

Civil Engineering Materials

Edited by N JACKSON

Third Edition

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Preface

The importance of an understanding of the materials used in civil engineering is widely recognised, but only in comparatively recent years has much emphasis been placed on the teaching of material properties at undergraduate level. This introductory textbook on materials satisfies a need for a single book covering the principle materials used in civil engineering.

The aim has been to provide the student with an authoritative text which will also serve as a valuable source of reference in his/her subsequent career. In this third edition additional sections on polymer materials and on bricks and blocks have been included, and the sections on metals, timber, concrete, bituminous materials and soils have been revised to give a more comprehensive and up-to-date coverage of civil engineering materials. Soils are included in recognition of their importance as constructional materials, the fundamental properties of soils being covered in greater depth than usual. Extensive references to all relevant British Standards are made throughout the book.

The treatment of material properties here is suitable for students studying for a degree or equivalent qualification in civil engineering, building science, architecture and other related disciplines. The particular point in a course at which the study of civil engineering materials is introduced will depend on the course structure of the individual educational institution but would generally be during the first two years of a three or four-year course. Similarly the extent of further formal study of civil engineering materials depends on the emphasis and structure of the course within a particular educational institution. However, it is not envisaged that further study of the basic material properties of metals, timber, concrete, polymer materials and bricks and blocks will be required, although the application of these materials within the general context of analysis and design might well continue throughout the remainder of a course. Further study of soils might normally be expected to continue, for civil engineering students, within the context of soil mechanics and further study of bituminous materials only where highway materials are studied in later years.

Throughout the book, the underlying theme is an emphasis on the factors affecting engineering decisions. It is hoped that this will promote an awareness in the reader of the importance of material behaviour in both design and construction, in order to ensure that the final product, whether structural, functional or purely decorative, will adequately fulfil the purpose for which it is provided.

N. Jackson

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I METALS

Introduction

The applications of metals in civil engineering are many and varied, ranging from their use as main structural materials to their use for fastenings and bearing materials. As main structural materials cast iron and wrought iron have been superseded by rolled-steel sections and limited use has been made of wrought aluminium alloys. Steel is also of major importance for its use in reinforced and prestressed concrete. On a smaller scale, metals are extensively used for fastenings, such as nails and screws, for bearing surfaces in the expansion joints of bridges and for decorative facings.

The properties of metals which make them unique among constructional materials are high tensile strength, the ability to be formed into plate, sections and wire, and the weldability or ease of welding of those metals commonly used for constructional purposes. Other properties typical of metals are electrical conductivity, high thermal conductivity and metallic lustre, which are of importance in some circumstances. Perhaps the greatest disadvantage of the common metals, and particularly steels, is the need to protect them from corrosion by moist conditions and the atmosphere, although weathering steels have been developed which require no protection from atmospheric corrosion.

When in service, metals frequently have to resist not only high tensile or compressive forces and corrosion, but also conditions of shock loading, low temperatures, constantly varying forces or a combination of several of these effects. Pure metals are relatively soft and weak, and do not meet these rigorous demands except for applications where the properties of high electrical conductivity or corrosion resistance are required. Normally one or more alloying elements are added to increase strength or to modify the properties in some other way. Metals and alloys are crystalline in character and in order to appreciate their properties and behaviour in service it is necessary to study their structure on an atomic scale, the types of crystal formed, the microstructure (the structure as observed under the microscope), the coarser macrostructure, and the ways in which these may be affected by heat treatment, stress, deformation and the environment.

1

Structure of Metals

1.1 Interatomic Bonding

The atoms of the chemical elements each consist of a positively charged nucleus surrounded by a number of negatively charged electrons. The number of electrons in the neutral atom is characteristic of the element; for example hydrogen has one electron, carbon six and iron twenty-six (see figure 1.1). The electrons move in well-defined orbitals and as a result are distributed in concentric layers about the nucleus. The electrons occupying the inner orbitals (the core electrons) are com-

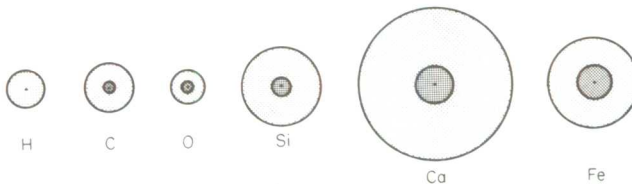


Figure 1.1 *Relative sizes of core and valence electron orbitals in the atoms of some important elements*

pactly and tightly bound to the nucleus, and only the outermost electrons (the valence electrons) take part in the interatomic chemical bonding. In assemblies of atoms, chemical bonding to form solid materials occurs whenever the valence electrons of the individual atoms can redistribute themselves to form more stable arrangements. This happens in different ways in different classes of materials. The energy associated with the rearrangement of electrons is the binding energy of the solid, responsible for its cohesion.

In combinations of nonmetallic elements (such as oxygen, hydrogen, carbon and silicon), the chemical bond is formed by the sharing of valence electron pairs between atoms in localised and directed covalencies. Electrons are transferred from individual orbitals to molecular orbitals embracing two atoms. This *covalent bond* between dissimilar atoms invariably involves unequal sharing of the bonding electrons, giving the bond some electrical polarity. Depending on the bonding capacity or valency of the elements involved, covalent bonding may give

rise to small molecules each containing only a few atoms (for example carbon dioxide, methane or water - figure 1.2*a*), or to chains, sheets or lattice structures (as in synthetic polymers, figure 1.2*c*, and natural organic materials like wood, materials which are discussed in sections VI and II respectively). Substances composed of small independent molecules have no chemical bonds *between* the individual molecules, but much weaker secondary forces arise between them owing to the electrical bond polarity mentioned above. Such substances are gases, liquids or mechanically weak solids, depending on temperature. On the other hand, materials with extended networks of covalent bonds (for example quartz and diamond) are hard, strong solids with high binding energies. The mechanical characteristics of many synthetic polymers (see section VI) are of an intermediate type.

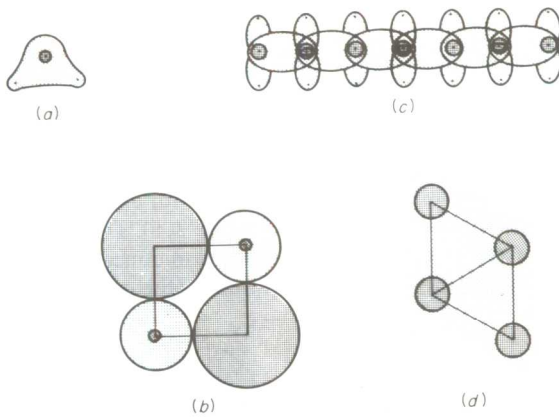


Figure 1.2 Types of atomic bonding in engineering materials. (a) Covalent O-H bonds in the water molecule H_2O . (b) The ionic bond in calcium oxide CaO . (c) Covalent bonds in the carbon chain $-CH_2-$ of polyethylene. (d) The metallic bond in iron

In ionic compounds (metallic salts, metal oxides and many other minerals) formed between metals and nonmetals, valence electrons are transferred from each of the atoms of the metallic element to neighbouring atoms (or groups of atoms) of the nonmetal. In the process the atoms become electrically charged or ionised, forming positively charged metal ions and negatively charged non-metal ions. These ions attract each other electrostatically and can assemble to form stable crystalline solids. Calcium oxide (lime) is an industrially important example of a simple ionic compound, figure 1.2*b*, in which Ca^{2+} and O^{2-} ions are formed by the transfer of two valence electrons from each calcium atom to oxygen. The *ionic bond* permits close packing of positive and negative ions (controlled by the relative ion sizes) to form crystalline materials in which bonding is continuous throughout the crystal. Ionic solids have high binding energies, particularly if small ions with multiple charges are present (for example as in aluminium oxide). Any displacement of the ions relative to each other would bring like-charged ions together. The force necessary for this displacement is normally equal to the breaking strength of the bond between the ions; hence fracture occurs without plastic deformation and ionic solids are hard and brittle.

Ionic and covalent bonding are often found together in the same material, as in the silicate and aluminosilicate minerals. For instance the Portland cement mineral dicalcium silicate (see chapter 12) contains calcium ions and silicate ions; however within each silicate ion the Si and O atoms are bound together by covalencies.

In metals the *metallic bond* predominates, although other types of bonds may occur in some compounds between metals or there may be mixed bonding in which more than one type of bond occurs. With metallic bonding the valence electrons become detached from the individual parent atoms (see figure 1.2*d*) and move freely within the solid as a delocalised electron 'gas'. These mobile electrons are responsible for the high electrical and thermal conductivity of metals. The bond between the metal atoms is nondirectional, hence it does not interfere with the packing together of the atoms to form structures of high packing density and, once certain stress levels have been exceeded, it permits the relative movement of atoms without rupture occurring. The strength, ductility and toughness of metals are due to the properties of the metallic bond and are discussed more fully in chapter 2.

1.2 Crystalline Structure of Metals

Solid metals consist of an aggregate of crystals or grains in which the atoms are arranged in a regular three-dimensional geometrical pattern called a space lattice. These are usually described by reference to a unit cell which, if repeated a large number of times in any direction, will generate the space lattice. Although the concept of the unit cell is necessary to describe the different types of space lattice it is often more convenient to consider the crystal as built up from successive planes of atoms. In metallic crystals a high density of packing occurs in the planes of atoms and in the stacking of these planes to form the crystal, although ideal close packing is not always achieved.

Figure 1.3*a* shows the ideal close-packed arrangement of spheres or atoms in a plane with the atoms lying on three sets of close-packed lines which are identical to each other. When planes of this type are stacked on top of each other in an ABCABCABC, etc., arrangement, as shown in figure 1.3*b*, a close-packed lattice results which may be described as a face-centred cubic lattice. In this lattice the unit cell shown in figure 1.3*c* has atoms at each corner of the cube and in the centre of each face. The close-packed planes from which it is built cut the diagonals of any three adjacent faces and this gives four sets of close-packed planes. One plane of this type is indicated as the plane XYZ in figure 1.3*c*. In this structure each atom has twelve equidistant close neighbours.

An alternative method of stacking close-packed planes places the third layer of atoms immediately above the first layer to give an ABABAB, etc., arrangement. This is shown in figure 1.4*a* and gives rise to the hexagonal close-packed structure shown in figure 1.4*b*. In this structure the hexagonal structure cell has atoms at each corner and the centre of the top and bottom faces, also three atoms within the unit cell. Although this structure is close-packed and each atom has twelve equidistant close neighbours, there is only one set of close-packed planes. In theory the ratio of the height to the side of the base should be 1.633 for the ideal hexagonal close-packed structure, but in practice some slight variation from this ratio is observed.