The Science and Technology of Building Materials

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THE SCIENCE AND TECHNOLOGY OF BUILDING MATERIALS

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THE SCIENCE AND TECHNOLOGY OF BUILDING MATERIALS

To
Dr. Warren Julian
Dean of the Faculty of Architecture
in the University of Sydney

Preface

This book deals with the physical and chemical properties of building materials, and the influence which these properties have on their use in the design of buildings. It does not assume any knowledge of physics or chemistry beyond elementary high school science. Concepts such as metallurgical phase diagrams, geological formations, and polymer formation are explained in the text where they are first needed. Chemical notation has been used throughout this book in addition to the English names of the chemical compounds, as it is a convenient shorthand, and $CaSO_4.2H_2O$ is clearer to some readers than calcium sulfate dihydrate. A short *Note on Chemical Formulas* has been included for the benefit of readers who are unfamiliar with chemistry. This should suffice for reading almost the entire book, except for short sections on the chemistry of cement and of plastics, which include some more complex chemical formulas; these could be omitted.

The first part of the book discusses the functions which building materials are required to perform. The second part then deals with the properties of each group of materials in turn, and how these affect their functional performance.

Not merely has the number of materials available for building construction grown at an ever increasing rate, but old materials have found new uses, in which they perform functions that our ancestors would have found surprising. The days of the "cookbook" on building materials, which stated precisely what materials could be used for any one purpose, have therefore passed, except for traditional building construction which is mostly limited to small buildings. There are several excellent books on that aspect of the use of materials, and this book is not endeavoring to replace them.

While the authors wish to encourage innovation, based on a sound understanding of the properties of the materials and the functions they are required to perform, they have been at pains to point to the pitfalls. It is possible to predict that some applications of some building materials will result in failure. The opposite cannot always be predicted with certainty, particularly where durability is a problem. However, many failures could be avoided by more careful analysis, and better use of available experimental data.

Both metric SI units and the traditional British/American units (in brackets) are used throughout this book. The *Note on the SI Metric System* giving conversion from one system of units to the other is therefore not really needed, but it may be helpful to readers who consult some of the references, and find that the data are in the "wrong" units.

Chapters 4, 15, and 16 were written mainly by P. R. Smith, and the others mainly by H. J. Cowan. Unless otherwise indicated, drawings are by P. R. Smith and photographs by H. J. Cowan.

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Sydney, Australia

H. J. C.
P. R. S.

ABBREVIATIONS

1. Chemical Symbols Used in this Book

Al	aluminum
C	carbon
Ca	calcium
Cl	chlorine
Fe	iron
H	hydrogen
Mg	magnesium
N	nitrogen
Na	sodium
O	oxygen
S	sulfur
Si	silicon

2. Units of Measurement Used in this Book

Btu	British thermal unit
C	Celsius
cd	candela
db	decibel
dbA	decibel on the A-scale
F	Fahrenheit
ft	foot
Hz	hertz
in.	inch
K	Kelvin
kg	kilogram
kJ	kilojoule
km	kilometer
ksi	kilopound per square inch
lb	pound
m	meter
MJ	megajoule = 1,000 kJ = 1,000,000 joule
mm	millimeter = 0.001 meter
μm	micrometer = 0.001 mm
MPa	megapascal = 1,000,000 Pa
nm	nanometer = 0.000 001 mm
Pa	pascal (the metric SI unit for pressure and stress; it equals 1 newton per square meter)
psi	pound per square inch
s	second
W	watt
°	degree
%	percent

3. Other Abbreviations

AC	alternating current
ASTM	American Society for Testing Materials
BS	British Standard
d	thickness
DC	direct current
δ	deflection
e	strain
E	modulus of elasticity
f	stress
h	boundary layer heat transfer coefficient
k	thermal conductivity
L	span
PVA	polyvinyl acetate
PVC	polyvinyl chloride
Q	quantity of heat
R	thermal resistance
sin	sine of angle (trigonometric function)
T	temperature
U	thermal transmittance
W	load

A NOTE ON CHEMICAL FORMULAS

The authors have used chemical formulas, although they appreciate that some readers may never have taken a course in chemistry. This is not strictly necessary to understand a simple formula. Chemical formulas and equations are a convenient method for explaining in a few letters what would otherwise take several lines, and they allow the reader to comprehend the composition of chemically simple materials at a glance. The rules are few and simple.

An atom is the smallest unit of a chemical element. Its valency is the number of free bonds that it has available to combine with other atoms to form a molecule. For example, a very common material is water, which consists of hydrogen and oxygen. H is 1-valent, and O is 2-valent, so that it takes 2 H and 1 O to make the simplest molecule, H_2O. These concepts are explained in Sections 2.2 and 18.1.

Only 12 chemical elements are mentioned in the formulas used in this book. Their names, chemical symbols, and valencies are as follows:

Chlorine (Cl), hydrogen (H), and sodium (Na) have a valency of 1.

Calcium (Ca), magnesium (Mg), and oxygen (O) have a valency of 2.

Aluminum (Al) has a valency of 3.

Carbon (C) and silicon (Si) have a valency of 4.

Iron (Fe) can have a valency of 2 or 3. Materials that have 2-valent iron are called *ferrous*, and materials that have 3-valent iron are called *ferric*.

Sulfur (S) can have a valency of 2, 4, or 6, and nitrogen (N) can have a valency of 3 or 5, but they occur only in very few formulas in this book.

The more complicated-looking chemical formulas occur in Chapter 13, dealing with cement, and in Chapter 18, dealing with plastics. Let us look at the meaning of these formulas.

Two of the raw materials used for making portland cement are alumina and silica. Alumina consists of aluminum and oxygen, and silica of silicon and oxygen. O is 2-valent, Al 3-valent, and Si 4-valent. Therefore the simplest molecule of alumina consists of 2 Al and 3 O ($2 \times 3 = 6$ and $3 \times 2 = 6$), giving Al_2O_3. The simplest molecule of silica consists of 1 Si and 2 O ($1 \times 4 = 4$ and $2 \times 2 = 4$), giving SiO_2.

Both of these materials are derived from clay, which contains alumina and silica in the proportion of 1 to 2. It also contains some chemically combined water, as do many other materials. We therefore get the formula $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ for clay.

Chapters 18 and 19 deal with so-called organic compounds (the term is explained in Section 18.1). These are compounds of carbon, in which carbon atoms combine with other carbon atoms to form chains or rings. These are a little more complicated.

Ethane is a chain molecule that consists of 2 carbon atoms linked to one another with a single bond, and surrounded by hydrogen atoms linked to the carbon atoms with a single bond (Fig. N.1). Each carbon atom has 4 bonds, but one is taken up by the link between them. Thus, each carbon atom has 3 links available for hydrogen atoms, so that they can combine with $2 \times 3 = 6$ hydrogen atoms, and the chemical formula of ethane is thus C_2H_6.

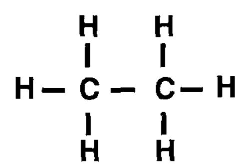

Fig. N.1. Chemical structure of ethane.

The carbon atoms could also be linked by two bonds (Fig. N.2) which leaves only two bonds for hydrogėn atoms, so that the 2 carbon atoms can combine with $2 \times 2 = 4$ H, and the chemical formula is C_2H_4, which is ethylene.

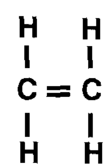

Fig. N.2. Chemical structure of ethylene.

Six carbon atoms can be linked as a continuous ring, with two bonds and one bond between these carbon atoms alternating (Fig. N.3). These links take up 3 of 4 available bonds, so that one is left for linking to hydrogen atoms, and the formula for this material (called benzene) is C_6H_6.

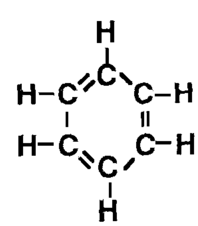

Fig. N.3. Chemical structure of benzene.

If we now take away one hydrogen atom from ethylene, we are left with C_2H_3, which has one vacant bond. Similarly, if we take one hydrogen atom from benzene, we are left with C_6H_5, which also has one vacant bond. These two can combine to form $C_2H_3{\cdot}C_6H_5$ (called styrene). We do not add up all the C's and H's, because the structure is clearer that way. The full stop (·) denotes a single bond between the two parts; a colon (:) is used to denote a double bond between two parts.

Contents

1

An Historical Introduction

Our construction methods for the use of timber and brick on the domestic scale do not differ greatly from those used in Ancient Rome, as the remains of Herculaneum, buried by an eruption of Mount Vesuvius two thousand years ago, illustrate. We rarely make use today of the sculpted natural stone that figures so prominently in buildings inherited from earlier centuries, however, because of the high labor costs involved.

The mortar and plaster, the paint, and the glass used today are different materials from those used prior to the nineteenth century. The greatest change, however, has occurred in the use of metals, which were only minor building materials prior to the eighteenth century. The adoption of steel-frame and reinforced-concrete construction have caused major changes in traditional construction practices.

1.1 MASONRY, CONCRETE, TIMBER, AND CANVAS

Building materials are among the oldest human artifacts, but today's materials differ appreciably from those used prior to the nineteenth century. Superbly sculpted buildings of natural stone, built several thousand years ago, survive to prove that the skill is of very ancient origin (Fig. 1.1.1). Even civilizations that lacked metal tools succeeded in working stone with remarkable precision (Fig. 1.1.2). These were exceptional buildings even in their own time, however, the most common building materials in the Ancient World, and in the developing countries until recently, being timber (or bamboo or reeds) and sun-dried bricks (or pisé). These readily available materials were, and are, nondurable, but simple buildings using them could, and can, be erected quickly and cheaply (Fig. 1.1.3).

Hard-burnt bricks have been found that are 10,000 years old. The amount of fuel needed to produce such durable building blocks, however, limited their use prior to the days of the Roman Empire, at which time they became a common building material; they have remained so in the Middle East.

In Western Europe during the Middle Ages, brick was considered a more expensive material than stone and was used almost exclusively in regions where natural stone was not available. In the thirteenth century, bricks became more common, and by the eighteenth century brick was increasingly substituted for stone to reduce costs (see Chap. 15).

This substitute brick was stuccoed or plastered and then painted with "joint" lines to imitate stone. These lines were eventually omitted, but it is still common practice to plaster external brick walls in European regions where natural stone was commonly used in the past. In the traditional "brick regions" of Europe, external brick walls, using face bricks, are usually left unplastered.

Concrete was invented by the Romans in the first century B.C., and it became the most common material for major public buildings during the Roman Empire. Falling into disuse in the fifth century A.D., it was rediscovered only in the eighteenth century as a result of a systematic scientific investigation (see Sec. 13.3).

Wood is, and probably always has been, the most common material for buildings on the domestic scale

Fig. 1.1.1. King Zoser's Mortuary Complex at Saqqara, Egypt.
Built about 2600 B.C., this is one of the oldest stone buildings in existence. The columns shown here consist mostly of original masonry; the walls between are restored work.

(Chap. 16). It has also been used for very large and important buildings in all countries that have a good supply of timber. Until the end of the nineteenth century, most of the important buildings in China and Japan were built from timber (Fig. 1.1.4).

Canvas was the principal material of nomads' tents, but it has also been used since antiquity for temporary cover. For example, the Romans used it for sun awnings in their open-air theatres; these were installed before the performance and removed afterwards (Ref. 1.3).

1.2 MORTAR AND PLASTER

It is much easier to lay blocks and bricks with mortar joints than to cut them to fit precisely with dry joints (Fig. 1.1.2). Today, mortar is usually made from sand, portland cement, and some additives, but, prior to the late nineteenth century, mortar usually consisted of sand and lime. Since lime is water-soluble, the mortar joints were a common source of weakness in stone and brick structures.

The Romans, as already mentioned, discovered materials with cementing properties (see Sec. 13.3), and used them to build very strong brick walls, many of which have survived to the present day, particularly in buildings later turned into churches. Nevertheless, they also built some stone structures with dry joints. The Greeks always used dry joints for their stone temples.

Gypsum was used as mortar in Egypt, and naturally occurring bitumen in Mesopotamia. In very important structures, the stone was sometimes set in molten lead—for example, in the Aya Sofya, the great By-

Fig. 1.1.2. Squared masonry from Cuzco, capital city of the Incas in the Peruvian highlands.
These stones were carefully fitted by prolonged rubbing with sand since the Inca civilization did not have metal tools. The joints are so tight that it is impossible to push a razor blade between the stones. No mortar was used. Because of the man-hours and precision required, this is a very expensive form of construction. It was used in Greek temples. One of the rare uses in modern times was in the Morgan Library (1903), where the multimillionaire Pierpont Morgan insisted on a revival of the Greek method to achieve perfect durability (Ref. 1.1).

zantine church built in Istanbul in the sixth century A.D.

Plastering has a similar purpose. It produces smooth surfaces on walls that would otherwise be rough. Many plastered walls in important buildings were decorated with pictures from the time of Ancient Greece to the eighteenth century. Fresco painting was done on wet lime plaster, and the paints dried and set with the plaster.

Modern plaster is usually made with portland cement, but gypsum plaster and lime plaster were used until the early years of this century (see Chap. 13).

1.3 PIGMENTS

When Greek architecture was rediscovered in the eighteenth century, it was admired particularly for the austere whiteness of its marble and limestone temples. This is still a widely held view of classical architecture, but we know today that most of the marble was painted; the paint has merely disappeared through weathering.

Paintings of the Ancient World survive in Egyptian tombs (see Fig. 19.1.1) and in buildings buried by volcanic action in the Greek island of Thera, in the fifteenth century B.C. (Ref. 1.4), as well as in Pompei and some villas nearby that were buried in the first century A.D.

Some of these paintings have high artistic merit in spite of the limited range of colors available in Egypt and Minoan Greece. White was made from lime, and black from soot. Yellow, red, and brown were made from earth pigments containing iron ore. Blue was obtained from various copper salts, and green by mixing blue with yellow. The Romans had a wider range of colors because they were able to import pigments from the various parts of their empire. Vitruvius described them in detail (Ref. 1.5). Green could be produced directly from malachite. A particularly good blue was imported from outside the empire (Armenia). There were several shades of red to supplement the earthy red ochre. Vermilion was manufactured from mercury, and purple was obtained from a shellfish. Vitruvius also described several substitute pigments for less important work which were cheaper; for example, blue was obtainable by dying chalk with woad.

The Middle Ages and the Renaissance added further to the range of pigments, but some were very expensive; for example, ultramarine blue was produced by grinding lapis lazuli, a semiprecious stone. In the Middle Ages, the cost of a painting depended more on the cost of the pigments than the wages of the painter.

Most of the pigments and the vehicles in which they are dispersed are today made synthetically, this being one group of building materials that has been radically transformed by modern technology (see Chap. 19).

1.4 GLASS

Glass was already made in ancient Egypt for use in jewelry. It did not become a major building material, however, until the Middle Ages. Although a few glass panes have been found, the Romans usually left their windows strictly as openings, or they covered them with transparent parchment. For some important buildings, thin, translucent slabs of alabaster or marble were used (see Fig. 12.6.4).

Medieval glass let in much more daylight than these stone slabs, but it was not transparent because of the many imperfections and air bubbles. *Sheet glass* was made from cylinders blown from liquid glass. The ends were cut off and the cylinder opened up into a flat sheet in an oven, but the surface of the glass was damaged by contact with the oven floor.

The other traditional process—*crown glass*—was perfected in the late Middle Ages. The liquid glass was blown into a rough globe and then spun until, by centrifugal force, it attained a wheel-like shape (see Fig. 17.2.2). This was then cooled and cut into panes. Since the glass did not touch any surface while soft, it was perfectly clear; however, only relatively small panes could be produced. The brilliantly clear, slightly curved crown-glass panes that were introduced into

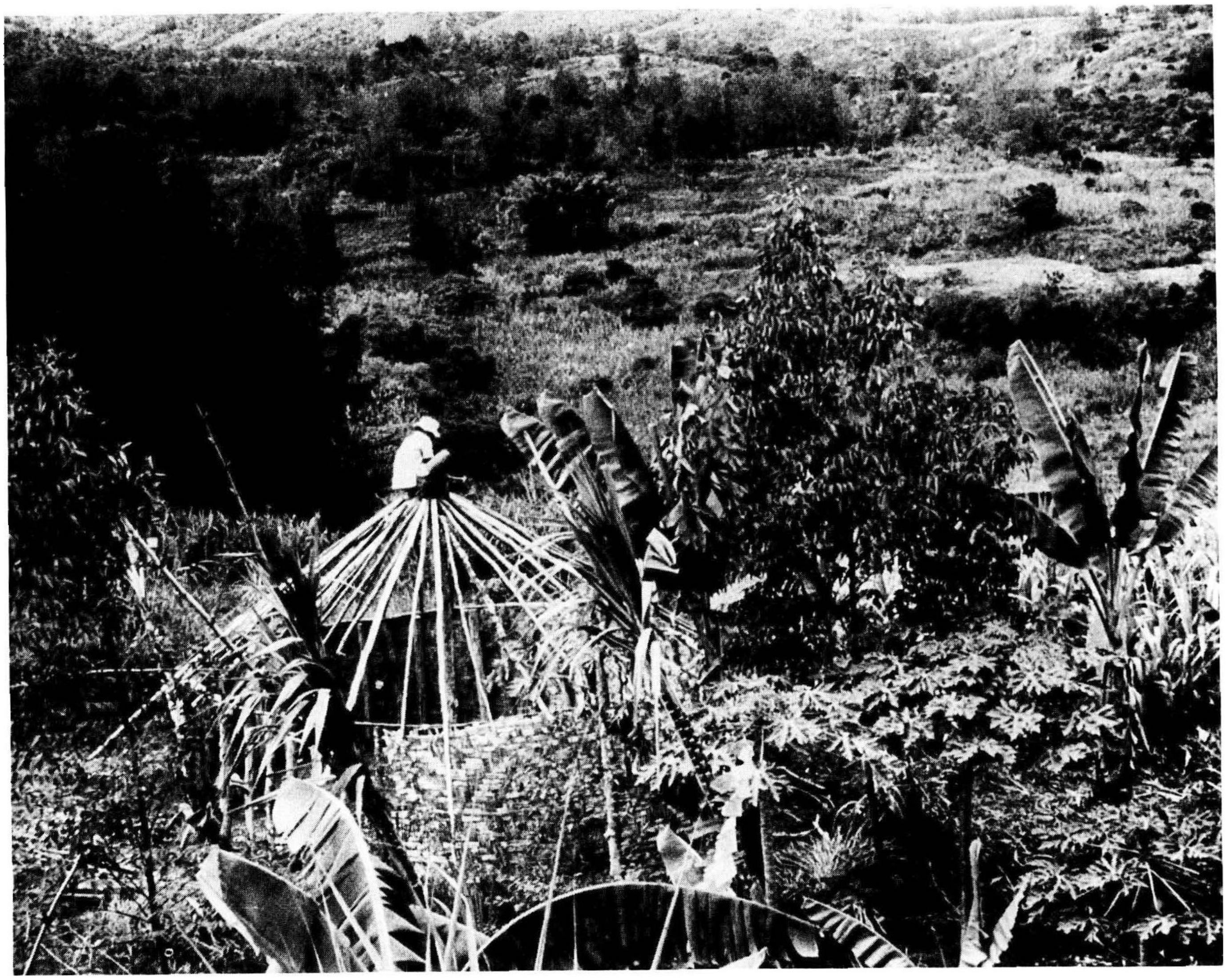

Fig. 1.1.3. Circular hut in the Highlands of New Guinea, made of bamboo tied together with vegetable fibers. The walls are woven mats and the roof is thatch. The hut can be erected by two people in a single day, if they have previously collected the materials from the surrounding countryside, cut the poles to length, and woven the mats.

England in the seventeenth century are one of the characteristics of the buildings of that period.

Glass is today produced by entirely different, improved, and cheaper processes developed in the twentieth century (see Sec. 17.2).

1.5 METALS

Metals played only a minor role in building construction prior to the eighteenth century. The Romans used lead extensively for water pipes and for roof covering, and they also used copper for these purposes. Copper is still used as a high-quality roofing material, but lead became too expensive in the early years of this century.

Wrought iron, copper, and copper alloys have been used since the Middle Ages, and possibly earlier, for door hinges and locks and sometimes for entire doors. Lead was used for joining the small panes of glass in medieval windows, and the assembled windows were then strengthened with iron bars.

The Greeks and Romans used bronze and iron for dowels and clamps to join blocks of stone laid without mortar (see Sec. 1.2). In Byzantine, and later in Muslim, arches and domes, the horizontal thrust was often absorbed by timber or metal bars, this being the earliest use of metal as a structural material. In the Renaissance, iron chains were used instead to absorb the outward thrust of domes (Ref. 1.6).

During the eighteenth century as new and cheaper processes were developed for the manufacture of iron, this metal came to be used extensively for machines and also for load-bearing beams and columns in the factories that housed the new machines.

During the nineteenth century, iron, and later steel (see Sec. 10.1), was increasingly employed for the structural parts of buildings. In the 1860s, reinforced

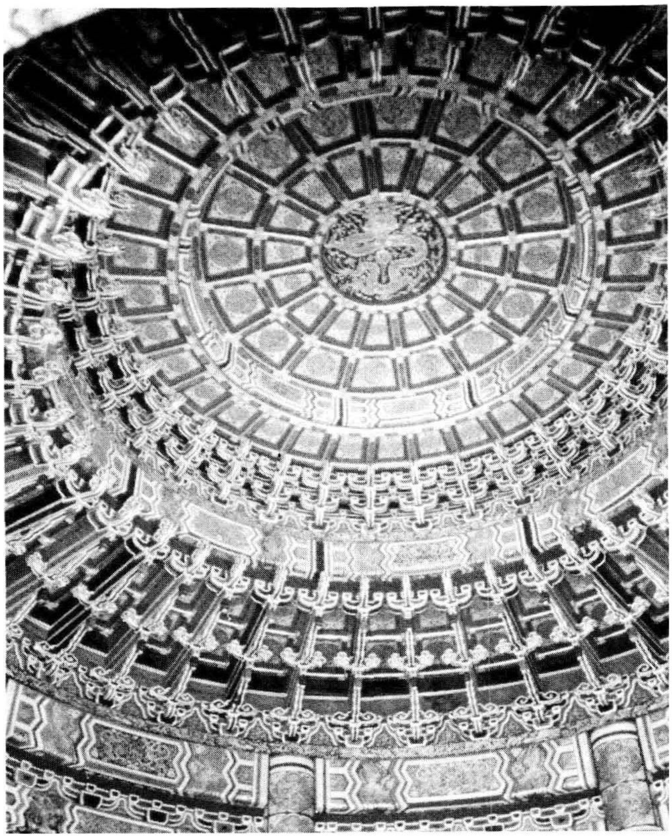

Fig. 1.1.4. Timber dome of the Temple of Heaven in Beijing, China. The dome is supported on huge circular timber columns; built in 1890, it replaces a previous temple destroyed by fire in 1889 (Ref. 1.2).

concrete was invented, and it became a major building material in the twentieth century.

The adoption of structural steel and reinforced concrete caused major changes in traditional construction practices. It was no longer necessary to use thick walls of stone or brick for multistory buildings, and it became much simpler to build fire-resistant floors. Both these changes served to reduce the cost of construction. It also became possible to erect buildings with greater heights and longer spans.

Corrugated iron was developed in the 1820s, and processes for coating it with zinc or tin for corrosion protection date from the 1830s. Because of its strength and relatively low weight, corrugated iron was exported as a roofing and walling material from Europe to its colonies and to America.

Metal (lead and later aluminum) was first used in the mid-nineteenth century in damp-proof courses (see Glossary); these had previously employed slate or other impervious stones.

Steel and aluminum windows, curtain walls, and partitions are developments of the present century.

1.6 MATERIALS ARE NOT ALWAYS WHAT THEY APPEAR TO BE

The ethics of using construction that imitates more expensive materials has been argued from time to time. Structural honesty was one of the tenets of many neo-Gothic theorists in the late nineteenth century, although John Ruskin was prepared to accept gilded wood on the ground that everybody knew it was not solid gold. Similar tenets were espoused by the Modern Movement, particularly in the 1950s and 60s.

It may also be argued that to produce construction that looks precisely like a more expensive one, and that fulfills the same purpose, is a mark of professional skill. The criterion is then whether the substitution produces an equally good or an inferior construction. At any rate, faking of expensive materials is an ancient craft. Several examples are given by Vitruvius; the following, describing vaulting imitated by stucco work, may serve as an example:

> When vaulting is required, the procedure should be as follows. Set up horizontal furring strips at intervals of not more than two feet apart, using preferably cypress, as fir is soon spoiled by decay and by age. Arrange these strips so as to form a curve, and make them fast to the joists of the floor above or to the roof, if it is there, by nailing them with many iron nails to ties fixed at intervals. These ties should be made of a kind of wood that neither decay nor time nor dampness can spoil, such as box, juniper, olive, oak, cypress, or any other similar wood, except common oak; for this warps and causes cracks in work in which it is used.
>
> Having arranged the furring strips, take cord made of Spanish broom, and tie Greek reeds, previously pounded flat, to them in the required contour. Immediately above the vaulting spread some mortar made of lime and sand, to check any drops that may fall from the joists or from the roof. If a supply of Greek reed is not to be had, gather slender marsh reeds, and make them up with silk cord into bundles all of the same thickness and adjusted to the proper length, provided that the bundles are not more than two feet long between any two knots. Then tie them with cord to the beams as above described, and drive wooden pegs into them. Make all the other preparations as above described.
>
> Having thus set the vaultings in their places and interwoven them, apply the rendering coat to their lower surface; then lay on the sand mortar, and afterwards polish it off with the powdered marble. After the vaultings have been polished, set the impost moulding directly between them. These obviously ought to be made extremely slender and delicate, for when they are large, their weight carries them down, and they cannot support themselves (Ref. 1.7).

Vitruvius then proceeds to explain how the walls should be stuccoed and the walls and the vault prepared