

# Contents

|          |  |    |
|----------|--|----|
| <b>1</b> | <b>Introduction</b> . . . . .  | 1  |
| 1.1      | Sustainable Development of Building Industry . . . . .   | 1  |
| 1.1.1    | The Consumption of Energy and Resources<br>in Building Industry . . . . .                                      | 1  |
| 1.1.2    | New Strategies for Sustainable Development<br>in Building Industry . . . . .                                   | 2  |
| 1.1.3    | The Significant Role of Concrete Industry<br>in Implementing “Sustainable Development”<br>Strategies . . . . . | 4  |
| 1.2      | Concrete Recycling and Reusing . . . . .   | 5  |
| 1.2.1    | The Life Cycle and Extension of Concrete<br>Structures . . . . .   | 5  |
| 1.2.2    | Waste Concrete . . . . .   | 6  |
| 1.2.3    | Recycled Aggregate Concrete . . . . .  | 7  |
| 1.3      | An Overview on the Worldwide and China’s Waste Concrete<br>Recycling Techniques . . . . .                      | 8  |
| 1.3.1    | Worldwide Waste Concrete Recycling Techniques . . . . .  | 8  |
| 1.3.2    | The Development of RAC Technology in China . . . . .   | 10 |
| 1.4      | Problems to Research RAC and Forecast of Developing<br>Trend . . . . .   | 11 |
| 1.4.1    | Primary Problems . . . . .   | 11 |
| 1.4.2    | Forecast of Developing Trend . . . . .   | 11 |
| 1.5      | Scientific Subject Chain in Civil Engineering . . . . .  | 12 |
| 1.6      | Book’s Outline . . . . .   | 12 |
|          | References . . . . .   | 13 |
| <b>2</b> | <b>Reclaim of Waste Concrete</b> . . . . .   | 15 |
| 2.1      | Introduction . . . . .   | 15 |
| 2.2      | Source of Waste Concrete . . . . .   | 15 |

- 2.2.1 General Sources—Pavement, Buildings, Bridges and Other Types of Constructions . . . . . 15
- 2.2.2 Disasters . . . . . 17
- 2.3 Quantity of Waste Concrete . . . . . 19
  - 2.3.1 Quantity in China . . . . . 19
  - 2.3.2 Future Tendency Forecast . . . . . 23
- 2.4 Classification of Waste Concrete . . . . . 25
  - 2.4.1 Standard . . . . . 25
  - 2.4.2 Classification . . . . . 26
- 2.5 Reduce Principle and Methods . . . . . 28
  - 2.5.1 Reasonable Plan . . . . . 28
  - 2.5.2 Elaborate Design . . . . . 29
  - 2.5.3 Ecological Materials . . . . . 30
  - 2.5.4 Green Construction . . . . . 30
- 2.6 Reuse Materials and Elements . . . . . 31
  - 2.6.1 Recycled Blocks . . . . . 32
  - 2.6.2 Reuse Elements . . . . . 32
- 2.7 Recycling . . . . . 33
  - 2.7.1 Low-Grade Recycling . . . . . 34
  - 2.7.2 High-Grade Recycling . . . . . 35
- 2.8 Concluding Remarks . . . . . 35
- References . . . . . 36
- 3 Recycled Aggregates . . . . . 39**
  - 3.1 Crushing and Sieving Techniques . . . . . 39
    - 3.1.1 Worldwide Waste Concrete Crushing Techniques . . . . . 39
    - 3.1.2 China’s Waste Concrete Crushing Techniques . . . . . 41
    - 3.1.3 Crushing Equipment . . . . . 44
  - 3.2 Recycled Fine Aggregates . . . . . 46
    - 3.2.1 Properties . . . . . 46
    - 3.2.2 Classification . . . . . 46
    - 3.2.3 Testing Method . . . . . 48
  - 3.3 Recycled Coarse Aggregates . . . . . 48
    - 3.3.1 Single Source of RCA . . . . . 48
    - 3.3.2 Multi Source of RCA . . . . . 53
  - 3.4 Method of Classifying and Testing for RCA . . . . . 55
    - 3.4.1 Study on RCA Classification . . . . . 55
    - 3.4.2 Testing Methods . . . . . 58
  - 3.5 Pre-treating and Enhancement . . . . . 59
    - 3.5.1 Adjusting Mix Proportion . . . . . 59
    - 3.5.2 Chemical Method . . . . . 60
    - 3.5.3 Physical Method . . . . . 60
  - 3.6 Concluding Remarks . . . . . 61
  - References . . . . . 61

- 4 Recycled Aggregate Concrete . . . . . 65**
  - 4.1 Requirement for Mix Proportion Design. . . . . 65
    - 4.1.1 General Points . . . . . 65
    - 4.1.2 Cementitious Material . . . . . 66
    - 4.1.3 Aggregates. . . . . 67
    - 4.1.4 Admixtures . . . . . 67
    - 4.1.5 Chemical Admixtures . . . . . 67
  - 4.2 Compressive Strength-Based Mix Proportion Design Method . . . . . 68
    - 4.2.1 Review Points . . . . . 68
    - 4.2.2 Calculation Steps. . . . . 68
  - 4.3 Durability-Based Mix Proportion Design Method. . . . . 73
    - 4.3.1 Review . . . . . 73
    - 4.3.2 Design Program. . . . . 74
  - 4.4 Other Mix Proportion Design Methods. . . . . 76
    - 4.4.1 Volumetric Design Method . . . . . 76
    - 4.4.2 Application of Computers in the Design of the Mix Proportion . . . . . 77
    - 4.4.3 Application of Artificial Neural Network. . . . . 77
    - 4.4.4 Application of Artificial Neural Network Expert System. . . . . 77
  - 4.5 Microstructure of RAC. . . . . 78
    - 4.5.1 Micro-Composition of RAC . . . . . 78
    - 4.5.2 SEM Testing . . . . . 79
    - 4.5.3 Pore Structure Testing . . . . . 80
  - 4.6 ITZ Nanoindentation . . . . . 82
    - 4.6.1 Testing Preparation . . . . . 82
    - 4.6.2 Grid Nanoindentation Results . . . . . 87
    - 4.6.3 Grid Nanoindentation on Paste Matrix . . . . . 90
    - 4.6.4 Imaging Nanoindentation Result . . . . . 91
  - 4.7 Damage of RAC. . . . . 92
    - 4.7.1 Initial Damage of RAC . . . . . 93
    - 4.7.2 Damage Evolution of RAC . . . . . 93
  - 4.8 Improvements of RAC . . . . . 95
    - 4.8.1 ITZ Improvements—Physical and Chemical . . . . . 95
    - 4.8.2 Two-Stage Mixing Approach. . . . . 96
  - 4.9 Concluding Remarks. . . . . 97
  - References. . . . . 97
- 5 Modeled Recycled Aggregate Concrete . . . . . 99**
  - 5.1 Concept and Realization. . . . . 99
    - 5.1.1 Philosophy. . . . . 99
    - 5.1.2 Method . . . . . 100

|          |   |            |
|----------|---|------------|
| 5.2      | Cracking Propagation of MRAC. . . . .   | 103        |
| 5.2.1    | Digital Image Correlation Technique. . . . .  | 103        |
| 5.2.2    | Loading System. . . . .   | 103        |
| 5.2.3    | Crack Pattern and Failure Mode . . . . .  | 104        |
| 5.3      | Stress Distribution in MRAC . . . . .   | 107        |
| 5.3.1    | Analytical Procedures . . . . .   | 107        |
| 5.3.2    | Simulation and Test Verification . . . . .  | 109        |
| 5.3.3    | Effects of Relative Properties of ITZs . . . . .                                    | 112        |
| 5.4      | Modification of Modeled Recycled Aggregate Concrete<br>by Carbonation . . . . .     | 115        |
| 5.4.1    | Experimental Program . . . . .  | 115        |
| 5.4.2    | Experimental Results and Discussions. . . . .                                       | 118        |
| 5.4.3    | Summary . . . . .   | 124        |
| 5.5      | Chloride Diffusion in Modeled Recycled Aggregate<br>Concrete . . . . .              | 125        |
| 5.5.1    | Specimen Design. . . . .  | 125        |
| 5.5.2    | Simulation Procedure. . . . .   | 126        |
| 5.5.3    | Parametric Study . . . . .  | 127        |
| 5.5.4    | Results and Discussions. . . . .  | 129        |
| 5.6      | Concluding Remarks. . . . .   | 141        |
|          | References. . . . .   | 142        |
| <b>6</b> | <b>Strength of Recycled Aggregate Concrete . . . . .</b>                            | <b>143</b> |
| 6.1      | Compressive Strength. . . . .   | 143        |
| 6.1.1    | The Characteristics of Cube Compressive Strength . . . . .                          | 144        |
| 6.1.2    | Factors Influencing the Cube Compressive Strength . . . . .                         | 145        |
| 6.2      | Distribution of the Compressive Strength . . . . .                                  | 146        |
| 6.2.1    | The Histogram of the Compressive Strength . . . . .                                 | 146        |
| 6.2.2    | Examining the Distribution Characteristics<br>of the Compressive Strength . . . . . | 148        |
| 6.2.3    | Simulation of the Compressive Strength<br>Distribution . . . . .                    | 148        |
| 6.2.4    | Strength Index Value. . . . .   | 150        |
| 6.3      | Tensile Strength and Flexural Strength . . . . .                                    | 151        |
| 6.3.1    | Tensile Strength. . . . .   | 151        |
| 6.3.2    | Flexural Properties. . . . .  | 152        |
| 6.4      | The Relationship of Mechanical Indexes . . . . .                                    | 153        |
| 6.4.1    | Cube Compressive Strength and Prism Compressive<br>Strength. . . . .                | 153        |
| 6.4.2    | Splitting Tensile Strength and Cube Compressive<br>Strength. . . . .                | 154        |
| 6.4.3    | Flexural Strength and Cube Compressive Strength . . . . .                           | 155        |
| 6.5      | Effects of Elevated Temperatures on Strength. . . . .                               | 156        |
| 6.5.1    | Residual Compressive Strength . . . . .   | 156        |

|          |  |            |
|----------|--|------------|
| 6.5.2    | Residual Flexure Strength . . . . .  | 160        |
| 6.5.3    | Comparisons Between Residual Compressive<br>and Flexural Strength of RAC . . . . . | 162        |
| 6.6      | Concluding Remarks. . . . .  | 163        |
|          | References. . . . .  | 164        |
| <b>7</b> | <b>Constitutive Relationship of Recycled Aggregate Concrete . . . . .</b>          | <b>167</b> |
| 7.1      | Stress–Strain Relationship Under Axial Compressive<br>Loading . . . . .            | 167        |
| 7.1.1    | Test . . . . .   | 167        |
| 7.1.2    | Curves of the Stress–Strain Relationship of RAC . . . . .                          | 169        |
| 7.1.3    | Peak Stress . . . . .  | 172        |
| 7.1.4    | Peak Strain . . . . .  | 172        |
| 7.1.5    | Ultimate Strain . . . . .  | 173        |
| 7.1.6    | Elastic Modulus. . . . .   | 173        |
| 7.1.7    | Poisson’s Ratio . . . . .  | 174        |
| 7.2      | Variation Evaluation of Stress–Strain Relationship for RAC . . . . .               | 174        |
| 7.2.1    | Experimental Programs . . . . .  | 174        |
| 7.2.2    | Experimental Results . . . . .   | 177        |
| 7.2.3    | Summary . . . . .  | 178        |
| 7.3      | Stress–Strain Relationship Under Axial Tensile Loading . . . . .                   | 181        |
| 7.3.1    | Experimental Descriptions. . . . .   | 181        |
| 7.3.2    | Results and Discussion . . . . .   | 184        |
| 7.3.3    | Simulation with Lattice Model . . . . .  | 191        |
| 7.4      | Stress–Strain Relationship Under Confinements . . . . .                            | 196        |
| 7.4.1    | Test . . . . .   | 196        |
| 7.4.2    | Analysis. . . . .  | 203        |
| 7.4.3    | Theoretical Analysis . . . . .   | 208        |
| 7.4.4    | Stress–Strain Relation of RCFS. . . . .  | 210        |
| 7.4.5    | Stress–Strain Relation of RCFF. . . . .  | 213        |
| 7.5      | Shear Stress–Slip Relationship Under Shear Loading . . . . .                       | 215        |
| 7.5.1    | Test . . . . .   | 215        |
| 7.5.2    | Analysis of Test Results . . . . .   | 224        |
| 7.6      | Compressive Behavior Under Impact Loading . . . . .                                | 232        |
| 7.6.1    | Experimental Program . . . . .   | 232        |
| 7.6.2    | Test Results. . . . .  | 236        |
| 7.6.3    | Test Analysis and Discussion . . . . .   | 239        |
| 7.7      | Concluding Remarks. . . . .  | 246        |
|          | References. . . . .  | 248        |
| <b>8</b> | <b>Long-Term Property of Recycled Aggregate Concrete . . . . .</b>                 | <b>251</b> |
| 8.1      | Shrinkage and Creep Characteristics. . . . .                                       | 251        |
| 8.1.1    | Experimental Programme. . . . .  | 251        |
| 8.1.2    | Experimental Results. . . . .  | 254        |

- 8.2 Carbonation Resistance Performance . . . . . 258
  - 8.2.1 Existing Prediction Models of Carbonation Depth. . . . . 258
  - 8.2.2 Carbonation Test of RAC . . . . . 261
- 8.3 Chloride Diffusion Resistance Performance . . . . . 270
  - 8.3.1 Rapid Chloride Test (RCT). . . . . 270
  - 8.3.2 Rapid Chloride Migration (RCM) Test . . . . . 280
- 8.4 Fatigue Behavior. . . . . 286
  - 8.4.1 Fatigue Testing . . . . . 286
  - 8.4.2 Compressive Fatigue Test Results and Analysis . . . . . 287
  - 8.4.3 Bending Fatigue Test Results and Analysis. . . . . 292
- 8.5 Concluding Remarks. . . . . 294
- References. . . . . 295
- 9 Bond–Slip Between Recycled Aggregate Concrete and Rebars . . . . . 299**
  - 9.1 Bond Between RAC and Normal Rebars . . . . . 299
    - 9.1.1 Test. . . . . 299
    - 9.1.2 Analysis. . . . . 302
  - 9.2 Bond Between RAC and Eroded Rebars . . . . . 308
    - 9.2.1 Test. . . . . 308
    - 9.2.2 Analysis. . . . . 311
  - 9.3 Concluding Remarks. . . . . 316
  - References. . . . . 318
- 10 Structural Behavior of Recycled Aggregate Concrete Elements. . . . . 321**
  - 10.1 RAC Beams . . . . . 321
    - 10.1.1 Flexural Behavior of RAC Beams. . . . . 321
    - 10.1.2 Shear Behavior of RAC Beams. . . . . 331
  - 10.2 RAC Semi-precast Beams. . . . . 337
    - 10.2.1 Design of RAC Semi-precast Beams. . . . . 338
    - 10.2.2 Flexural Behavior of RAC Semi-precast Beams . . . . . 342
    - 10.2.3 Shear Behavior of RAC Semi-precast Beams . . . . . 346
  - 10.3 RAC Slabs . . . . . 352
    - 10.3.1 Flexural Behavior of RAC Gradient Slabs. . . . . 352
    - 10.3.2 Punching Shear Behavior of RAC Slabs . . . . . 365
  - 10.4 RAC Columns . . . . . 381
    - 10.4.1 Design of RAC Columns. . . . . 381
    - 10.4.2 Analysis of RAC Columns . . . . . 381
    - 10.4.3 Reliability Analysis of RAC Columns. . . . . 385
  - 10.5 Concluding Remarks. . . . . 391
  - References. . . . . 392
- 11 Seismic Performance of Recycled Aggregate Concrete**
  - Columns. . . . . 395**
    - 11.1 Introduction . . . . . 395

|           |  |            |
|-----------|--|------------|
| 11.2      | Low-Frequency Reversed Loading of Semi-Precast Columns . . .                             | 397        |
| 11.2.1    | Experimental Program . . . . .   | 397        |
| 11.2.2    | Test Analysis . . . . .  | 403        |
| 11.3      | Low-Frequency Reversed Loading on Tube-Confined<br>Columns . . . . .                     | 414        |
| 11.3.1    | Experimental Program . . . . .   | 414        |
| 11.3.2    | Test Analysis . . . . .  | 418        |
| 11.4      | Concluding Remarks . . . . .   | 428        |
|           | References . . . . .   | 431        |
| <b>12</b> | <b>Seismic Performance of Recycled Aggregate Concrete<br/>Structures . . . . .</b>       | <b>433</b> |
| 12.1      | Introduction . . . . .   | 433        |
| 12.2      | Low-Frequency Reversed Loading on Frame Joints . . . . .                                 | 433        |
| 12.2.1    | Experimental Program . . . . .   | 433        |
| 12.2.2    | Test Result . . . . .  | 436        |
| 12.2.3    | Test Analysis . . . . .  | 437        |
| 12.2.4    | Nonlinear Analysis . . . . .   | 440        |
| 12.3      | Low-Frequency Reversed Loading on Plane Frame . . . . .                                  | 444        |
| 12.3.1    | Experimental Program . . . . .   | 444        |
| 12.3.2    | Test Analysis . . . . .  | 447        |
| 12.4      | Shaking Table Test on Cast-in-Situ Space Frame . . . . .                                 | 453        |
| 12.4.1    | Experimental Program . . . . .   | 453        |
| 12.4.2    | Test Analysis . . . . .  | 457        |
| 12.4.3    | Nonlinear Analysis . . . . .   | 465        |
| 12.5      | Shaking Table Test on Precast Space Frame . . . . .                                      | 484        |
| 12.5.1    | Experimental Program . . . . .   | 484        |
| 12.5.2    | Test Results and Analysis . . . . .  | 490        |
| 12.5.3    | Simulation Modeling . . . . .  | 504        |
| 12.5.4    | Simulated Results and Validation . . . . .   | 507        |
| 12.5.5    | Parametric Study . . . . .   | 518        |
| 12.6      | Concluding Remarks . . . . .   | 522        |
|           | References . . . . .   | 523        |
| <b>13</b> | <b>Seismic Performance of Recycled Aggregate Concrete Block<br/>Structures . . . . .</b> | <b>525</b> |
| 13.1      | Design of the RAC Hollow Block Walls . . . . .   | 525        |
| 13.1.1    | Test Specimens . . . . .   | 525        |
| 13.1.2    | Test Set-up, Instruments, and Procedure . . . . .  | 527        |
| 13.2      | Test Results of the RAC Hollow Block Walls . . . . .                                     | 528        |
| 13.2.1    | Failure Patterns . . . . .   | 528        |
| 13.2.2    | The Role of Tie Column . . . . .   | 530        |
| 13.2.3    | Main Results . . . . .   | 530        |

- 13.3 Seismic Performance Analysis . . . . . 530
  - 13.3.1 Hysteresis Curve . . . . . 530
  - 13.3.2 Skeleton Curve . . . . . 531
  - 13.3.3 Ductility Analysis . . . . . 532
  - 13.3.4 Energy Dissipation Capacity . . . . . 534
  - 13.3.5 Stiffness Degradation. . . . . 535
  - 13.3.6 Overall Deformation . . . . . 536
  - 13.3.7 Steel Strain . . . . . 537
- 13.4 Verification of Shear Bearing Capacity Formula for Hollow Block Walls . . . . . 537
- 13.5 Design of the RAC Block Masonry Building . . . . . 542
  - 13.5.1 Materials . . . . . 542
  - 13.5.2 Construction . . . . . 543
- 13.6 Shake Table Tests. . . . . 543
  - 13.6.1 Description of Shake Table . . . . . 543
  - 13.6.2 Seismic Wave Selection and Arrangement of Instruments . . . . . 544
  - 13.6.3 Loading Program. . . . . 548
  - 13.6.4 Cracking and Failure Pattern . . . . . 550
- 13.7 Earthquake Response Analysis of the RAC Block Masonry Building . . . . . 552
  - 13.7.1 Dynamic Characteristics of the Structure. . . . . 552
  - 13.7.2 Acceleration Response. . . . . 556
  - 13.7.3 Earthquake Action. . . . . 558
  - 13.7.4 Displacement Response. . . . . 559
  - 13.7.5 Inter-storey Shear Response. . . . . 560
  - 13.7.6 Fragility Curves for RAC Block Masonry Building . . . 564
- 13.8 Concluding Remarks. . . . . 566
- References. . . . . 567
- 14 Products and Constructions with Recycled Aggregate Concrete. . . . . 569**
  - 14.1 Premix . . . . . 569
    - 14.1.1 Premix Recycled Concrete. . . . . 570
    - 14.1.2 RA Mortar. . . . . 572
    - 14.1.3 Cement Stabilizing RA . . . . . 572
  - 14.2 Precast . . . . . 573
    - 14.2.1 Brick and Block . . . . . 573
    - 14.2.2 Recycled Concrete Hollow Block Masonry. . . . . 577
    - 14.2.3 RAC Panel . . . . . 580
  - 14.3 Quality Control by Nondestructive Inspection . . . . . 582
    - 14.3.1 Rebound Hammer Test . . . . . 582
    - 14.3.2 Ultrasonic Pulse Velocity Test (UPV). . . . . 583



|           |  |            |
|-----------|--|------------|
| 14.4      | Case Study . . . . .   | 583        |
| 14.4.1    | Pavements—In China . . . . .   | 583        |
| 14.4.2    | Cast-in-situ RAC Frame Structure . . . . .   | 589        |
| 14.4.3    | Precast RAC Frame Structure . . . . .  | 590        |
| 14.4.4    | RAC Masonry and Other Structures . . . . .   | 591        |
| 14.4.5    | RAC Frame-Shear Wall Structure . . . . .   | 591        |
| 14.4.6    | Steel Frame Filled with RA Bricks . . . . .  | 594        |
| 14.5      | Efficiency Analysis . . . . .  | 596        |
| 14.5.1    | Introduction . . . . .   | 596        |
| 14.5.2    | Economic Benefits . . . . .  | 596        |
| 14.5.3    | Overall Environmental Benefits . . . . .   | 598        |
| 14.6      | Management Strategies . . . . .  | 601        |
| 14.6.1    | The Recycled Concrete Industry Chain . . . . .   | 602        |
| 14.6.2    | Management Strategies of RAC . . . . .   | 604        |
| 14.6.3    | The Application of Computer Technology in RAC<br>Production Management . . . . .         | 607        |
| 14.7      | Concluding Remarks . . . . .   | 609        |
|           | References . . . . .   | 610        |
| <b>15</b> | <b>Guidelines for Recycled Aggregate Concrete Materials<br/>and Structures . . . . .</b> | <b>611</b> |
| 15.1      | Waste Concrete . . . . .   | 611        |
| 15.2      | Crush and Sieving . . . . .  | 612        |
| 15.2.1    | Processing and Grading of Recycled Aggregates . . . . .                                  | 612        |
| 15.2.2    | Quality Standard for Recycled Aggregates . . . . .                                       | 613        |
| 15.2.3    | Testing Methods for Recycled Aggregates . . . . .  | 613        |
| 15.2.4    | Regulations for Inspection of Recycled Aggregates . . . . .                              | 614        |
| 15.2.5    | Production and Management of Recycled Coarse<br>Aggregates . . . . .                     | 615        |
| 15.2.6    | Application of Recycled Fine Aggregates . . . . .  | 616        |
| 15.3      | Mix Proportion . . . . .   | 616        |
| 15.3.1    | Methods for the Design of the Mix Proportion . . . . .                                   | 616        |
| 15.3.2    | Preparation and Transportation . . . . .   | 616        |
| 15.4      | Materials . . . . .  | 619        |
| 15.4.1    | General Regulations . . . . .  | 619        |
| 15.4.2    | Mechanical Properties . . . . .  | 620        |
| 15.4.3    | Suggestions on the Design of Recycled Concrete<br>Blocks . . . . .                       | 623        |
| 15.5      | Infrastructure . . . . .   | 626        |
| 15.5.1    | Design Suggestions for Recycled Concrete<br>Pavements . . . . .                          | 626        |
| 15.5.2    | Suggestions on the Design of Recycled Concrete<br>Structural Components . . . . .        | 627        |

|        |   |           |
|--------|---|-----------|
| 15.6   | Construction . . . . .  | 630       |
| 15.6.1 | Casting and Molding . . . . .                                       | 630       |
| 15.6.2 | Concrete Curing . . . . .   | 630       |
| 15.6.3 | Quality Inspection . . . . .  | 631       |
|        | References. . . . .   | 632       |
|        | <b>Erratum to: Recycled Aggregate Concrete Structures . . . . .</b> | <b>E1</b> |



<http://www.springer.com/978-3-662-53985-9>

Recycled Aggregate Concrete Structures

Xiao, J.

2018, XLVI, 632 p. 502 illus., Hardcover

ISBN: 978-3-662-53985-9