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1 Introduction

This chapter provides an overview of mankind's use of materials, comparing the use of materials in various industrial sectors, and making clear the point that construction is the world's largest consumer of materials. It goes on to examine the importance of material properties in their selection for use, and outlines the various types and classes of materials and their importance in construction. A discussion of the service behaviour of materials and the problems of degradation and failure follows. Finally, in view of the current importance of sustainability, their environmental impact is stressed, and an outline of the book's contents brings the chapter to a close.

Contents

1.1 The industrial use of materials

The science and use of materials is central to all branches of industry, and as such is a subject of enormous importance. The range of materials we have at our disposal is enormous, and is being added to as the results of research and development are put to use week by week and month by month. The industries using materials include construction, aerospace, automobile, shipbuilding, white goods, electronics, railways, etc. Each industry has its own particular concerns about materials; in the aircraft business, the over-riding concern is with lightness and weight-saving, with cost being secondary to this. This is well illustrated at the present time with the advent of the Boeing 787 Dreamliner, which is pioneering the use of fibre-reinforced composite materials instead of the usual aluminium alloys for the construction of the airframe. Although aluminium is already a light metal, its use is being abandoned in favour of fibre-reinforced polymeric materials which are lighter still.

In the automobile industry, the luxury car sector currently is turning to the use of aluminium alloys for body structures in place of the traditional steel, and again the driver for this is weight-saving, with the consequent saving in running (fuel) costs. This may well be the precursor for the wider, progressive replacement of steel with light metals or reinforced polymers. In the construction industry, the *leitmotif* is most often low cost, i.e. weight-saving is not usually an issue, whereas keeping costs down to a minimum is very important. Having said this, in the construction of very tall buildings, engineers do take steps to save weight, usually in the construction of the upper floors of skyscrapers, in an effort to reduce the enormous loads that need to be borne by their foundations. Steel and concrete are such popular materials in construction; steel possesses high stiffness, high tensile and compressive strength and good ductility, with prices starting at around £500 per tonne, and concrete represents the cheapest way to buy one unit of compressive strength. Both are excellent value for money and this is most important in construction.

Each industry has its own preoccupations with the types of materials used. In most cases the products made will be created in a well-regulated, factory environment. In construction, on the other hand, the product is created on site in a less well-regulated environment, and this factor must be borne in mind. In most industries materials can be tested before they are used, to ascertain their quality and fitness for purpose. In construction, however, concrete falls outside this rule as it is made and used on site in one operation. If serious mistakes are made, the defective piece of concrete may have to be broken out and replaced. Concrete is the most widely used material of all, with over 12 billion tonnes being used worldwide each year, and yet it differs from all other important materials in not being able to be tested before it is used.

Construction also uses a lot of timber, a traditional construction material which has been used for centuries. We often lose sight of the fact that timber is a 'smart' material when it is growing as part of a tree. In a growing tree, timber can sense where compressive stresses are increasing due to weight increase brought about by the growth of new timber, and is able to respond by increasing the size of branches that are bearing the increased weight. So far engineers have not been able to produce such a remarkable material.

Finally, we must remember that whatever the industry using and specifying materials, what they are really doing is *specifying desirable properties*. We shall return to this fact later. It has been estimated that we currently have between 40,000 and 80,000 different materials (Ashby, 1992) at our disposal, if we count separately all the different alloy steels, all the different polymers, species of timber, types of glass, types of composites, etc. Making the correct selection can be a complex matter. Furthermore, for certain applications we cannot always meet our requirements from single materials among the 40,000–80,000 available. Sometimes none of these have the particular combination of properties we need; in such cases we may have to make recourse to *composite materials*; we shall look in more detail at these later in the book.

1.2 Importance of construction materials

In the UK, the construction industry is one of the largest, employing 1.0–1.5 million people (Harvey & Ashworth, 1997), and it rivals the NHS in size. It is responsible for at least 8 per cent of the UK's gross domestic product, currently being worth in excess of £60 billion per year. Roughly half of the industry's work involves new build, while the other half is maintenance, repairs and refurbishment. In addition, there is the UK building materials industry: brick-making, cement production, steel-making, as well as the industries that produce glass, plastics, gypsum plaster products, timber products, paints, fasteners, etc.

The construction industry in the UK consists of over 170,000 individual companies, the overwhelming preponderance of which are very small. Fewer than 50 firms employ more than 1,200 people.

Only 100 have more than 600 employees, so construction is often called a fragmented industry, and this is the situation in most of the countries of the world. These firms are located all over the UK; everyone has their local builders, plumbers, joiners, etc. One of the main reasons for the large number of small firms is that the barriers to entry to the industry are so low as to be virtually non-existent. By this we mean that little capital is required to begin. A skilled (or in some cases, unskilled!) bricklayer or roofer can set himself up in business very easily. The result is that every week in the construction industry in the UK, scores of firms cease trading, while new firms are started every week.

Another reason for the presence everywhere of construction firms is that unlike the products of the manufacturing industry, buildings are erected in a particular place; they cannot, in general, be built and transported. Because of this everyone needs their local builder.

Because the industry is so large, it is therefore a huge consumer of materials, both in the UK and worldwide. In fact, it is the largest consumer of materials in the UK and worldwide by a considerable margin. The total weight of materials consumed by all other industries combined is barely a quarter of that used in construction. The consequence of this is twofold: first, our use of construction materials has a major impact on our environment; and second, it is of the utmost importance that these materials are used correctly and as efficiently as possible.

Construction uses a wider range of materials than any other. Materials used include cement and aggregates to make concrete, metals – primarily steel, but with significant amounts of copper, copper alloys and aluminium alloys – timber, fired clay products, glass, gypsum products, polymers, bituminous materials, etc. The global consumption of the principal materials is shown in Table 1.1.

The table shows the proportion of these materials going to construction. It does not include fired clay products, which are widely used in construction, because global figures for this material are difficult to obtain. Such materials are not used in significant amounts by the other industrial sectors.

For comparison, the automotive industry consumes just 15 per cent of the world's steel output, a total of just over 200,000,000 tonnes. Steel is the principal material of the car makers, and the other materials it uses are 40 per cent of the world's rubber and 25 per cent of the world's glass output. So automobile production uses a tiny fraction of the quantities used in construction, and the aerospace business uses less still. The two major constructors of large passenger aircraft, Boeing (US) and Airbus Industrie (Europe), each deliver between 300 and 500 planes per year, depending upon the economic climate. If the average weight of each plane is 250 tonnes, this gives a total material consumption of 250,000 tonnes in a good year. Globally, the annual consumption of materials in the aircraft business is therefore under 1,000,000 tonnes. However, these materials will be very high value, with aero-engine materials in particular costing up to £1,000,000 per tonne.

The shipbuilding industry is another large consumer of material; steel is the one used in the greatest amounts. The present size of the world's merchant fleet stands at 1.0 billion tonnes dead-weight, and comprises just under 43,000 vessels. For the purposes of these statistics, a merchant ship must be over

Table 1.1 World production of principal materials, and the approximate proportion going to the construction industry

Material	*Annual world production (tonnes)*	*% of world production used in construction*
Cement	2,400,000,000	95–100
Aggregates	12,000,000,000	95–100
Steel	1,450,000,000	Up to 50
Timber	1,000,000,000	*c.*60
Polymers	150,000,000	*c.*20–25
Total	17,000,000,000	

Table 1.2 Approximate global annual consumption of materials by construction, shipbuilding, automobile and aircraft production

Industry	*Annual consumption of materials (tonnes)*
Construction	At least 10,000,000,000
Shipbuilding	At least 500,000,000
Automobiles	Around 400,000,000
Aircraft	Under 1,000,000

70 m long (about 230 feet). This tonnage is being added to at the rate of nearly 100,000,000 tonnes per year, with China now being the largest constructor. These figures do not include naval construction, or the construction of smaller vessels of less than 70 m length. The consumption of steel in shipbuilding may therefore be taken as between 150,000,000 and 200,000,000 tonnes per annum. Table 1.2 compares the approximate amounts of material consumed annually by construction, shipbuilding, automobile manufacture and aircraft production.

Of course, steel is also used in agriculture, white goods manufacture, machine tools, etc. But Table 1.2 shows the predominance of construction in material consumption.

Finally, all industries have used more and more materials as the years go by, i.e. the production and consumption graphs are all climbing with time. However, in the developed world, more materials are going into buildings as a proportion of the total than ever before (see Figure 1.1). Figure 1.1 gives data for the United States, but the pattern is the same all over the developed world.

The graphs shown in Figure 1.1 are very interesting. We can see that consumption of all classes of materials increased during the 100 years from 1900 to 2000. The peaks caused by the World Wars, and the

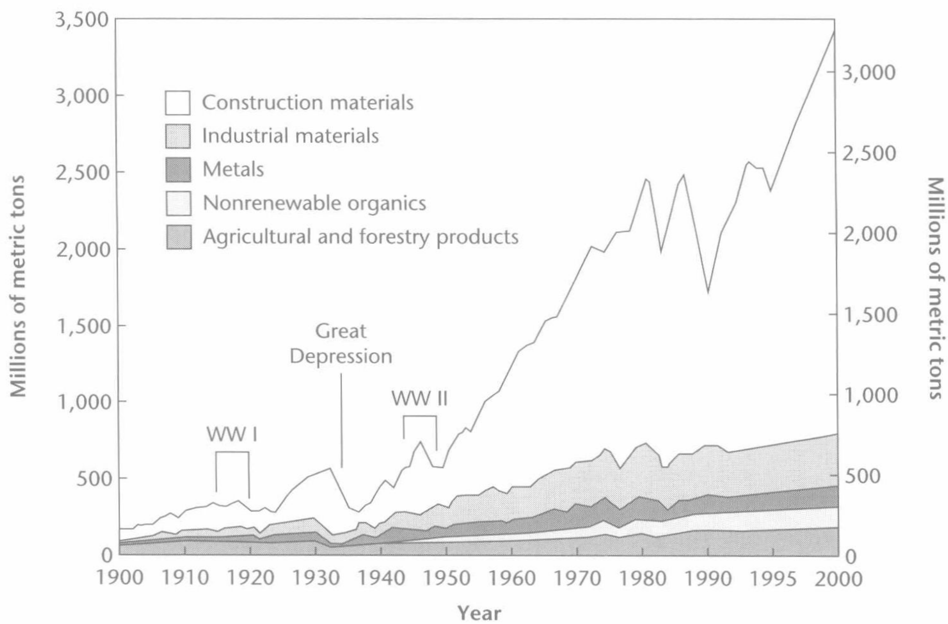

Figure 1.1 Consumption trends of various materials by the United States for the twentieth century

(*Source:* United States Geological Survey) troughs occasioned by the Great Depression of the early 1930s, and the mid 1970s and 1980 oil crises are clearly visible. However, two features are noteworthy: (1) the increase in consumption of materials for construction far outstrips all other classes of materials, and (2) economic recessions have a disproportionately large effect on the construction industry. The data are for the United States, but the same trends are widely observed across the rest of the world. In short, this graph illustrates the pre-eminent importance of construction and its consumption of materials, and this theme will be returned to in the final chapter of this book.

1.2.1 Brief history of building materials

The finding and provision of shelter is one of the most basic human needs. When *homo sapiens* first appeared on Earth, they existed as hunter-gatherers, and would find shelter in caves and other convenient natural features. Around 8000 BC, however, mankind began to make the transition from hunter-gatherer to farmer, and men ceased to be nomadic and settled on their farmland. The need to build permanent settlements on their land became a major concern, and this step initiated the development of man as a building constructor. At this time, the population of the Earth would be perhaps 20,000,000 people in all. Once the human population density reached more than two people per square mile, the hunter-gatherer lifestyle was no longer sustainable, and more intensive methods for providing food became imperative.

In building his shelter man would utilise the materials that came to hand locally, such as timber, stone, animal skins and bone, etc. The mastery and use of fire led to the discoveries of ceramics, including fired clay, glass and also the smelting of metals. As millennium followed millennium, men discovered how to utilise a gradually increasing array of materials. So important were the materials used by men that the ages of mankind's development were named after the materials used, i.e. Stone Age, Bronze Age, Iron Age, and so on.

The Industrial Revolution, beginning at the start of the eighteenth century, initiated an acceleration in the pace of discovery and technological development, so that by the end of the nineteenth century, man had perhaps 100 or so materials at his disposal to meet all of his needs. The twentieth century saw the acceleration become an explosion in the number of available materials; Ashby (1992) has suggested that we now have between 40,000 and 80,000 different materials from which to choose.

The balance between types of materials has changed dramatically over time. In early historical times (10000 BC onwards) ceramics and glasses were important, together with the use of natural polymers and elastomers, and early composites such as straw-reinforced bricks and paper. The use of metals was known, but only a few metals had been identified – gold and copper being two of the earliest. By the middle of the twentieth century, metals had become the single most important class of materials. Since that time discoveries in the fields of polymer and ceramics have redressed that balance, and developments of engineering composites have also had a major impact. Figure 1.2 illustrates the balance between the various material types over time. It is important to recognise that the figure shows relative importance of the various material types and not absolute amounts. For example, at the start of the twentieth century, the total annual consumption of materials was well under one billion tonnes, whereas now it runs at over 16–17 billion tonnes.

However, the need for shelter is just as important as it ever was; this is true for all peoples in all countries. The construction industry has grown and developed to meet this need, and as a result it is the largest industry in the UK and in the rest of the world. This industry is the largest consumer of materials by far, as well as using a much wider range of material types than any other. The manufacture and use of all this material has an enormous impact on our world, which is our natural environment. This whole area of environmental impact and sustainability is a matter of increasing concern; we shall need to say something about this, and this discussion will be found in the last chapter of this book.

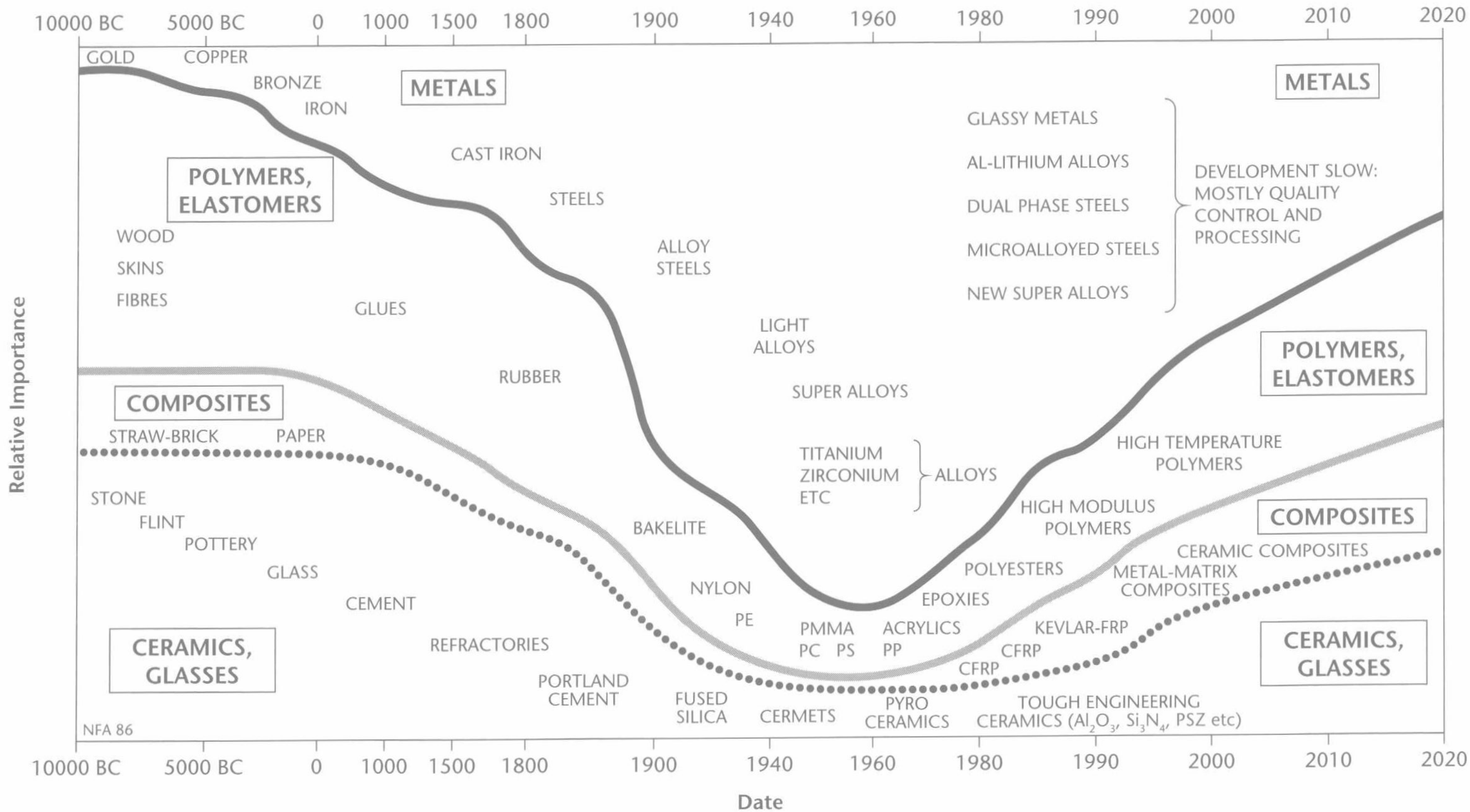

Figure 1.2 The evolution of engineering materials

(After Ashby, 1992)

1.2.2 The materials of construction

A wider range of materials are used in building construction than any other branch of industry. This range includes steel and certain other non-ferrous metals, cement, concrete, plaster, clay bricks and tiles, timber, glass, polymers, bituminous materials, natural stone, etc. For convenience, we shall classify these materials in three groupings:

1 metals, ferrous and non-ferrous
2 ceramics and other inorganic materials
3 polymers and natural organic materials.

It will be necessary to spend a little time on some of the underlying scientific principles governing the behaviour of materials. We need to appreciate the reasons why metals used in construction such as steel, lead and copper are ductile, and concrete and bricks, for example, are not.

1.3 Properties of materials

When a builder, architect or engineer specifies a material, he or she is really specifying a property or combination of properties. Materials are used for the properties that they possess, whether it be compressive strength, thermal insulation, high electrical conductivity, appearance, low cost or whatever. The properties that materials possess derive from their structures, i.e. the way that their component atoms and molecules are put together. This book does not set out to be a physics, chemistry or engineering text, but we require a little insight into the structures of materials if we are to understand how they perform in service.

It is worth bearing in mind that when we use a material, as was pointed out earlier, we are really making use of its properties. For this reason it will be a valuable exercise to look next at the process of *selecting* materials. This is not something usually covered in books on construction materials; the topic has rather been the subject of texts produced for engineers. However, materials selection will be dealt with as part of Chapter 18, under the heading of rational selection methods.

However, it will be useful to take a preliminary look at the range of properties we have at our disposal, and it is illuminating to consider properties by material classes such as ceramics, metals, polymers and composites. Such is the very wide range of property values that the values have to be plotted on a logarithmic scale. Figure 1.3 compares values of yield strength σ_y for ceramic, metallic, polymeric and composite materials. We can immediately see that ceramics have very much higher strengths than polymers, while metals have a much wider range of strengths, from alloy steels down to some very soft, pure metals.

Similar wide variations are seen for stiffness values (E), in Figure 1.4, and for density (ρ), in Figure 1.5.

Note the very wide variation in properties shown in Figure 1.3. The strength covers six orders of magnitude, i.e. the highest value (diamond) is nearly one million times stronger than the lowest (foamed polymer).

In Figure 1.4, again note the wide variation in stiffness values, with the data spanning six orders of magnitude. The stiffest material (diamond) is a million times stiffer than the least stiff material (foamed polymer).

Density values shown in Figure 1.5 span three orders of magnitude, with the densest metals (platinum and tungsten) being about 1000 times more dense than the lightest (foamed polymers).

1.4 Behaviour of materials in service

We shall consider the conditions under which materials serve in buildings, including the loadings to which they are subjected and the environmental influences which surround them. This is very important because we need to be as economical with materials, which are precious resources, as we can.

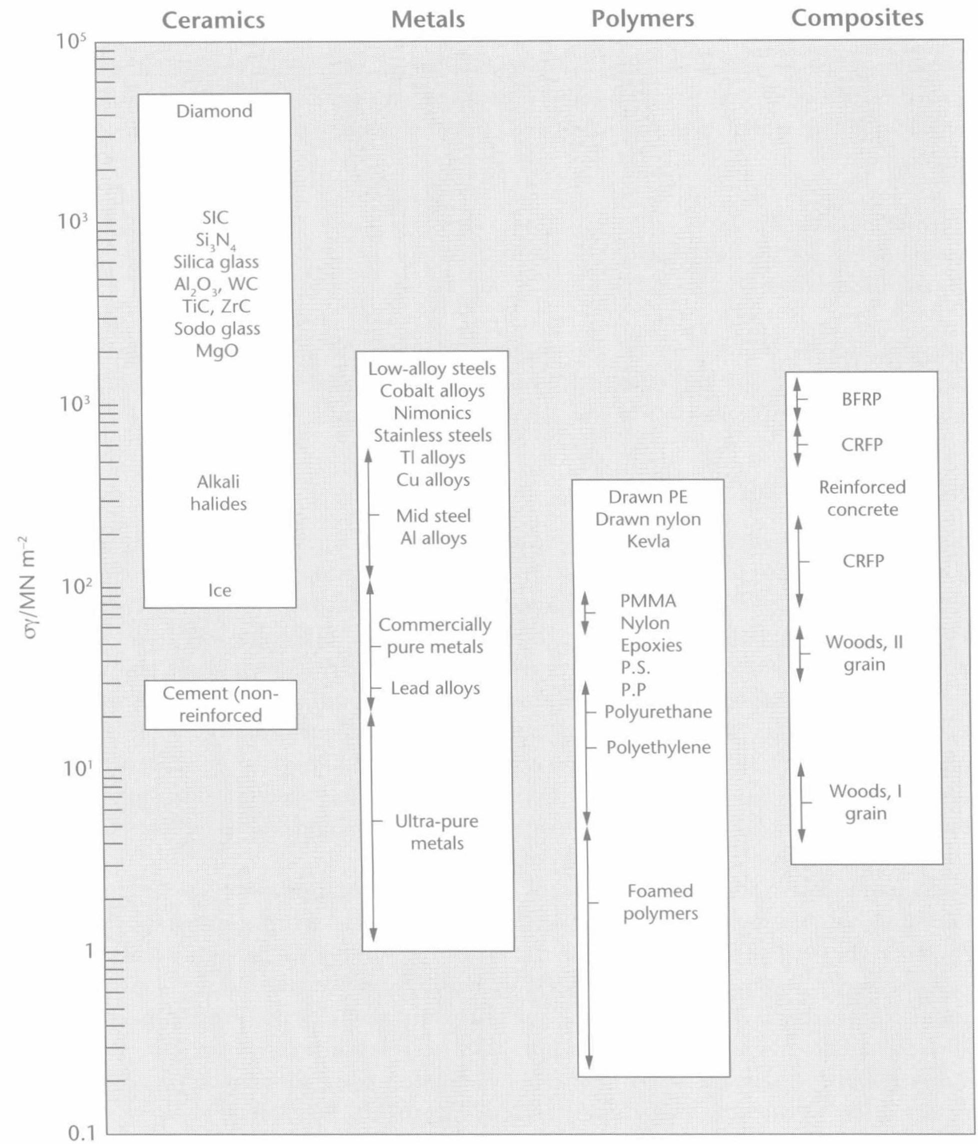

Figure 1.3 Bar chart of data for yield strength, σ_y (MN/m^2)

(After Ashby & Jones, 1980)

In service, we are nearly always concerned with the durability of our materials. Unlike motor vehicles, which have a life of perhaps a decade, buildings are usually expected to last considerably longer, and massive repair and maintenance costs are not welcome to those who are responsible for them. Durability is the term used to describe the robustness of materials in the face of the service conditions that they endure; in simple terms, how long they last.

In Victorian times, mankind had perhaps 100 or so different materials which had to meet all of our needs, and which were somewhat less than ideal for their application. Fortunately, most of those materials

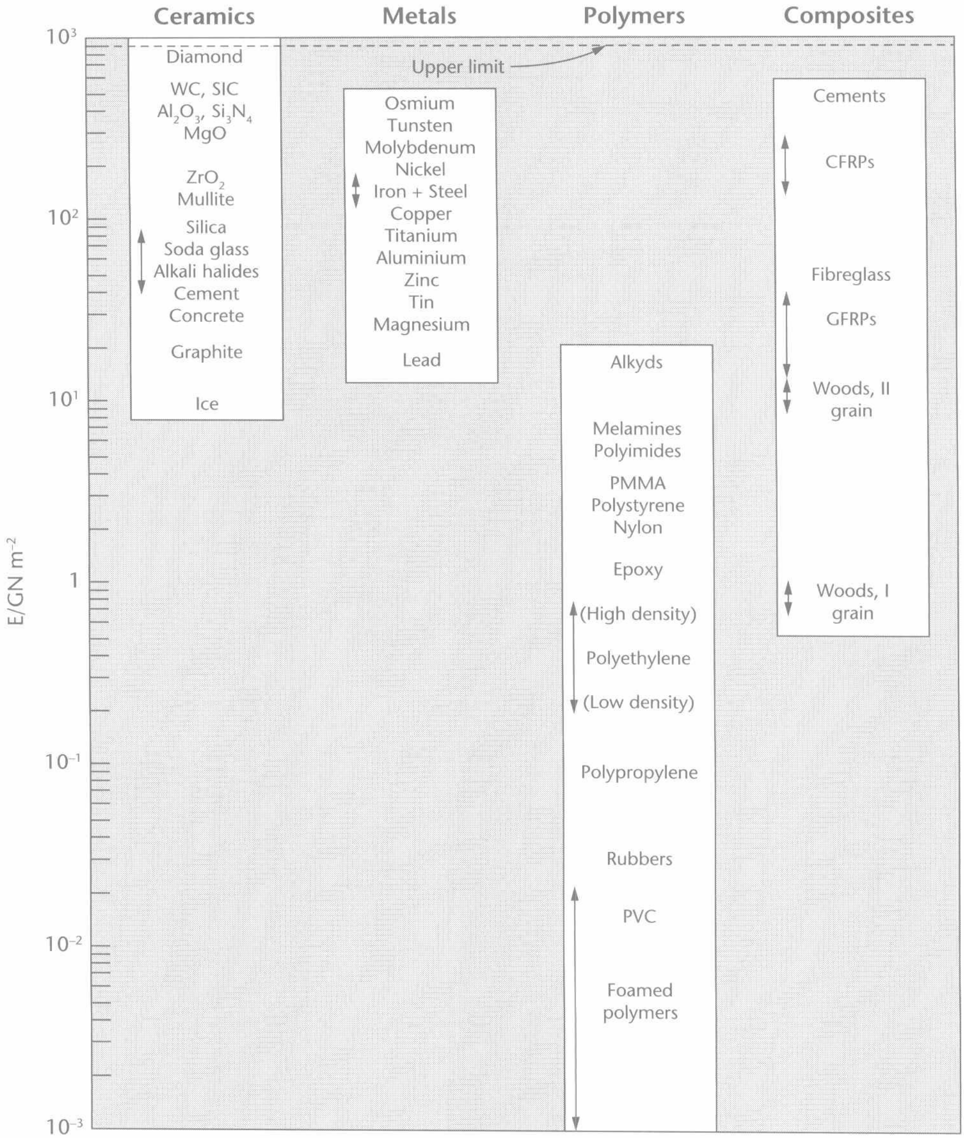

Figure 1.4 Bar chart of data for Young's modulus, E (GN/m^2)

(After Ashby & Jones, 1980)

were tolerant of abuse, and while not totally suited to their use nevertheless performed adequately. We are much more fortunate today, in the twenty-first century, in having a very much greater number of available materials, including composites, so that we can select materials having optimal properties for the particular application that we wish to fulfil.

An important part of this book will be to deal with how the various materials perform in service, together with the ways in which they can fail. We need to appreciate the environmental conditions in which the materials serve, as well as the types of events they may encounter or endure during their service lives.

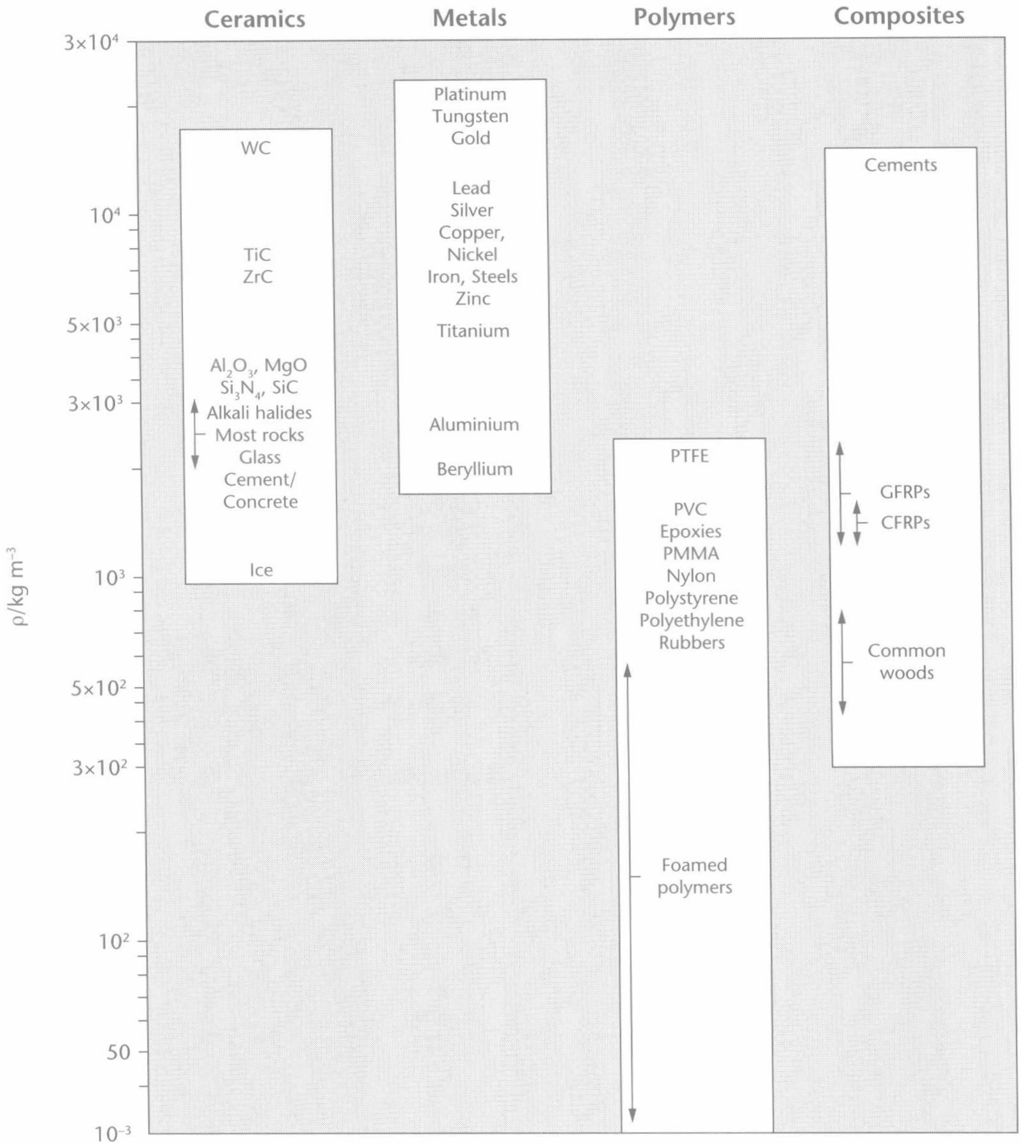

Figure 1.5 Bar chart of data for density, ρ (kg/m^3)

(After Ashby & Jones, 1980)

In the first place, buildings stand, apparently doing nothing, and are subject to the elements of the weather, and local meteorological conditions. On a day-to-day basis, this includes variations in temperature, precipitation and humidity, and wind conditions. If the building is in an urban location, vibrations from vehicular traffic may be a factor. The temperature may fall below 0 °C from time to time, and this can pose serious problems if water has been absorbed into cracks in structures or into individual materials. On freezing, water undergoes a 9 per cent volume increase, and this can cause stressing and cracking of those material which are inherently brittle.

This fact raises another very important factor in material performance, and that is the subject of porosity in materials. Some materials are porous, such as clay bricks, concrete and timber. Others are fully dense and impermeable to water. Such materials include metals, sheet plastics, glass, etc. The porosity will determine whether water will be absorbed by materials during service or not. Porosity will also be a determinant of the mechanical properties of materials, as we shall see. The phenomenon of capillarity means that porous materials can absorb water when they are exposed to it, and also tend to retain it even when the surplus water has drained from their surfaces. The water does not always have to be in liquid form, porous materials containing moisture will equilibrate with their surroundings and absorb moisture from the atmosphere during times when the weather is wet or humid. Similarly, they will then dry out when the weather is dry or less humid. These effects cause expansion and contraction effects in addition to those caused by temperature variations.

Another factor that is sometimes overlooked is that although buildings are static structures, they are always under stress. A very large building will possess an enormous weight, and this load is carried by the structural elements and foundations. For example, the Empire State Building in New York weighs over 300,000 tonnes. The stresses induced will be mainly compressive and monotonic. However, we need to bear in mind that while the weight will be responsible for the so-called dead loads on the structure, there will also be the live loads, i.e. those that are continuously varying from hour to hour and day to day. The live loads will include loads due to wind pressure, varying occupancy, etc. In bridge structures some of the stresses can be tensile in nature.

If the stresses vary in a cyclical way with time, they can lead to fatigue in metallic structural elements. Such conditions can occur in bridge structures, and several historically famous bridge failures have occurred because of fatigue.

However, even simple monotonic compressive stress can cause problems with some materials. Under such conditions, the phenomenon of *creep* can occur. Creep can occur in many types of materials including metals, concrete, polymers, masonry, glass and timber. Some of the expensive mistakes made in the construction of multi-storey tower blocks in the 1960s arose because creep and other relative movement effects were not taken into account. We shall examine this later.

In addition to these routine environmental variations, we must also consider other events such as fires, explosions and earthquakes. In the UK, fire is the commonest of these hazards. Explosions also occur, though less frequently than fires. One of the most common causes of explosions is gas leaks in domestic properties. Such explosions can be very destructive, often resulting in the partial or complete demolition of the house in which the leak occurred. During such events, the materials from which the building structure is made are subjected to rapid, dynamic loading, and the response of materials to such loading can be markedly different from their response to gradually or more slowly applied loads. This is also true for seismic activity. Fortunately, earthquakes are infrequent and relatively minor events in the UK. In other parts of the world, building design codes are written to take account of earthquakes, and the dynamic loading that they give rise to. In the UK, such earthquakes as do occur are mid-plate phenomena, like the one that occurred in January 2008, which measured 5.4 on the Richter scale. This was sufficient to cause only very minor damage to some buildings.

1.4.1 The use of materials and their impact on the environment

Because at least three-quarters of the materials used on planet Earth go into buildings and infrastructure, and because this is such a huge quantity, the manufacture, use and disposal of building materials has an enormous impact on our environment. The consequences of their use include energy consumption, pollution effects in air, water and soil, despoliation of landscapes, resource depletion, etc., on a correspondingly large scale. Unless energetic steps are taken to minimise and mitigate these effects, there is a real danger that we shall leave a degraded world to our successors and descendants rather than one enhanced for its occupants.

The impact that the use of materials has is not simple, and can have several ramifications. For example, extraction of raw materials can lead to spoiling of the landscape, as also can the deposit of waste materials from the production process. The production process can give rise to the emission of dust and gases into the atmosphere, as well as waste liquids and other solids. We need ways of measuring or quantifying these effects if we are to control these adverse impacts, and this question will be re-visited in the last chapter of the book. This is a topic of considerable current importance, with concerns increasingly being expressed about how sustainable our present mode of life will be in the long term. Unfortunately, the word sustainable is now very widely used, and not always by people who understand what it might mean. In the serious academic community, its meaning is still being debated and clarified. This topic will be dealt with in the final chapter of this book.

1.5 The contents of this textbook

The construction industry uses a very wide range of materials, wider in fact than that used by any other industry. Metals, ceramics, organics – natural and man-made – are used in enormous quantities. It is important that these materials are used economically and efficiently and not wasted, as construction materials in the past unfortunately have been (Anon, 1987). Waste is the hallmark of the present age. Archaeologists and anthropologists learn a good deal about ancient civilisations by excavating their middens and waste dumps. Archaeologists of the future (if they are still around) will be amazed at what our current civilisation throws away! But in today's increasingly environmentally conscious world, waste is belatedly being seen for what it is – gross mismanagement of our planet's resources. This theme will be taken up in the final chapter of the book.

As far as the main body of the book is concerned, it falls into three sections:

1. *Basic principles*. First, the book will attempt to cover the basic science of the materials of construction. The aim will be to give the minimum coverage to the principles governing the behaviour and properties of these materials. This first section will also include a chapter on the basic principles of structures, since many materials are used to build structures.
2. *Individual materials and classes of materials*. The second section will then deal in detail with the individual types of materials and how they perform in service. It will therefore have something to say about how construction materials in buildings degrade and fail. This section will build on the basic science of the first section and will move on to deal with the individual types of material in turn.
3. *Materials in service, durability and failure*. The third section will deal with those issues arising when materials are put into service, including different modes of failure, the effects of corrosion and solar irradiation, the effects of stress and types of fracture, and the effects of fire, etc.

Finally, since construction is by far the largest industry globally and the largest consumer of materials, and given the current preoccupation with sustainability, the enormous impact that construction has on our environment will be dealt with in the concluding chapter.

1.6 Critical thinking

The aim of this section is to provide the student with the opportunity to reflect on what he/she has learned, and to think about some of the main ideas outlined in the chapter. Questions for thought will be outlined in a critical thinking box, and other questions will be set out for students to work through, to help their understanding of important sections of the text.