

**The Science and Technology  
of Civil Engineering Materials**

# 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  
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

**Library of Congress Cataloging-in-Publication Data**

Young, J. Francis.  
The science and technology of civil engineering materials /  
J. Francis Young . . . [et al.].  
p. cm. --(Prentice Hall international series in civil engineering  
--and engineering mechanics)  
Includes bibliographical references and index.  
ISBN: 0-13-659749-1  
I. Materials I. Young, J. Francis. II Series.  
TA403.S419 1998  
624.1'8--DC21

97-31972  
CIP

Acquisitions editor: William Stenquist  
Editor-in-chief: Marcia Horton  
Production editor: Irwin Zucker  
Managing editor: Bayani Mendoza de Leon  
Director of production and manufacturing: David W. Riccardi  
Copy editor: Sharyn Vitrano  
Cover director: Jayne Conte  
Manufacturing buyer: Julia Meehan  
Editorial assistant: Margaret Weist



©1998 by Prentice-Hall, Inc.  
Simon & Schuster/A Viacom Company  
Upper Saddle River, New Jersey 07458

All rights reserved. No part of this book may be  
reproduced, in any form or by any means,  
without permission in writing from the publisher.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

**ISBN 0-13-659749-1**

Prentice-Hall International (UK) Limited, London  
Prentice-Hall of Australia Pty. Limited, Sydney  
Prentice-Hall Canada Inc., Toronto  
Prentice-Hall Hispanoamericana, S.A., Mexico  
Prentice-Hall of India Private Limited, New Delhi  
Prentice-Hall of Japan, Inc., Tokyo  
Simon & Schuster Asia Pte. Ltd., Singapore  
Editora Prentice-Hall do Brasil, Ltda., Rio de Janeiro

# Preface

The modern civil engineer needs to deal with a variety of materials that are often integrated in the same structure, such as steel and concrete, or are used separately for construction projects, such as pavements from asphalt and portland cement concretes. Many of these construction materials have been with us for centuries, like timber, while others, like portland cement concrete and steel, are relatively new and have been used mainly during the last century. The civil engineering field is also making headway in the use of even more modern materials, such as polymers and composites. The modern principles of materials science have been applied extensively over the past three decades to construction materials, and the benefits of this approach can be seen clearly on site: The traditional construction materials used at present are far superior to those of the past (achieving, for example, concrete strength levels greater by an order of magnitude), and there is increased use of synthetic and composite materials that are specially formulated for civil engineering applications.

As a result of these changes and the expected dynamic developments in this field, there is a clear trend in the industry to move from the empirical-technological approach of the past to one which incorporates both the technology and materials science concepts. In view of this modern trend, there is a need for a revision in the materials education of the civil engineer. Traditionally, materials science and construction materials have been taught almost as separate entities. Materials science teaching was based mainly on texts developed for courses for engineering areas in which metals are of the greatest interest, with some reference to other materials, such as polymers and ceramics. Construction materials were taught thereafter independently, giving greater attention to their technology and much less to their science. As a result, civil engineers were limited in their overall view of construction materials and were lacking some of the concepts of materials science, such as surface properties, which are of prime importance in construction materials but receive hardly any attention in the traditional materials science texts.

This book offers a new approach, in which the science and technology are integrated. It is divided into four parts; the first two provide the general concepts of materials, referring to their fundamental structure and mechanical properties (Part I is titled "The Fundamentals of Materials," and Part II is "Behavior of Materials under Stress"). The other two parts of the book deal with specific construction materials (the titles are as follows: Part III, "Particulate Composites: Portland Cement and Asphalt Concretes"; Part IV, "Steel, Wood, Polymers, and Composites"). The parts of this book dealing with general materials science concepts are presented in an approach which is directed toward civil engineering needs and emphasizes surface properties and amorphous structures. The parts of this book dealing with the actual construction materials are written with the view of combining the materials science and engineering approaches with an emphasis on materials characteristics of particular interest for civil engineering applications.

This book is designed primarily for use at the undergraduate level, but it can also serve as a guide for the professional engineer. Thus it includes reference to

standards and specifications. It is intended to serve as a basis for a two-semester course. However, it is designed to be flexible enough to be adjusted for shorter courses. Such a course could be based on all of Part I, three of the chapters in Part II (Chapter 5, "Response of Materials to Stress," Chapter 6, "Failure and Fracture," and Chapter 7, "Rheology of Fluids and Solids"), and selected chapters dealing with specific construction materials, in view of the intended scope of the shortened course.

# 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
<b>4</b>	<b>SURFACE PROPERTIES</b>	<b>66</b>
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
 <b>Part II: Behavior of Materials Under Stress 83</b>		
<b>5</b>	<b>RESPONSE OF MATERIALS TO STRESS</b>	<b>85</b>
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>
<b>6</b>	<b>FAILURE AND FRACTURE 115</b>
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>
<b>7</b>	<b>RHEOLOGY OF FLUIDS AND SOLIDS 138</b>
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>
<b>8</b>	<b>FATIGUE 152</b>
8.1	Introduction 152



8.2	The Nature of Fatigue Failure	153
8.2.1	<i>Crack Initiation</i>	153
8.2.2	<i>Crack Propagation</i>	154
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</i>	164
8.7.2	<i>Material Properties</i>	169
8.7.3	<i>Environmental Conditions</i>	169
8.8	Experimental Methods in Fatigue	170
8.8.1	<i>Fatigue Machines</i>	172
8.8.2	<i>Fatigue Test Procedures</i>	173
<b>Part III: Particulate Composites: Portland Cement and Asphalt Concretes</b>		<b>177</b>
<b>9</b>	<b>PARTICULATE COMPOSITES</b>	<b>179</b>
9.1	Introduction	179
9.2	Concepts of the Mechanics of Particulate Composites	181
9.2.1	<i>Elastic Behavior</i>	181
9.2.2	<i>Failure in Particulate Composites</i>	183
9.3	Composition and Structure	186
9.4	Interfacial Properties	186
9.5	Mechanical Behavior	187
<b>10</b>	<b>AGGREGATES</b>	<b>189</b>
10.1	Introduction	189
10.2	Composition and Structure	190
10.3	Characteristics	192
10.3.1	<i>Geometrical Properties</i>	192
10.3.2	<i>Physical Properties</i>	196
10.3.3	<i>Strength and Toughness</i>	199
10.3.4	<i>Other Properties</i>	199
<b>11</b>	<b>PORTLAND CEMENT CONCRETE</b>	<b>204</b>
11.1	Introduction	204
11.2	The Cementitious Phase	205
11.2.1	<i>Composition and Hydration of Portland Cement</i>	206
11.2.2	<i>Microstructure and Properties of Hydration Products</i>	210
11.2.3	<i>Portland Cements of Different Compositions</i>	214
11.2.4	<i>Blended Cements and Mineral Admixtures</i>	215
11.2.5	<i>Porosity and Pore Structure</i>	218

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

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

<b>16</b>	<b>FIBER-REINFORCED COMPOSITES</b>	<b>359</b>
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
	<b>SOLUTIONS TO NUMERICAL PROBLEMS</b>	<b>374</b>
	<b>INDEX</b>	<b>377</b>

\_\_\_\_\_ Part I \_\_\_\_\_

**THE FUNDAMENTALS  
OF MATERIALS**



# 1

---

## Atomic Bonding

### 1.1 INTRODUCTION

---

Introductory courses in chemistry have discussed atomic structure and the way in which chemical bonds serve to ensure that atoms achieve stable electron configurations by adding, removing, or sharing electrons. In this chapter we will simply review the characteristics of the various types of bonds that can form in materials. These are summarized in Table 1.1 and Fig. 1.1 and can be divided into two major categories: the strong (primary) bonds between atoms (ionic, covalent, and metallic) and the weak (secondary) van der Waals bonds between molecules. The position of an element in the periodic table determines the type of chemical bonds it can form.

### 1.2 IONIC BONDS

---

Elements in Groups I and II readily lose electrons to form cations (i.e., they are strongly electropositive), while at the other end of the periodic table, elements in Groups VI and VII readily gain electrons (they are strongly electronegative). Thus, when these elements are brought together there will be an exchange of electrons to form ionic compounds containing  $M^+$  and  $X^-$ , where  $M$  is a Group I element and  $X$  is a Group VII element; or  $M^{2+}$  and  $X^{2-}$ , where  $M$  is a Group II element and  $X$  is a Group VI element.

The interaction energy between a pair of ions is proportional to  $(z^+z^-e^2)/r$ , where  $z$  is the ionic charge and  $r$  is the distance between ions. However, we seldom find discrete ion pairs; rather ions of a given charge try to be surrounded by as many ions of the opposite charge as possible (Fig. 1.1b). In the crystalline state

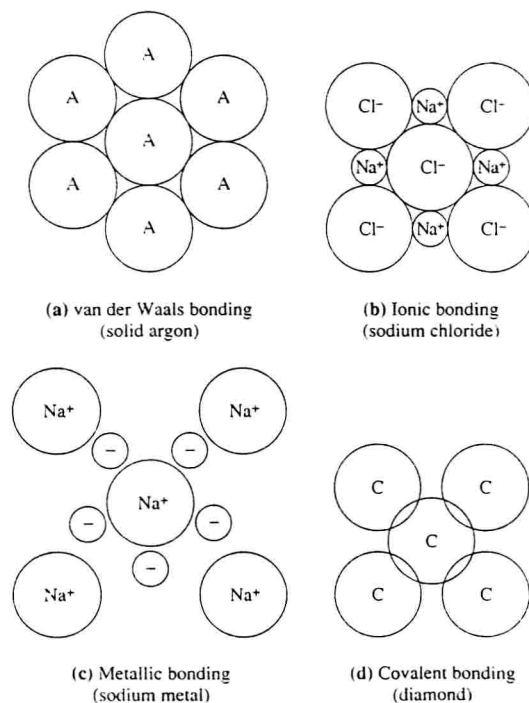
TABLE 1.1 Summary of bond types.

Bond Type	Bond Energies (kJ · mol <sup>-1</sup> )	Typical Materials	Typical Elements	Remarks
Ionic	500–1200 <sup>a</sup>	Ceramic Oxides Gypsum Rock salt Calcite	Compounds of Gp I, Gp II	All exist as crystalline solids.
Covalent	150–750 <sup>a, b</sup>	Diamond Glasses Silicon carbide	Gp IV, Gp V, Gp VI	States of matter at room temperature depend on intermolecular attraction.
Metallic	50–850 <sup>a</sup>	Metals	Elements of Gp I– III. Transition metals. Heavy elements of Gp IV and V.	May be liquid or solid depending on binding energies.
Hydrogen	10–30 <sup>c</sup>	Water	F, O, N	Can be considered weak ionic or strong van der Waals. Strongly influences material behavior.
van der Waals	0.05–5	Thermoplastic polymers	Compounds of all elements	Primarily intermolecular bonds. Dominate the beha- vior and microstructure of construction material, such as concrete and asphalt.

<sup>a</sup> Lattice energies of crystal.<sup>b</sup> Isolated multiple covalent bonds (as formed in N<sub>2</sub>, for example) can be as strong as 950 kJ · mol<sup>-1</sup>.<sup>c</sup> Single hydrogen bond is about 2 kJ · mol<sup>-1</sup>.

Figure 1.1

The principal types of crystalline binding. In (a) neutral atoms with closed electron shells are bound together weakly by the van der Waals forces associated with fluctuations in the charge distributions. In (b) electrons are transferred from the alkali atoms to the halogen atoms, and the resulting ions are held together by attractive electrostatic forces between the positive and negative ions. In (c) the valence electrons are taken away from each alkali atom to form a community electron sea in which the positive ions are dispersed. In (d) the neutral atoms appear to be bound together by the overlapping parts of their electron distributions.





(see Chapter 2), they take up specific arrangements to maximize the interactions between ions of opposite charge; but in the gaseous or liquid state these ions are free to move about. Hence, ionic solids will not conduct electricity unless they are either in the molten state or dissolved in water, where the ions are free to move under electric gradients.

### 1.3 COVALENT BONDS

---

For most elements, the need to lose or gain electrons will not be sufficient to form ions (or the ions will be unstable), and valency requirements are satisfied by sharing electrons. The simplest situation is the sharing of one pair of electrons between two elements, as in hydrogen ( $H_2$ ) or methane ( $CH_4$ ), where there are four covalent C—H bonds. Two atomic orbitals, which each contain one electron, overlap and combine to form a single molecular orbital lying between the two atomic nuclei (Fig. 1.1d). When more than one covalent bond is formed by an element, the atomic orbitals may combine to adopt certain directional arrangements to increase their degree of overlap with other atomic orbitals and hence the strength of the covalent bond. This process is called hybridization. More than one atomic orbital from each atom may be involved, leading to multiple bonds between atoms.

Another complication is that electrons are seldom shared equally between two dissimilar atoms, but usually the electrons spend more time near the more electronegative atom (i.e., the atom with a greater tendency to attract electrons). There is thus a statistical separation of charge so that the bond has a permanent *dipole*. Such a bond is said to have partial ionic character, since an ionic bond implies complete separation of charge. Conversely, an ionic bond can be said to have some covalent character; in this case, the atomic orbitals of the ions are distorted, leading to a distortion of the ideal packing of ions in the crystal toward more directional arrangements that favor this distortion.

Covalent bonds thus lead to the formation of a specific grouping of atoms (molecules) in which all the atoms achieve stable electron configurations. Only a few materials are bound together principally by covalent forces acting between atoms in all directions; natural diamond and synthetic silicon carbide are common examples. Most covalent materials are composed of covalently bonded molecules; whereas the bonds between the atoms within the molecules are strong, the bonds between atoms in adjacent molecules are generally much weaker and involve van der Waals forces (see discussion in Sec. 1.5). Covalent molecules may range from simple molecules, like  $H_2$ , to the very complex macromolecules, such as organic polymers, which may contain many thousands or millions of atoms in a single molecule.

### 1.4 METALLIC BONDS

---

Atoms of electronegative elements (e.g., chlorine, oxygen, or sulfur) can satisfy their electron needs through covalent bonding. But this possibility is not open to the electropositive elements since these elements wish to lose electrons while covalent bonding effectively adds electrons to an atom. This problem is solved by the metallic bond: All atoms give up electrons to a “common pool,” becoming positive ions with a stable electron configuration. The free electrons occupy extended delocalized orbitals lying between the positive metal ions (Fig. 1.1c) so that the electrons are independent of any particular ion. These electron “clouds” bind the ions together but