CSBL	Carboxylic styrene butadiene latex
DC	Direct current
EAFSAs	Furnace slag aggregates
ECC	Engineered cementitious composites
EIT	Electrical impedance tomography
EM	Electromagnetic
EMAS	Engineered Material Arresting System
EMW	EM wave
ESEM	Environmental Scanning Electron Microscope
FBG	Fiber Bragg Grating
FRP	Fiber-reinforced polymer
GF	Glass fiber
GITD	Glow-in-the-dark
HCFRP	Hybrid CF-reinforced polymer
HFDS	Perfluorodecyltriethoxysilane

HFRCC	Hybrid fiber-reinforced self-healing concrete
HPC	High-performance concrete
HSC	High-strength concrete
ICCP	Impressed current CP
IR	Infrared Spectroscopy
ISSC	Intrinsic self-sensing concrete
ITZ	Interfacial transition zone
LWA	Lightweight aggregate
MEA	MgO expansion agent
MK	Metakaolin
MWCNT	Multiwalled CNT
NCB	Nano-CB
NISSC	Non-intrinsic self-sensing concrete
NP	Nickel powder
NSC	Normal-strength concrete
NVC	Normally vibrated concrete
NWA	Normal weight aggregate
NY	Nylon
OHA	Organosilicon hydrophobic agent
P(St-co-HEMA)	Poly (styrene-co-hydroxyethyl methacrylate)
PC-baded SPs	Polycarboxylate-based SPs
PCMs	Phase change materials
PDMS	Polydimethylsiloxane
PE	Polyethylene
PEG	Polyethylene glycol
PFA	Pulverized fly ash
PMHS	Polymethyl-hydrosiloxane
POF	Plastic optical fiber
PP	Polypropylene
PSA	Wastepaper sludge ash
PVA	Polyvinyl alcohol
PVDF	Piezoelectric polymer film
PZT	Piezoelectric ceramics
RH	Relative humidity
SAP	Super absorbing polymer
SCC	Self-compacting concrete
SE	Shielding effectiveness
SEM	Scanning Electron Microscope
SF	Steel fiber
SMA	Shape memory alloy
SP	Superplasticizer
SRA	Shrinkage reducing admixture
SWCNT	Single-walled CNT
UHPC	Ultra-high-performance concrete
UV	Ultraviolet

VM	Vitrified microspheres
w/b	Water-to-binder ratio
WSPVA	Water-soluble PVA
XCT	X-ray Computed Tomography
XEDS	X-ray Energy-dispersive Spectroscopy

Chapter 1

General Introduction of Smart and Multifunctional Concrete

Abstract Smart and multifunctional concrete refers to the structural material accompanied with one or more types of intelligent or functional behaviors. Its “smartness and function” properties are achieved mainly through composition design, special processing, introduction of other functional components, or modification of microstructure of conventional concrete, thus leading to the concrete possessing bionic features. Smart and multifunctional concrete is a very broad category of materials. More than 20 types of smart and multifunctional concrete have been developed in the recent 30 years, and more new types of smart and multifunctional concrete are still emerging one after another. As a dissipative structure system, smart and multifunctional concrete can maintain energy quality to protect entropy increment, thus matching sustainable development trend of materials and infrastructures.

Keywords Concrete · Smart · Multifunctional · Dissipative structure · Philosophical foundation

1.1 Introduction

Concrete is a composite composed of aggregate bonded together with fluid binder which hardens over time. Commonly used concrete can be categorized into lime-based concrete, asphalt concrete, and polymer concrete according to its different types of binder used. Most used concrete is lime-based concrete including Portland cement concrete or concretes made with other hydraulic cements, for example, high alumina cement, supersulphated cement, and geopolymer cement. Another type of very frequently used concrete is asphalt concrete for road surfaces, and the binder used is bitumen. In addition, polymer concretes are sometimes used with polymer as the binding material for new construction or repairing of old concrete. However, in this book, smart and multifunctional concrete refers to Portland cement concrete unless otherwise stated, because previous research and application focused mainly on smart and multifunctional concrete fabricated with

Portland cement. In addition, it should be noted that concrete here is a generalized concept which means it can be concrete (containing coarse and fine aggregates), cement mortar (containing fine aggregates), or cement paste (containing no aggregate, whether coarse or fine) [1–9].

As shown in Fig. 1.1, concrete is a multicomponent, multiphase, and multiscale composite in nature. Its components include cement, water, aggregates, chemical additives, and mineral additives. The proportion of these components can vary within a flexible and wide range. Hardened concrete contains solid, liquid, and gas phases. Its structure covers over ten orders of magnitude in size, ranging from nanometers (e.g., hydration product) to micrometers (e.g., binder), and then from millimeters (e.g., mortar and concrete) to tens of meters (final structures). In addition, the concrete features time-variant characteristic because cement hydration is a long-term evolutionary progress and hydration products feature thermodynamic instability. Furthermore, since concrete is an open composite system, a lot of

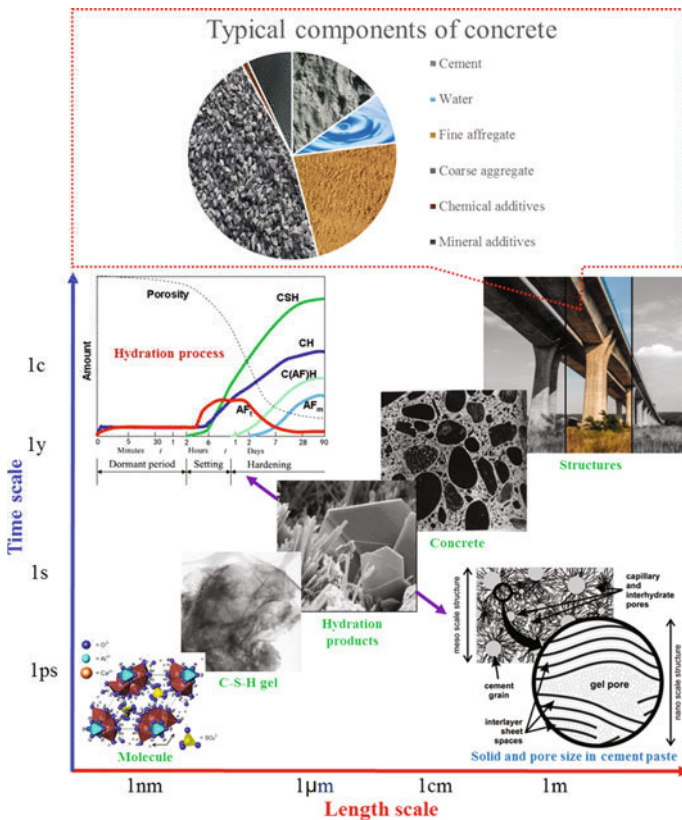


Fig. 1.1 Multicomponent, multiphase, and multiscale nature of concrete

modification materials (e.g., fiber filler, powder filler, polymer) or components (e.g., sensors and actuators) can be easily integrated with it. Therefore, it is potentially possible to make concrete smart and multifunctional [10–15].

This chapter will first give an overall introduction to smart and multifunctional concrete including its definition and classification, and then, the origin of smart and multifunctional concrete is also briefly summarized. Finally, the philosophical foundation of smart and multifunctional concrete is discussed based on a dissipative structure theory.

1.2 Definition of Smart and Multifunctional Concrete

Smart and multifunctional concrete is an intelligent system. It has properties different from those of conventional concrete, such as self-sensing, self-healing, electrically conductive, thermal, and electromagnetic properties, or has the ability to react upon an external stimulus, such as stress and temperature. Smart and multifunctional concrete is usually designed to meet specific requirements by tailoring its properties to improve safety, longevity, and function of infrastructures and to reduce life cycle costs, resource consumption, and environment pollution. The “smartness and multifunction” of concrete is achieved through composition design, special processing, introduction of other functional components, or modification of microstructure of conventional concrete. The basic principle of smart and multifunctional concrete is based on biomimetic design, and multiscale and multicomponent compositization [16–18].

Conventional concrete serves as a structural material and has no or poor smart and multifunctional abilities. However, smart and multifunctional concrete possesses not only basic structural function, but also one or more types of intelligent or functional behaviors (e.g., self-sensing, self-healing, self-adjusting, electrically conductive, thermal, and electromagnetic behaviors). As shown in Fig. 1.2, composition, processing, structure, and property of materials are closely related to each other. Because the smart and multifunctional concrete is a composite system in nature, it is expected that the specific smartness and function of smart and multifunctional concrete can be designed and achieved according to processing and application requirements.

1.3 Classification of Smart and Multifunctional Concrete

In the past few decades, considerable effort has been put toward the research of smart and multifunctional concrete and many innovative achievements have been gained in the development and application of smart and multifunctional concrete. More than 20 types of smart and multifunctional concrete with different behaviors and matrix materials have been developed [19–31]. Their classification, together with the chapter distribution of this book, is summed up in Table 1.1.

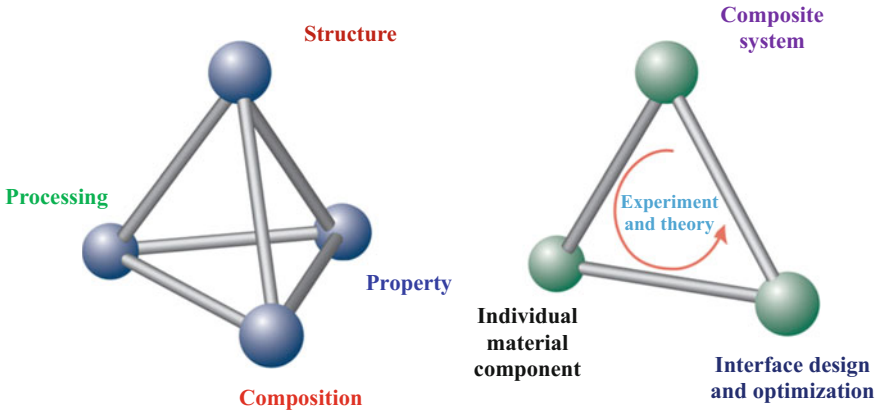


Fig. 1.2 Element model of materials

Table 1.1 Classification of smart and multifunctional concrete in different criteria

Criteria	Classification	
Matrix materials	Cement concrete-based	
	Asphalt concrete-based	
	Polymer concrete-based	
Smartness or function	Smartness	Self-compacting (Chap. 2)
		Self-expanding (Chap. 3)
		Self-curing (Chap. 4)
		Self-shaping (Chap. 5)
		Self-sensing (Chap. 6)
		Self-healing (Chap. 7)
		Self-adjusting (Chap. 8)
		Self-cleaning (achieved through photocatalytic function (Chap. 17) and hydrophobic/superhydrophobic function (Chap. 20))
		Self-damping (i.e., damping (Chap. 9))
		Self-heating (i.e., electrothermal (Chap. 14))
		Self-light-emitting (i.e., light-emitting (Chap. 16))
		Mechanical function
	Anti-spalling (belongs to self-adjusting property) (Chap. 10)	
Wear-resisting (Chap. 11)		
Aircraft arresting (Chap. 12)		
Electrical function	Electrically conductive (Chap. 13)	
	Electrothermal (Chap. 14)	

(continued)

Table 1.1 (continued)

Criteria	Classification	
Optical function		Light-transmitting (Chap. 15)
		Light-emitting (Chap. 16)
		Photocatalytic (Chap. 17)
Electromagnetic wave/radiation shielding/absorbing function		Electromagnetic wave shielding (Chap. 18)
		Electromagnetic wave absorbing (Chap. 18)
		Radiation shielding (Chap. 19)
Function related to water		Hydrophobic/superhydrophobic (Chap. 20)
		Permeable (Chap. 21)
		Non-dispersible underwater (Chap. 22)
	Energy-harvesting function (Chap. 23)	

1.4 Origin of Smart and Multifunctional Concrete

Although some specific types of smart and multifunctional concrete (e.g., electrically conductive concrete, light-transmitting concrete, and self-expanding concrete) were proposed 40 years ago, the true concept of smart and multifunctional concrete was firstly proposed by Japanese researchers in the late 1980s. Since then, Yanagida developed “self-test concrete” by involving glass and carbon fibers into concrete in 1992. Dry embedded polypropylene fibers that contained calcium nitrite into concrete for anti-corrosion of steel reinforcement bars in 1992. So far, more than 20 types of smart and multifunctional concrete as listed in Table 1.1 have constantly emerged. Researchers have carried out extensive investigations on design, fabrication, test and characterization, and performances and mechanisms of smart and multifunctional concrete. Some types of smart and multifunctional concrete have been successfully applied in practical engineering [16]. The concept and the research and application status of each type of smart and multifunctional concrete will be, respectively, introduced in the following chapters as listed in Table 1.1.

1.5 Philosophical Foundation of Smart and Multifunctional Concrete

Materials have defects and exist in a metastable state because various factors compete with each other during their forming process. As a result, the structures of material feature metastability and non-homogeneity. In addition, the materials are in an open system during their use. Therefore, the performances of materials will degenerate with time until reaching life span under complex action of external

environment (including mechanical, chemical, and thermal actions). For example, according to the model of failure stress and strength of materials as shown in Fig. 1.3, there is enough safety margin at the beginning of material use if stress and strength are accorded with normal distribution. As time goes by, the strength decreases because of the deterioration of material performance and the destruction of the environment. As a result, two normal distribution curves intersect. Therefore, a failure occurs in an overlapping area as shown in Fig. 1.3. The failure mode of other performances of materials is similar to this. Materials feature instability in nature, which trends random equilibrium state. This is a spontaneous process of entropy increment. In addition, external environment tries to break order for achieving entropy increment, thus reaching a low-level equilibrium state.

As shown in Fig. 1.4, according to the dissipative structure theory, conventional concrete has no negative entropy input through matter, energy, or information exchange with external stimuli during its service period. However, smart and multifunctional concrete is a dissipative structure. It can be provided with matter, energy, and/or information through various channels such as chemical, physical, or biological approaches. This means that there is a negative entropy input caused by matter, energy, or information exchange between smart and multifunctional concrete and external stimuli. The negative entropy imported into the system of smart and multifunctional concrete has two benefits: (1) The entropy increment caused by external disturbance and damage can be counteracted so that concrete performances can be maintained or even enhanced during the service period; (2) some new functions of concrete can be produced. Therefore, smart and multifunctional concrete acts in similar biological behaviors. It is a new generation of concrete

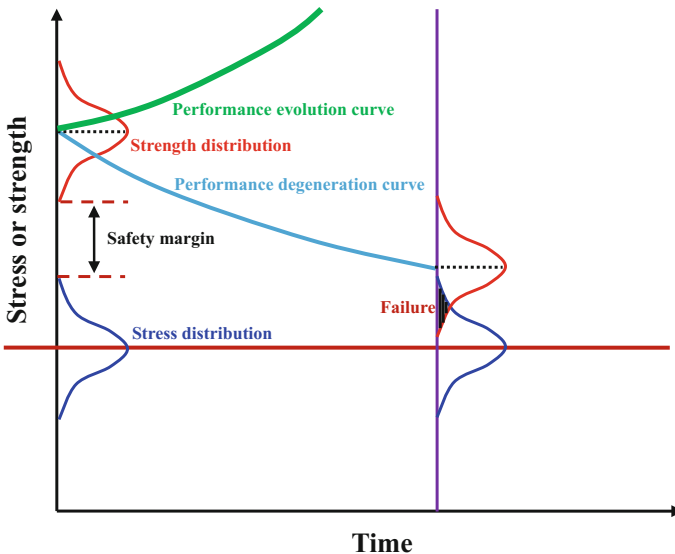


Fig. 1.3 Model of stress–strength of materials

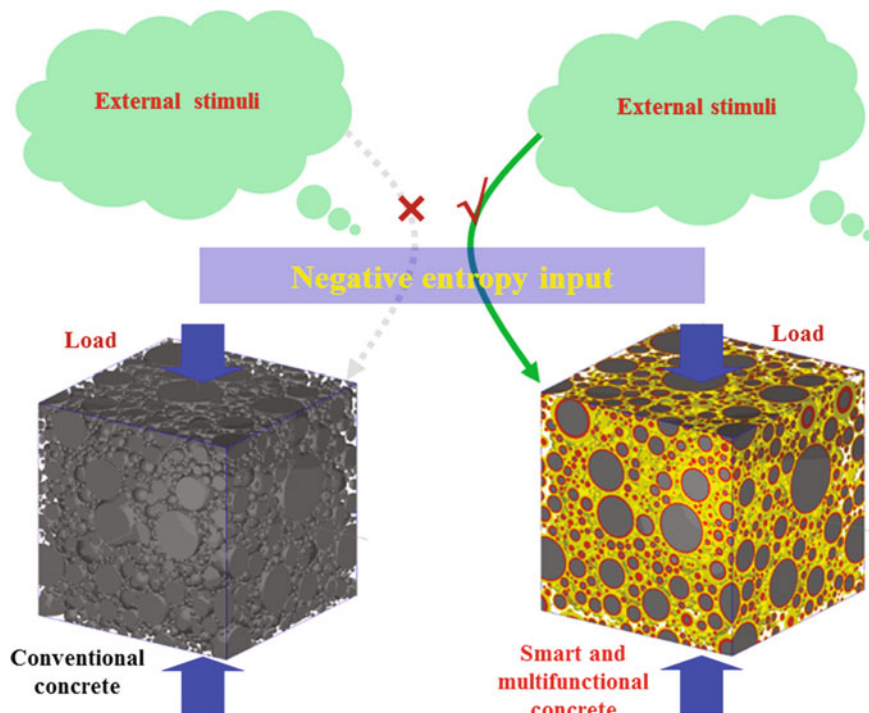


Fig. 1.4 Comparison between conventional concrete and smart and multifunctional concrete

materials with inherent intelligence/function that feature self-organization and adaptive capabilities to external stimuli (e.g., loads or environment) while maintaining or even improving mechanical properties and durability [31, 32].

1.6 Summary

Smart and multifunctional concrete integrates smartness or function with their excellent mechanical properties and durability. It can actively undertake and adapt environmental changes and consciously resist external damage. Smart and multifunctional concrete represents the development trend of concrete materials and infrastructures because it can maintain energy quality to protect entropy increment. The combination of science and technology promotion, social demands driving, and inherent characteristics of concrete makes it possible to develop various types of smart and multifunctional concrete with different behaviors. Compared with conventional concrete, a properly designed smart and multifunctional concrete can be used to optimize safety, longevity, and function of infrastructures and to reduce life cycle costs, resource consumption, and environment pollution.

References

1. B.G. Han, X. Yu, J.P. Ou, *Self-Sensing Concrete in Smart Structures* (Elsevier, Amsterdam, 2014)
2. B.G. Han, X. Yu, J.P. Ou, Chapter 1: Multifunctional and smart carbon nanotube reinforced cement-based materials, in *Nanotechnology in Civil Infrastructure: A Paradigm Shift*, vol. 276, ed. by K. Gopalakrishnan, B. Birgisson, P. Taylor, N.O. Attoh-Okine (Springer, New York, 2011), pp. 1–47
3. D.D.L. Chung, Self-monitoring structural materials. *Mater. Sci. Eng. R Rep.* **22**(2), 57–78 (1998)
4. B.G. Han, Properties, sensors and structures of pressure-sensitive carbon fiber cement paste. Dissertation for the Doctor Degree in Engineering, Harbin Institute of Technology (2006)
5. P.K. Mehta, P.J.M. Monteiro, *Concrete: Microstructure, Properties and Materials* (McGraw-Hill, New York, 2006)
6. M. Saafi, K. Andrew, P.L. Tang, D. McGhon, S. Taylor, M. Rahman, S.T. Yang, X.M. Zhou, Multifunctional properties of carbon nanotube/fly ash geopolymeric nanocomposites. *Constr. Build. Mater.* **49**, 46–55 (2013)
7. P.C. Aitcin, Cements of yesterday and today concrete of tomorrow. *Cem. Concr. Res.* **30**, 1349–1359 (2009)
8. B. Mather, Concrete durability. *Cement Concr. Compos.* **26**, 3–4 (2004)
9. J.P. Ou, Some recent advances of intelligent health monitoring systems for civil infrastructures in HIT. *Proc. SPIE* **5851**, 147–162 (2005)
10. M.L. Gambhir, *Concrete Technology: Theory and Practice* (Tata McGraw-Hill Publishing Company Limited, New Delhi, 2000)
11. A.J. Boyd, S. Mindess, *Materials Science of Concrete: Cement and Concrete: Trends and Challenges* (American Ceramics Society, Westerville, 2002)
12. J.B. Newman, B.S. Choo, *Advanced Concrete Technology Set* (Butterworth-Heinemann, Oxford, 2003)
13. Y. Malier, *High Performance Concrete: From Material to Structure* (Taylor and Francis, Abingdon, 1992)
14. O.E. Gjorv, K. Sakai, *Concrete Technology for a Sustainable Development in the 21st Century* (CRC Press, Boca Raton, 1999)
15. F. Pacheco-Torgal, S. Jalali, J. Labrincha, V.M. John, *Eco-Efficient Concrete* (Elsevier, Amsterdam, 2013)
16. B. Han, Y. Wang, S. Dong, L. Zhang, S. Ding, X. Yu, J. Ou, Smart concretes and structures: A review. *J. Intell. Mater. Syst. Struct.* **26**(11), 1303–1345 (2015)
17. M.V. Gandhi, B.D. Thompson, *Smart Materials and Structures* (Springer, New York, 1992)
18. M. Schwartz, *Smart Materials* (CRC Press, Boca Raton, 2008)
19. B.G. Han, S.F. Dong, L.Q. Zhang, S.Q. Ding, S.W. Sun, Y.Y. Wang, Chapter 6: Functional civil engineering materials. in *R&D of China's Strategic New Industries – Functional Materials*, vol. 439 (China Machine Press, Beijing, 2016), pp. 195–298
20. L.Q. Zhang, S.Q. Ding, S.W. Sun, B.G. Han, X. Yu, J.P. Ou, Chapter 2: Nano-scale behavior and nano-modification of cement and concrete materials, in *Advanced Research on Nanotechnology for Civil Engineering Applications*, ed. by A. Khitab, W. Anwar (IGI Global, Hershey, PA, 2016), pp. 28–79
21. B.G. Han, S.Q. Ding, S.W. Sun, L.Q. Zhang, J.P. Ou, Chapter 33: Chemical modification of carbon nanotubes/nanofibers for application in cement and concrete field, in *Chemical Functionalization of Carbon Nanomaterials: Chemistry and Applications*, ed. by V.K. Thakur (Taylor & Francis CRC, Boca Raton, 2015), pp. 748–773
22. B.G. Han, S.W. Sun, S.Q. Ding, L.Q. Zhang, S.F. Dong, X. Yu, Chapter 8: Nano carbon materials filled cementitious composites: Fabrication, properties and application, in *Innovative Developments of Advanced Multifunctional Nanocomposites in Civil and Structural Engineering*, ed. by K.J. Loh, S. Nagarajaiah (Elsevier, Amsterdam, 2015), pp. 153–181