

CIVIL ENGINEERING MATERIALS

Nagaratnam Sivakugan | Carthigesu T. Gnanendran | Rabin Tuladhar | M. Bobby Kannan



Civil Engineering Materials

Nagaratnam Sivakugan

James Cook University, Australia

Carthigesu T. Gnanendran

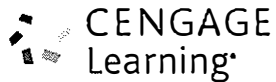
*The University of New South Wales
at the Australian Defence Force
Academy, Australia*

Rabin Tuladhar

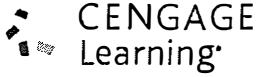
James Cook University, Australia

M. Bobby Kannan

James Cook University, Australia



Australia • Brazil • Mexico • Singapore • United Kingdom • United States



CENGAGE
Learning

Civil Engineering Materials,
First Edition

**Authors: Nagaratnam Sivakugan,
Carthigesu T. Gnanendran,
Rabin Tuladhar, and M. Bobby Kannan**

Product Director, Global Engineering:
Timothy L. Anderson

Associate Media Content Developer:
Ashley Kaupert

Product Assistant: Teresa Versaggi

Marketing Manager: Kristin Stine

Director, Higher Education Production:
Sharon L. Smith

Content Project Manager: Megan Guiliani

Production Service: RPK Editorial
Services, Inc.

Copyeditor: Lori Martinsek

Proofreader: Jason Pankoke

Indexer: Shelly Gerger-Knechtl

Compositor: SPi Global

Senior Art Director: Michelle Kunkler

Cover and Internal Designer:
Stratton Design

Cover image: Photo Art by
Mandy/Moment/Getty Images

Intellectual Property

Analyst: Christine Myaskovsky

Project Manager: Sarah Shainwald

Text and Image Permissions Researcher:
Kristiina Paul

Manufacturing Planner: Doug Wilke

© 2018 Cengage Learning®

ALL RIGHTS RESERVED. No part of this work covered by the copyright herein may be reproduced or distributed in any form or by any means, except as permitted by U.S. copyright law, without the prior written permission of the copyright owner.

For product information and technology assistance, contact us at
Cengage Learning Customer & Sales Support, 1-800-354-9706.

For permission to use material from this text or product,
submit all requests online at
www.cengage.com/permissions.

Further permissions questions can be emailed to
permissionrequest@cengage.com.

Library of Congress Control Number: 2016952402

ISBN: 978-1-305-38664-8

Cengage Learning

20 Channel Center Street

Boston, MA 02210

USA

Cengage Learning is a leading provider of customized learning solutions with employees residing in nearly 40 different countries and sales in more than 125 countries around the world. Find your local representative at www.cengage.com.

Cengage Learning products are represented in Canada by Nelson Education Ltd.

To learn more about Cengage Learning Solutions, visit
www.cengage.com/engineering.

Purchase any of our products at your local college store or at our preferred online store www.cengagebrain.com.

Unless otherwise noted, all items © Cengage Learning.

Printed in Canada

Print Number: 01 Print Year: 2016

Preface		xiii
About the Authors		xviii
Chapter 1	Engineering Behavior of Materials— Some Fundamentals	1
1.1	Introduction	1
1.2	Stress-Strain Relations and Constitutive Models	3
	1.2.1 <i>Some Simple Material Models</i>	4
	1.2.2 <i>Other Material Models</i>	6
1.3	Types of Loadings	9
1.4	Special Loading Situations	10
	1.4.1 <i>Generalized Stress-Strain Relationships</i>	12
	1.4.2 <i>Plane Strain Loading</i>	15
	1.4.3 <i>Plane Stress Loading</i>	17
	1.4.4 <i>Axisymmetric Loading</i>	18
1.5	Strain-Displacement Relations	18
1.6	Equations of Equilibrium	19
1.7	Laboratory Measurements and Measuring Devices	20
1.8	Material Variability and Sample Statistics	22
1.9	Numerical Modeling	23
1.10	Standards, Units, and Safety	23
1.11	Sustainability	26
1.12	Summary	27
	Exercises	27
Chapter 2	Chemistry of Materials	30
2.1	Introduction	30
2.2	Atomic Structure and Bonding	30
	2.2.1 <i>Atomic Structure</i>	31
	2.2.2 <i>Bonding</i>	33
2.3	Arrangement of Atoms	36
2.4	Classification of Materials	44
2.5	Imperfection in Materials	45
2.6	Strengthening in Materials	48
2.7	Characterization of Materials	50

	2.7.1 <i>X-Ray Diffraction (XRD)</i>	50
	2.7.2 <i>Optical Microscope</i>	50
	2.7.3 <i>Electron Microscopes</i>	52
	2.7.4 <i>Atomic Force Microscope (AFM)</i>	54
2.8	Summary	55
	Exercises	56
	References	57
Chapter 3	Soils	58
3.1	Introduction	58
3.2	Civil Engineering Applications	58
	3.2.1 <i>Traditional Geotechnical Applications</i>	59
	3.2.2 <i>Backfilling Underground Mines</i>	59
	3.2.3 <i>Land Reclamation Using Dredge Spoils</i>	60
3.3	Formation of Soils	61
	3.3.1 <i>Elements of Earth</i>	61
	3.3.2 <i>Igneous, Sedimentary, and Metamorphic Rocks</i>	63
	3.3.3 <i>Residual and Transported Soils</i>	65
3.4	Soils versus Other Engineering Materials	66
3.5	Soil Classification	66
3.6	Compaction and Earthworks	69
	3.6.1 <i>Moisture–Density Relationships</i>	69
	3.6.2 <i>Laboratory Tests</i>	71
	3.6.3 <i>Field Compaction, Specifications, and Control</i>	72
3.7	Permeability	73
	3.7.1 <i>Darcy's Law</i>	73
	3.7.2 <i>Typical Values</i>	74
	3.7.3 <i>Laboratory and Field Tests</i>	74
3.8	Strength and Stiffness	74
	3.8.1 <i>Failure in Soils</i>	75
	3.8.2 <i>Deformations in Soils</i>	76
	3.8.3 <i>Effective Stress Theory and Drained/Undrained Loading</i>	76
	3.8.4 <i>Laboratory and Field Measurements</i>	77
3.9	Measurements of Soil Properties	78
	3.9.1 <i>Laboratory Tests</i>	79
	3.9.2 <i>In Situ Tests</i>	79
	3.9.3 <i>Instrumentation</i>	80
3.10	New Materials	80
3.11	Summary	82
	Exercises	83
	References	85

Chapter 4	Rocks	86
4.1	Introduction	86
4.2	Rock Engineering Applications	87
	4.2.1 <i>Rocks as Construction Materials</i>	87
	4.2.2 <i>Other Civil Engineering Applications, using Rocks</i>	89
4.3	Common Rocks in Construction	90
4.4	Rock Mass and Intact Rock	91
4.5	Strength and Stiffness of Intact Rocks	92
	4.5.1 <i>Rock Cores and RQD</i>	93
	4.5.2 <i>Strength and Stiffness Parameters</i>	95
4.6	Laboratory Tests for Intact Rocks	101
4.7	Field Tests for Rocks	105
4.8	Rock Mass Classification	108
4.9	Rockfills	108
4.10	Summary	109
	Exercises	110
	References	112
Chapter 5	Aggregates	114
5.1	Introduction	114
5.2	Origin, Geology and Classification of Parent Rocks	115
5.3	Properties and Testing of Aggregates	117
	5.3.1 <i>Particle Size and Grading</i>	118
	5.3.2 <i>Types of Grading and Relationship with Density</i>	120
	5.3.3 <i>Shape and Surface Texture</i>	128
	5.3.4 <i>Strength and Stiffness</i>	132
	5.3.5 <i>Hardness, Toughness, and Abrasion Resistance</i>	133
	5.3.6 <i>Soundness and Durability</i>	136
	5.3.7 <i>Chemical Stability of Aggregate in PCC</i>	137
	5.3.8 <i>Cleanness and Deleterious Substances</i>	138
	5.3.9 <i>Affinity for Asphalt Cement</i>	138
	5.3.10 <i>Moisture and Asphalt Binder Absorption</i>	139
	5.3.11 <i>Relative Density (or Specific Gravity) and Bulk Density</i>	140
5.4	Uses of Aggregates	143
5.5	Lightweight and Heavyweight Aggregates	146
5.6	Aggregates from Industrial By-Products and Waste	147
5.7	Handling, Transportation, and Storage of Aggregates	149
5.8	Summary	150

	Exercises	151
	References	153
Chapter 6	Geosynthetics	154
6.1	Introduction	154
6.2	Types of Geosynthetics, Polymers Used, Manufacture, and Common Use	155
	6.2.1 <i>Types of Geosynthetics</i>	155
	6.2.2 <i>Polymers Used in Geosynthetics</i>	155
	6.2.3 <i>Geotextiles</i>	157
	6.2.4 <i>Geogrids</i>	160
	6.2.5 <i>Geonets</i>	161
	6.2.6 <i>Geomembranes</i>	162
	6.2.7 <i>Geocells</i>	164
	6.2.8 <i>Geomats</i>	164
	6.2.9 <i>Geocomposites—Geosynthetic Clay Liners (GCLs), Prefabricated Vertical Drains (PVDs), Geopipes, Geofoams, and Others</i>	164
6.3	Properties and Testing of Geosynthetics	166
	6.3.1 <i>Tensile Properties and Testing</i>	168
	6.3.2 <i>Fill-Soil Interface Shear Properties and Testing</i>	171
	6.3.3 <i>Hydraulic- or Flow-Related Properties and Testing</i>	174
	6.3.4 <i>Endurance, Integrity, Durability and Long-Term Performance-Related Properties and Testing</i>	179
6.4	Functions, Mechanisms and Engineering Applications	183
	6.4.1 <i>Reinforcement</i>	183
	6.4.2 <i>Separation</i>	188
	6.4.3 <i>Filtration</i>	189
	6.4.4 <i>Drainage</i>	191
	6.4.5 <i>Containment</i>	192
	6.4.6 <i>Erosion Control</i>	193
	6.4.7 <i>Typical Examples of Geosynthetics Use in the Field</i>	193
6.5	Selection of Geosynthetics	194
	6.5.1 <i>Available versus Required Property</i>	197
	6.5.2 <i>Selection of a Geosynthetic</i>	201
6.6	Summary	203
	Exercises	204
	References	207
Chapter 7	Asphalt Cement and Hot Mix Asphalt Concrete	208
7.1	Introduction	208
7.2	Types of Asphalt Cements or Bituminous Materials	209

7.3	Common Asphalt Cement Products and Their Grading	211
	<i>7.3.1 Standard Penetration Grading</i>	<i>211</i>
	<i>7.3.2 Viscosity Grading</i>	<i>211</i>
	<i>7.3.3 Aged Residue Grading</i>	<i>214</i>
	<i>7.3.4 Performance Grading</i>	<i>215</i>
	<i>7.3.5 Other Asphalt Products</i>	<i>215</i>
7.4	Typical Uses of Asphaltic Materials	218
7.5	Properties and Testing of Asphalt Cement	218
	<i>7.5.1 Consistency and Rate of Curing of Asphalt Cement</i>	<i>220</i>
	<i>7.5.2 Durability and Other Properties of Asphalt Materials</i>	<i>223</i>
7.6	Overview of Pavements	228
7.7	Bituminous Surfacing Treatments and Sealing in Pavements	229
7.8	Asphalt Concrete	233
	<i>7.8.1 HMA Design</i>	<i>234</i>
	<i>7.8.2 Density and Voids Analysis of HMA</i>	<i>235</i>
	<i>7.8.3 Marshall Method</i>	<i>241</i>
	<i>7.8.4 Superpave Mix Design</i>	<i>243</i>
	<i>7.8.5 HMA Production</i>	<i>245</i>
	<i>7.8.6 Characterization of HMA for Pavement Design</i>	<i>247</i>
7.9	Use of Additives and Recycling	250
7.10	Summary	250
	Exercises	251
	References	252
Chapter 8	Cement and Concrete	254
8.1	Introduction	254
	<i>8.1.1 History of Concrete</i>	<i>254</i>
	<i>8.1.2 Advantages of Concrete</i>	<i>255</i>
	<i>8.1.3 Limitations of Concrete</i>	<i>256</i>
8.2	Constituents of Concrete	257
	<i>8.2.1 Portland Cement</i>	<i>257</i>
	<i>8.2.2 Supplementary Cementitious Material</i>	<i>263</i>
	<i>8.2.3 Water</i>	<i>266</i>
	<i>8.2.4 Aggregates</i>	<i>267</i>
	<i>8.2.5 Admixture</i>	<i>272</i>
8.3	Different Stages of Concrete	274
	<i>8.3.1 Plastic State</i>	<i>274</i>
	<i>8.3.2 Setting State</i>	<i>275</i>
	<i>8.3.3 Hardening State</i>	<i>275</i>

8.4	Properties of Fresh Concrete	275
	8.4.1 <i>Workability</i>	275
	8.4.2 <i>Consistency</i>	276
	8.4.3 <i>Cohesiveness</i>	278
	8.4.4 <i>Early-Age Performance of Concrete</i>	278
8.5	Site Practice of Concrete	282
	8.5.1 <i>Compaction</i>	282
	8.5.2 <i>Finishing</i>	283
	8.5.3 <i>Curing</i>	284
8.6	Properties of Hardened Concrete	284
	8.6.1 <i>Compressive Strength</i>	285
	8.6.2 <i>Tensile Strength of Concrete</i>	287
	8.6.3 <i>Modulus of Elasticity of Concrete</i>	289
	8.6.4 <i>Poisson's Ratio</i>	289
	8.6.5 <i>Creep in Concrete</i>	289
	8.6.6 <i>Shrinkage in Concrete</i>	290
	8.6.7 <i>Durability of Concrete</i>	291
8.7	Concrete Mix Design	294
	8.7.1 <i>Mix Design Procedure</i>	294
8.8	Summary	302
	Exercises	303
	References	307
Chapter 9	Metals and Alloys	309
9.1	Introduction	309
9.2	Ferrous Alloys	309
	9.2.1 <i>Iron-Carbon Diagram</i>	310
	9.2.2 <i>Steels</i>	311
	9.2.3 <i>Cast Irons</i>	314
	9.2.4 <i>Stainless Steels</i>	314
	9.2.5 <i>Heat-Treatment Techniques</i>	315
9.3	Nonferrous Metals and Alloys	316
	9.3.1 <i>Copper</i>	316
	9.3.2 <i>Aluminum</i>	317
	9.3.3 <i>Magnesium</i>	317
9.4	Types of Failures	318
	9.4.1 <i>Fracture</i>	318
	9.4.2 <i>Fatigue</i>	321
	9.4.3 <i>Creep</i>	323
	9.4.4 <i>Corrosion</i>	324
9.5	Summary	330
	Exercises	330
	References	331

Chapter 10	Steel	332
	10.1 Introduction	332
	10.2 Advantages of Steel	332
	10.3 Limitations of Steel	333
	10.4 Iron- and Steel-making	334
	10.4.1 Basic Oxygen Steelmaking (BOS)	335
	10.4.2 Electric Arc Furnace (EAF)	336
	10.5 Wrought Iron	337
	10.6 Cast Iron	338
	10.7 Carbon Steel	338
	10.8 Structural Steel	340
	10.8.1 Hot-Rolled Steel	342
	10.8.2 Cold-formed Steel	344
	10.8.3 Reinforcing bars	345
	10.9 Heat Treatment of Steel	347
	10.9.1 Quenching	347
	10.9.2 Tempering	347
	10.9.3 Annealing	348
	10.10 Mechanical Properties of Steel	348
	10.10.1 Tension test	348
	10.10.2 Poisson's Ratio (ν)	351
	10.10.3 Shear Modulus of Elasticity (G)	351
	10.11 Summary	352
	Exercises	353
	References	355
Chapter 11	Polymers, Ceramics, and Composites	357
	11.1 Introduction	357
	11.2 Polymers	357
	11.2.1 Chemistry	359
	11.2.2 Thermosetting and Thermoplastic Polymers	361
	11.2.3 Mechanical Properties	362
	11.2.4 Degradation	362
	11.3 Ceramics	363
	11.3.1 Chemistry	364
	11.3.2 Mechanical Properties	365
	11.3.3 Glass-Ceramics	366
	11.4 Composites	367
	11.4.1 Fiber-Reinforced Plastics	367
	11.4.2 Metal Matrix Composites	370

	<i>11.4.3 Ceramic Matrix Composites</i>	371
	<i>11.4.4 Failure</i>	371
	<i>11.4.5 Applications</i>	371
11.5	Summary	372
	Exercises	372
	References	373
Chapter 12	Wood	374
12.1	Introduction	374
12.2	Advantages of Lumber	376
12.3	Limitations of Wood	376
12.4	Structure of Wood	377
12.5	Types of Wood	378
12.6	Chemical Composition of Wood	380
12.7	Anisotropic Behavior of Wood	380
12.8	Conversion and Processing of Wood	381
	<i>12.8.1 Flat or Plain Sawing</i>	<i>382</i>
	<i>12.8.2 Quarter Sawing</i>	<i>382</i>
	<i>12.8.3 Rift sawing</i>	<i>382</i>
12.9	Seasoning of Wood	382
12.10	Defects in Wood	383
12.11	Degradation of Wood and Preservative Treatment	385
	<i>12.11.1 Degradation of wood</i>	<i>386</i>
	<i>12.11.2 Protective Coatings and Preservative Treatments</i>	<i>386</i>
12.12	Physical Properties of Wood	387
	<i>12.12.1 Density and Specific Gravity</i>	<i>387</i>
	<i>12.11.1 Moisture Content</i>	<i>387</i>
12.13	Mechanical Properties of Lumber	388
	<i>12.13.1 Modulus of Elasticity</i>	<i>389</i>
	<i>12.13.2 Compressive Strength</i>	<i>389</i>
	<i>12.13.3 Modulus of Rupture</i>	<i>389</i>
	<i>12.13.4 Tensile Strength</i>	<i>389</i>
	<i>12.13.5 Creep</i>	<i>390</i>
	<i>12.13.6 Determination of Mechanical Properties</i>	<i>390</i>
12.14	Engineered Lumber Products	390
	<i>12.14.1 Laminated Veneer Lumber (LVL)</i>	<i>391</i>
	<i>12.14.2 Glued Laminated Lumber (Glulam)</i>	<i>392</i>
	<i>12.14.3 Cross Laminated Timber (CLT)</i>	<i>392</i>

	<i>12.14.4 I-Beams</i>	392
	<i>12.14.5 Plywood</i>	392
12.15	Summary	393
	Exercises	393
	References	395
Chapter 13	Sustainability of Construction Materials	396
13.1	Introduction	396
13.2	Sustainable Development	396
	<i>13.2.1 Embodied Energy and Operational Energy</i>	<i>398</i>
	<i>13.2.2 Life-Cycle Assessment (LCA)</i>	<i>400</i>
13.3	Sustainability of Construction Materials	402
	<i>13.3.1 Cement and Concrete</i>	<i>403</i>
	<i>13.3.2 Steel</i>	<i>406</i>
	<i>13.3.3 Wood</i>	<i>406</i>
	<i>13.3.4 Soils, Rocks, and Aggregates</i>	<i>407</i>
	<i>13.3.5 Asphalt Concrete</i>	<i>408</i>
13.4	Summary	409
	Exercises	410
	References	411
	Appendix A Unit Conversions	413
	Index	415

Materials science and engineering is a multidisciplinary area that is offered in undergraduate and graduate programs at many leading universities. It covers all engineering materials such as metals, ceramics, plastics, composites, and nanomaterials. When it comes to traditional engineering undergraduate programs such as civil, mechanical, electrical, or chemical engineering, their specific materials science educational needs are quite different. While civil engineers deal mostly with steel, concrete, timber, and soils, their mechanical engineering counterparts are interested in different alloys and composite materials. With rapid economic development and the scarcity of natural resources, the use of synthetic materials (e.g., polymers, composites), industrial by-products (e.g., slag, fly ash), recycled materials and their combinations with traditional materials (e.g., concrete and soils) has recently become more prevalent in civil engineering projects. Hence, there is a growing need for civil engineers to learn more about these advanced materials in addition to traditional materials.

Civil engineering mainly deals with the design and construction of civil infrastructure (e.g., dams, embankments, roads, buildings and bridges) and the provision of services such as water supply and sewerage. Civil engineering projects involve the use of various materials for design and construction. It is commonly expected that civil engineers have an in-depth knowledge of these conventional and advanced materials to select the materials sensibly, determine the material properties, and effectively carry out the design and construction.

Civil Engineering Materials covers all major traditional civil engineering materials through separate chapters. Sustainability is an important consideration these days among civil and construction engineering professionals. It is and will be a critical element in the material selection process. Chapter 13 discusses the sustainability, life cycle analysis, and other important issues relevant to civil and construction materials.

The civil engineering materials course is almost always taught in a broad-brush approach rather than providing comprehensive coverage. Generally, students learn the subject in the early years of a civil engineering program, and with the content covering a wide range of rather independent topics, it is necessary to provide a broad-brush treatment without relying on too many prerequisites. The students subsequently take more detailed courses in soils, rocks, concrete, steel, etc. that offer higher-level coverage.

All four co-authors are passionate about what we do in our respective areas, with excellent track records in teaching and learning. We are also active researchers who are up-to-date with the recent developments. Being young or young at heart, we have a good blend of experience; the young ones are eager to provide good taste and layout that is appealing to the new generation, and the senior ones take charge and contribute through their experiences. Having four co-authors with different backgrounds is one of the strengths here. This has enabled us to develop the chapters with genuine expertise in areas that we have been teaching for years.