

The Science and Technology of Civil Engineering Materials

PRENTICE HALL INTERNATIONAL SERIES IN CIVIL ENGINEERING AND
ENGINEERING MECHANICS, WILLIAM HALL, SERIES EDITOR

J. Francis Young

*Professor of Civil Engineering and Materials Science and Engineering
University of Illinois at Urbana-Champaign*

Sidney Mindess

*Professor of Civil Engineering and Associate Vice President Academic
University of British Columbia*

Robert J. Gray

*Consultant
Vancouver, British Columbia*

Arnon Bentur

*Professor of Civil Engineering and Vice President Research
Technion—Israel Institute of Technology*



Prentice Hall
Upper Saddle River, New Jersey 07458

Contents

PREFACE *xiii*

Part I: The Fundamentals of Materials 1

1 ATOMIC BONDING 3

- 1.1 Introduction 3
- 1.2 Ionic Bonds 3
- 1.3 Covalent Bonds 5
- 1.4 Metallic Bonds 5
- 1.5 Van Der Waals Bonding 6
 - 1.5.1 Hydrogen Bonding, 7
- 1.6 Bonding Energies 8
- 1.7 Thermal Properties of Solids 9
- 1.8 Bonding Forces 12

2 THE ARCHITECTURE OF SOLIDS 15

- 2.1 The Crystalline State 15
 - 2.1.1 Metallic Crystals, 15
 - 2.1.2 Ionic Crystals, 17
 - 2.1.3 Covalent Crystals, 21
 - 2.1.4 Crystals and Unit Cells, 25
- 2.2 Defects and Atomic Movements in Crystalline Solids 26
 - 2.2.1 Defects in Crystals, 26
 - 2.2.2 Atomic Movements, 32
- 2.3 The Amorphous State 37
- 2.4 The Polymeric State 39
 - 2.4.1 The Polymeric Molecule, 39
 - 2.4.2 Thermoplastic Polymers, 41
 - 2.4.3 Elastomeric Polymers, 45
 - 2.4.4 Thermosetting Polymers, 45
 - 2.4.5 Rigid Rod Polymers, 46
- 2.5 The Composite Structure 47

3 DEVELOPMENT OF MICROSTRUCTURE 50

- 3.1 Introduction 50
- 3.2 Solidification 50
 - 3.2.1 Crystallization from Melts, 51
 - 3.2.2 Crystallization from Solution, 54

3.3	Phase Changes on Heating and Cooling	55
3.4	Phase Diagrams	55
3.4.1	<i>One-component Systems</i>	55
3.4.2	<i>Two-component Systems</i>	56
3.4.3	<i>Systems with Partial Immiscibility</i>	58
3.4.4	<i>Three- and four-component Systems</i>	60
3.5	Sintering	60
3.6	Microstructure	62
3.6.1	<i>Porosity</i>	62
3.6.2	<i>Grain Size</i>	62
3.6.3	<i>Composite Microstructures</i>	63
4	SURFACE PROPERTIES	66
4.1	Surface Energy and Surface Tension	66
4.2	Interfaces	69
4.3	Wetting	69
4.4	Adsorption	70
4.5	Surfactants	72
4.6	Capillary Effects	73
4.7	Adhesion	75
4.8	Colloids	76
4.8.1	<i>Structure of Colloids</i>	76
4.8.2	<i>Stability of Colloids</i>	77
4.9	The Double Layer	79
	Part II: Behavior of Materials Under Stress	83
5	RESPONSE OF MATERIALS TO STRESS	85
5.1	Tension	86
5.1.1	<i>Elastic Behavior</i>	87
5.1.2	<i>Inelastic Behavior</i>	88
5.1.3	<i>Definitions of Stress and Strain</i>	91
5.1.4	<i>Experimental Determination of Tensile Properties</i>	92
5.2	Compression	94
5.3	Bending	96
5.3.1	<i>Behavior in Pure Bending</i>	96
5.3.2	<i>Failure in Pure Bending</i>	97
5.3.3	<i>Types of Bending Tests</i>	97
5.3.4	<i>Limitations in Bending Tests</i>	99
5.4	Torsion	100
5.4.1	<i>Stress and Strain Relationships in Torsion</i>	100
5.4.2	<i>Failure in Torsion</i>	101

5.4.3	<i>Test Methods in Torsion, 103</i>
5.4.4	<i>Sources of Error in Torsion Tests, 103</i>
5.5	Direct Shear 103
5.6	Multiaxial Loading 104
5.6.1	<i>Transverse Stresses, 106</i>
5.7	Hardness 107
5.7.1	<i>Scratch Hardness, 107</i>
5.7.2	<i>Indentation Hardness, 107</i>
5.7.3	<i>Microhardness Tests, 112</i>
5.7.4	<i>Vickers Diamond Pyramid, 112</i>
6	FAILURE AND FRACTURE 115
6.1	Failure Theories 115
6.1.1	<i>Maximum Shear Stress Theory, 116</i>
6.1.2	<i>Maximum Distortional Strain Energy Theory, 116</i>
6.1.3	<i>Comparison of the Failure Theories, 117</i>
6.1.4	<i>Mohr's Strength Theory, 117</i>
6.2	Fracture Mechanics 120
6.2.1	<i>Griffith Theory, 122</i>
6.2.2	<i>Stress-Intensity Factor, 123</i>
6.2.3	<i>Compressive Failure, 126</i>
6.2.4	<i>Notch Sensitivity, 126</i>
6.2.5	<i>Crack Velocity, 127</i>
6.3	The Ductile-Brittle Transition 127
6.4	Fracture Energy 130
6.5	Effect of Rate of Loading 131
6.5.1	<i>Effect of Loading Rate on Brittle Materials, 131</i>
6.5.2	<i>Static Fatigue, 133</i>
6.5.3	<i>Effect of Loading Rate on Metals, 133</i>
7	RHEOLOGY OF FLUIDS AND SOLIDS 138
7.1	Elastic and Viscous Behavior 138
7.2	Simple Rheological Models 140
7.3	Rheology of Fluids 141
7.4	Rheology of Viscoelastic Solids 143
7.4.1	<i>Maxwell Model, 143</i>
7.4.2	<i>Kelvin Model, 144</i>
7.4.3	<i>Prandtl Model, 144</i>
7.4.4	<i>Complex Rheological Models, 144</i>
7.5	Creep of Engineering Materials 146
7.5.1	<i>Creep in Metals, 147</i>
7.5.2	<i>Creep in Polymers and Asphalts, 148</i>
7.5.3	<i>Creep in Portland Cement Concrete and Wood, 150</i>
8	FATIGUE 152
8.1	Introduction 152

8.2	The Nature of Fatigue Failure	153
	8.2.1	<i>Crack Initiation, 153</i>
	8.2.2	<i>Crack Propagation, 154</i>
8.3	Types of Fatigue Loading	157
8.4	Behavior under Fatigue Loading	157
8.5	The Statistical Nature of Fatigue	160
8.6	The Statistical Presentation of Fatigue Data	162
8.7	Factors Affecting Fatigue Life	163
	8.7.1	<i>Stressing Conditions, 164</i>
	8.7.2	<i>Material Properties, 169</i>
	8.7.3	<i>Environmental Conditions, 169</i>
8.8	Experimental Methods in Fatigue	170
	8.8.1	<i>Fatigue Machines, 172</i>
	8.8.2	<i>Fatigue Test Procedures, 173</i>

Part III: Particulate Composites: Portland Cement and Asphalt Concretes 177

9 PARTICULATE COMPOSITES 179

9.1	Introduction	179
9.2	Concepts of the Mechanics of Particulate Composites	181
	9.2.1	<i>Elastic Behavior, 181</i>
	9.2.2	<i>Failure in Particulate Composites, 183</i>
9.3	Composition and Structure	186
9.4	Interfacial Properties	186
9.5	Mechanical Behavior	187

10 AGGREGATES 189

10.1	Introduction	189
10.2	Composition and Structure	190
10.3	Characteristics	192
	10.3.1	<i>Geometrical Properties, 192</i>
	10.3.2	<i>Physical Properties, 196</i>
	10.3.3	<i>Strength and Toughness, 199</i>
	10.3.4	<i>Other Properties, 199</i>

11 PORTLAND CEMENT CONCRETE 204

11.1	Introduction	204
11.2	The Cementitious Phase	205
	11.2.1	<i>Composition and Hydration of Portland Cement, 206</i>
	11.2.2	<i>Microstructure and Properties of Hydration Products, 210</i>
	11.2.3	<i>Portland Cements of Different Compositions, 214</i>
	11.2.4	<i>Blended Cements and Mineral Admixtures, 215</i>
	11.2.5	<i>Porosity and Pore Structure, 218</i>

11.3	Properties of Concrete	222
	11.3.1	<i>Fresh Concrete, 223</i>
	11.3.2	<i>Behavior during Setting, 227</i>
	11.3.3	<i>Chemical Admixtures, 228</i>
	11.3.4	<i>Properties of Hardened Concrete, 231</i>
11.4	Durability of Concrete	241
	11.4.1	<i>Permeability and Diffusivity, 241</i>
	11.4.2	<i>Composition of Pore Solutions, 243</i>
	11.4.3	<i>Chemical Attack, 243</i>
	11.4.4	<i>Physical Attack, 245</i>
11.5	Corrosion of Steel in Concrete	249
	11.5.1	<i>Corrosion Mechanism, 249</i>
	11.5.2	<i>Corrosion Protection, 250</i>
11.6	Concrete Mix Design	252
12	ASPHALT CEMENTS AND ASPHALT CONCRETE	256
12.1	Introduction	256
12.2	Asphalt Cements	257
	12.2.1	<i>Introduction, 257</i>
	12.2.2	<i>Composition and Structure, 258</i>
	12.2.3	<i>Properties, 261</i>
	12.2.4	<i>Grading of Asphalt Cements, 267</i>
12.3	Liquid Asphalts	268
12.4	Binder-Aggregate Bonding	269
12.5	Asphalt Concrete Mixtures	270
	12.5.1	<i>Introduction, 270</i>
	12.5.2	<i>Composition and Structure, 271</i>
	12.5.3	<i>Response to Applied Loads, 272</i>
	12.5.4	<i>Response to Moisture, 275</i>
	12.5.5	<i>Response to Temperature, 276</i>
	12.5.6	<i>Response to Chemicals, 277</i>
	12.5.7	<i>Additives and Fillers, 277</i>
	12.5.8	<i>Mix Design Methods, 278</i>
Part IV:	Steel, Wood, Polymers, and Composites	281
13	STEEL	283
13.1	Introduction	283
13.2	Composition and Structure	284
	13.2.1	<i>Composition, 284</i>
	13.2.2	<i>Microstructure, 284</i>
13.3	Strengthening Mechanisms	289
	13.3.1	<i>Alloying, 289</i>
	13.3.2	<i>Work (Strain) Hardening, 290</i>
	13.3.3	<i>Heat Treatment, 291</i>
13.4	Mechanical Properties	295
	13.4.1	<i>Stress-Strain Behavior, 296</i>

	13.4.2	Fracture Energy (Toughness), 296	
	13.4.3	Weldability, 299	
13.5		Corrosion and Corrosion Protection	300
	13.5.1	Corrosion Mechanism, 300	
	13.5.2	Forms of Corrosion, 301	
	13.5.3	Corrosion Control, 302	
13.6		Classification and Properties of Structural Steels	303
14		WOOD AND TIMBER	309
14.1		Introduction	309
14.2		The Structure of Wood	310
	14.2.1	Macrostructure of Wood, 311	
	14.2.2	Microstructure of Wood, 312	
	14.2.3	Molecular Structure of Wood, 314	
	14.2.4	Cell Wall Structure in Wood, 317	
14.3		The Engineering Properties of Wood	318
	14.3.1	Orthotropic Nature of Wood, 318	
	14.3.2	Effects of Relative Density, 318	
	14.3.3	Effects of Moisture Content, 319	
	14.3.4	Mechanical Properties of Wood, 322	
14.4		Defects and Other Nonuniformities in Wood	328
14.5		Effects of Flaws on Mechanical Properties of Timber	329
14.6		Grading	332
	14.6.1	Visual Grading, 332	
	14.6.2	Mechanical Grading, 332	
	14.6.3	Description of Visual Stress Grades, 332	
14.7		Design Properties	334
14.8		Wood-based Composites	337
	14.8.1	Plywood, 337	
	14.8.2	Glued-laminated Timber, 339	
	14.8.3	Manufactured Wood Products, 339	
14.9		Durability	341
	14.9.1	Fire, 341	
	14.9.2	Decay, 342	
	14.9.3	Termites, 343	
	14.9.4	Marine Borers, 344	
	14.9.5	Preservative Treatments, 344	
15		POLYMERS AND PLASTICS	346
15.1		Introduction	346
15.2		Classification and Properties	346
15.3		Additives and Fillers	353
15.4		Properties for Civil Engineering Applications	353
	15.4.1	Mechanical Performance, 354	
	15.4.2	Thermal and Fire Performance, 354	
	15.4.3	Weathering and Durability, 355	
	15.4.4	Adhesion, 356	

16	FIBER-REINFORCED COMPOSITES	359
16.1	Introduction	359
16.2	Mechanics of Fiber-reinforced Composites	363
	16.2.1 Overall Mechanical Behavior,	363
	16.2.2 Bonding,	367
	16.2.3 Influence of Bonding on Composite Behavior,	369
	16.2.4 Effect of Fiber Orientation,	369
16.3	Fibers and Matrices	371
	SOLUTIONS TO NUMERICAL PROBLEMS	374
	INDEX	377