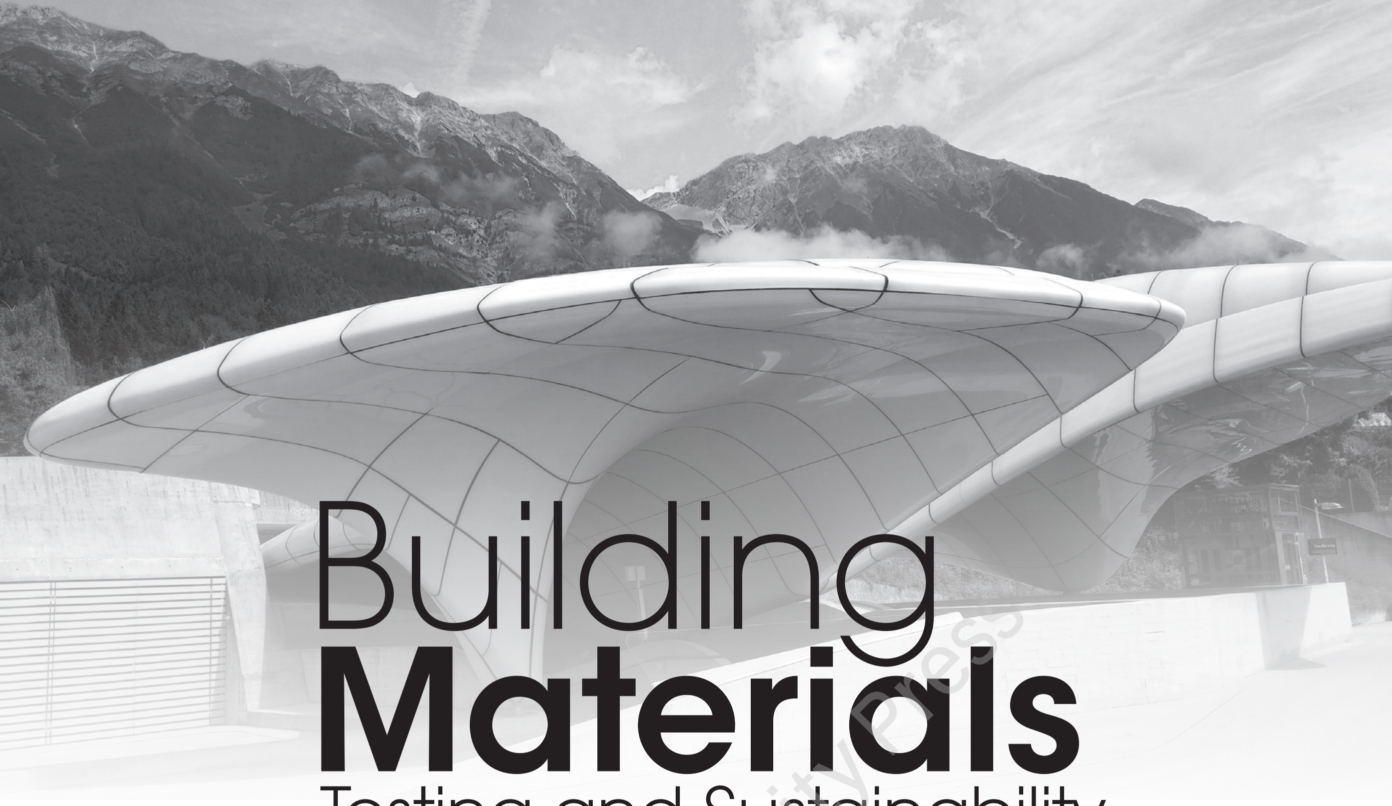

Building **Materials**
Testing and Sustainability

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PREFACE

Ancient civilization lived in caves. After fire and tools were discovered, they started to use natural products such as stones, bricks, and wood to build habitats, which provided protection from the natural environment. Bricks have been found in Egypt as early as 14,000 BC. By 200 BC, the Romans successfully used concrete in the majority of their construction (though the present day concrete construction is much different from theirs). In the industrial age (between the mid-1700s and 1840), several manufacturing processes to produce cement (Joseph Aspdin, 1824), concrete, macadam roads (John Loudon McAdam, c. 1815), mass production of steel from molten pig iron by the Bessemer Process (Henry Bessemer, 1856), method of converting pig iron into wrought iron (Henry Cort, 1784), etc., were invented, resulting in the extensive use of concrete and steel. Now, concrete is the most widely used substance on earth, after water. We now use a variety of materials in our buildings and constructions ranging from stones, bricks, cement, reinforced concrete, steel, stainless steel, wood and wood products, glass, fibreglass, aluminium, plastics, ceramics, gypsum, paints and varnishes, bitumen, to copper, zinc, and aluminium alloys.

The exploding population growth (3 billion in 1960 to an estimated 7.7 billion in 2019) and the resulting urbanization has resulted in greater energy use [according to BP's Statistical Review of World Energy, world primary energy consumption reached 157 terawatt-hour (TWh) in 2017]; it has to be noted that materials such as cement and steel require large amounts of energy as their production requires them to be heated to temperatures exceeding 1300°C in kilns. This causes emission of huge quantities of greenhouse gases like CO_2 and also large amounts of industrial waste by-products like fly ash, which are harmful to the environment. In addition, indiscriminant mining of natural resources for the production of building materials has resulted in severe adverse effects on the environment, including loss of biodiversity, erosion, contamination of surface and ground water, and soil. Several (rocky) mountains are disappearing and river beds and even beaches (which took numerous years to form) are being denuded of sands. As these natural resources are limited, there is a shortage of coarse aggregates and sand in several parts of the world, necessitating the use of alternate materials or recycling of used materials and even the use of industrial wastes like fly ash. Several other materials such as plastics and lead are harmful to the environment or to the heath of human beings and have to be handled carefully. In addition, some materials like paints, varnishes, or wood impregnated with preservative chemicals may off-gas volatile organic compounds (VOC), which may affect the health of people living in air-conditioned interiors.

Almost all materials that are used in the construction have to follow the norms stipulated in the national codes (Bureau of Indian Standards has numerous codes on building materials). In addition, as buildings account for about one-third of worldwide energy consumption and are one of the largest contributors to GCG emissions, several countries including India have recently developed *Energy Conservation Building Codes*. They usually contain mandatory and voluntary provisions on insulation, thermal and solar properties of the building envelope, heating, ventilation and air conditioning, and also hot water supply systems, lighting, and electrical power.

From the above discussions, it is clear that all those engaged in the design and construction of buildings should have a sound knowledge about the manufacture, energy required in the manufacture, properties, effect on health, environmental friendliness, recyclability, sustainability, etc., of the materials they are using and also the norms prescribed for these materials. This book has been written to fulfill these needs. This text is based on several latest Indian Standard codes on building materials. SI units have been used throughout the book.

About the Book

Building Materials, Testing, and Sustainability is a comprehensive text book designed to meet the requirements of the undergraduate students of civil engineering, based on the recent AICTE syllabus on *Materials, Testing & Evaluation*. This book will also be useful to students of architecture (who usually specify the materials), students of diploma courses in civil engineering and will serve as an invaluable reference to postgraduate students and practising engineers, as well as researchers.

Each chapter starts with an introduction about the origin and development of the material discussed in that chapter, the manufacture, properties, uses, advantages and disadvantages, and sustainability of that material. After presenting the subject, multiple-choice questions (MCQ) and review questions are provided at the end of each chapter, which will help the students assimilate the topics presented in the chapters. Answers to the MCQ are given at the end of each chapter, so that the students can check their answers. Several interesting case studies are also included as part of every chapter.

Key Features

The following features in the book make it stand out among the other books in this area:

- It covers traditional materials to the most modern materials such as plastics, gypsum, and ceramics.
- Each chapter covers a brief history, composition, classification, manufacture, properties, advantages and disadvantages, use in buildings, environmental effects, sustainability, etc., of the material discussed in that chapter.
- Several Indian codes are available which stipulate norms for these materials. Most of these codes are cited in the book and important extracts are provided. The list of several codes, which are not cited, are also included in the references of each chapter and included in the online resource centre (ORC). In addition, a bibliography is provided in the book which lists the important references, for further study and research.
- Several topics, which are normally not found in other books, such as different types of brick kilns, substitutes for bricks, green cement, industrial by-products that can be used to replace cement, green substitutes for coarse aggregates and sand, green mortars, green and special concrete, mix design of concrete, controlled permeability formwork (CPF), industrial timber products, various reinforcing bars, structural insulated panel (SIP), sustainability of various materials, green building rating systems, bamboo, nano-materials, composite materials and concrete canvas, health effects and precautions to be taken while handling certain materials, etc., are discussed.
- 30 interesting practical case studies are provided.
- Students and engineers will find the separate chapter on testing and evaluation of these materials to be useful.
- A rich pedagogy provides the required rigour for students to excel in this subject in the examinations: Over 750 review questions and 440 multiple-choice questions (with answers) to test the understanding of the students; over 300 illustrative figures and photographs and 200 tables to supplement the text; more than 1440 references, which include relevant Indian and American codes.
- Provides most updated information in this subject covering the state-of-the-art trends and developments.

Online Resources

The following resources are available to support the faculty and students using this text:

For faculty

- Lecture PPTs

For students

- List of references

Using the Book

The text is divided into 25 chapters and completely covers the undergraduate (UG) curriculum of most of the universities. The teacher adopting this book is requested to exercise discretion to select portions of the text to be presented for a particular course. It is suggested that portions of Chapters 2–8, 11–13, 15–18, and 25 may be taught and Chapters 1, 9–10, 14, and 19–24 may be left for self-study.

Although relevant information from some important codes of practice has been included in the text, readers are advised to buy and refer to the latest codes published by the Bureau of Indian Standards, New Delhi. It is recommended that readers should use the book along with the latest codes/publications released by the Bureau of Indian Standards, for better clarity.

Contents and Coverage

The text is divided into 25 chapters.

Chapter 1 deals with the general information on physical, mechanical, thermal, and other properties of materials. It also gives some indications on sustainable (healthy and ecological) materials. Introduction to various green building systems is given and a comparison of structural steel, reinforced and pre-stressed concrete, and wood, which are the major materials used in construction, is provided. A discussion on Alternative Building Materials and building codes is also included.

Various aspects of stone including durability, deterioration, preservation, selection and uses of stones are discussed in ***Chapter 2***. It also has brief introduction to stone masonry and a comparison of stone and brick masonry.

Bricks, which are usually used for constructing the walls of buildings, are the subject of ***Chapter 3***. In India, the current brick manufacturing is through the use of highly polluting, energy inefficient, and uneconomical kilns. Hence various types of kilns are discussed and the vertical shaft brick kiln/tunnel kiln is suggested. Qualities of good bricks, properties, characteristics, etc., of bricks are provided. Several substitutes for bricks are also suggested.

Chapter 4 deals with lime, which is a green material, and was used in olden days; this chapter discusses its manufacture, types, classifications, uses, and precautions while handling it. The manufacture, chemical composition, properties, and hydration of various types of cement, which is an important ingredient of concrete, are explained in ***Chapter 5*** along with the various pozzolana/green cement replacement materials. ***Chapter 6*** deals with the characteristics and properties of coarse and fine aggregates, which are mainly used in concrete, and include topics on grading of aggregates, alkali–aggregate reaction, and green substitutes for coarse aggregates and sand. ***Chapter 7*** is concerned with mortars and plasters, which are used in building masonry and providing protective coating on walls and ceilings, respectively.

Various aspects of concrete and RCC, which is used extensively in India in buildings, bridges, dams, etc., are covered in ***Chapter 8***. Various special concretes such as ready mixed concrete, high-strength/high-performance concrete, self-compacting concrete (which is the material of the future), structural light weight concrete, foamed concrete, fibre reinforced concrete, ultra-high performance concrete, polymer concrete, geoploymer concrete, prestressed concrete, precast concrete, decorative concrete, etc., are discussed in ***Chapter 9***. As concrete contributes to about 5–6% of global emissions of greenhouse gases, the methods to reduce these emissions by the use of industrial by-products such as fly ash, GGBS, etc., (which also improve the properties of concrete) are also described in Chapter 9.

Chapter 10 describes gypsum, a fire retardant and sustainable material, requiring low energy in its production, and mostly used in wall panels. The technology developed at IITM, using glass fibre reinforced gypsum panels, could reduce the cost and time required to build houses.

Wood is the most sustainable and renewable building material having a low level of embodied energy, and wood products can be carbon negative. In order to use it we should maintain sustainable forestry. ***Chapter 11*** explains the classifications, defects, conservation, seasoning and preservation, properties, selection and testing of timber. Several wood products such as layered timber composites, parallel laminates, particle composites, fibre composites, and timber-concrete composites are now available; their use and properties are briefly explained along with cork and linoleum.

Chapter 12 deals with the various forms of iron (pig, wrought, cast) and ***Chapter 13*** describes steel, which is the second most used structural material. Steel could be alloyed with other elements (mainly with carbon) to improve the properties. It has equal strength in tension and compression, but its main drawback is its corrosion. Steel is used in various forms from structural sections to bolts, nuts, and nails. Hot rolled and cold-formed steel sections are available. Rebars used in concrete and prestressed concrete are usually made of high strength steel. Several techniques have been developed to mitigate the corrosion problem including the development of stainless steel and weathering steel. The production of steel is also energy intensive and requires high temperatures (up to 1650°C), but is considered sustainable due to its 100% recyclability. ***Chapter 14*** is concerned with non-ferrous materials such as aluminium, copper, zinc, lead, etc., and its alloys like brass and bronze. Steel is galvanized using zinc.

Glass, which is obtained from silica sand, lime, soda, and alumina, and mainly used in windows and curtain walls of multi-storey buildings, is discussed in ***Chapter 15***. Common types (sheet, plate, float, and extra clear) and special types of glass (safety, translucent, etched, tinted, reflective/coated, insulated, double-glazed, glass blocks) are described. Clay roofing tiles of various types and ceramic products are discussed in ***Chapter 16***. ***Chapter 17*** discusses plastics, which were invented in the 1800s and have revolutionized the construction industry and being used in a variety of applications. This chapter describes its classification, methods of production, properties, and uses. Most of the plastics are not recyclable and are not bio-degradable and hence have to be used with caution.

Details about paints and varnishes are provided in ***Chapter 18*** and asphalt, bitumen, and tar in ***Chapter 19***. ***Chapters 20–22*** deal with thermal and sound insulating materials and waterproofing materials, respectively. Miscellaneous and recent materials are discussed in ***Chapter 23***. A brief description of deformation and fracture of materials is provided in ***Chapter 24***. ***Chapter 25*** describes the various tests that are performed on some of the important materials, in order to evaluate them.

Though care has been taken to present error-free material, some errors might have crept in inadvertently. I would highly appreciate if these errors are brought to the attention of publishers. Any suggestions for improvement are also welcome.

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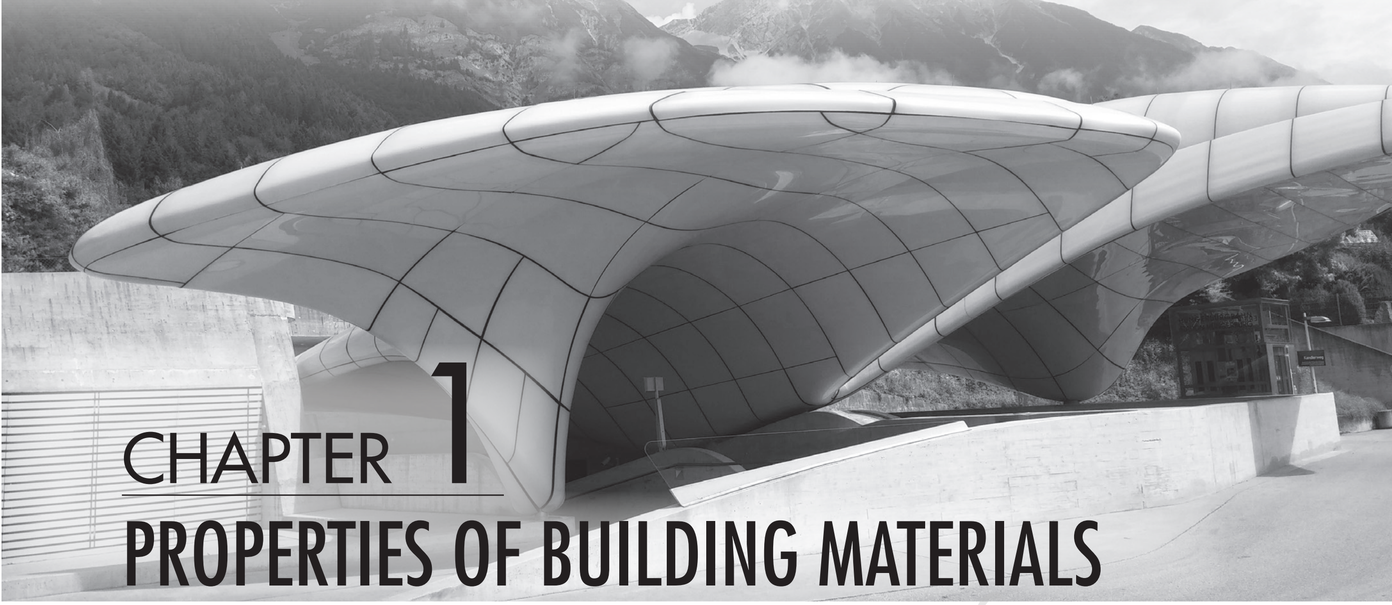
N. Subramanian

BRIEF CONTENTS

DETAILED CONTENTS



CHAPTER 1
PROPERTIES OF BUILDING MATERIALS

1.1 Introduction

In the early societies, human beings lived in caves and almost certainly rested in the shade of trees. Gradually, they learnt to use naturally occurring materials such as stone, timber, mud, and biomass (e.g., leaves, grasses, and natural fibres) to construct houses, which was then followed by brick making, rope making, and glass and metal work (see Table 1.1). From these early beginnings, the modern materials–manufacturing industries developed.

The principal modern building materials are bricks, cement, concrete (e.g., mass, reinforced, and prestressed), timber, structural steel (in rolled and fabricated sections), aluminium, glass, paints, plastics, and ceramic products. All these materials have particular advantages in certain applications and hence the construction of a building may include various materials; for example, a commercial multi-storey

Table 1.1 Historical developments in building materials

Material	Period
Mud, stones, and thatch	400,000 BC
Sun-dried bricks	7500 BC
Timber	5000 BC
Fired bricks	2000 BC (First appeared in the Middle East)
Lime	3000 BC
Glass	2500 BC (The Egyptians provided the first examples with silica and calcium.)
Iron	1350 BC
Lime–pozzolana cement	300 BC–AD 476 (Romans and Greeks)
Aluminium	In 1808, it was discovered by English chemist Sir Humphrey Davy. In addition, the smelting process was discovered by Charles Martin Hall of the USA in 1886.
Portland cement	Invented by Joseph Aspdin in 1824
Natural rubber	A method of processing invented by Charles Goodyear in 1839
Steel	In 1855, Sir Henry Bessemer invents the Bessemer process for the mass production of steel
Plastics	In 1862, by Alexander Parkes at the 1862 Great International Exhibition in London
Stainless steel	Invented by Henry Brearly in 1913

building may have concrete/steel frame, infilled, and partition walls made of bricks or concrete blocks, wooden doors, and double-glazed windows of aluminium. The architect or design engineer has to think about the various alternatives and suggest a suitable material, which will satisfy economic, aesthetic, functional, and ecological/sustainability requirements.

Since construction is the largest consumer of natural materials, India was one of the first few countries in the world to add a specific provision on environment protection in its Constitution, through the 42^{nd} Amendment, during 1976. The Environment (Protection) Act, 1986 was introduced as an umbrella legislation that provides a holistic framework for the protection and improvement to the environment.

1.2 Functions of a Building

The major requirement of any building is to shelter its occupants from the environmental conditions and offer a pleasant, comfortable, and healthy indoor environment. Thus, a well-designed building will provide good weather resistance (adequate resistance to rain and wind penetration), ample lighting, proper ventilation, adequate thermal insulation (to prevent heat loss to the environment in cool areas and heat gain in hot areas), low noise levels (to prevent airborne sound and impact sound from outside and prevent the passage of sound from one inner space to another inner space), have adequate strength and stability, privacy, security, and fire resistance (for the occupants to exit safely in the case of major fires), proper ingress and egress, good appearance, durability, and have reasonable cost. These requirements can be achieved by the proper selection of building materials and products. Proper site location, shape, orientation, and vegetation around the building may also help in obtaining better lighting and thermal performance (Reid, 1984).

1.3 Choosing Materials for Construction

Building materials may be categorized based on the source of availability as natural and manufactured. They may also be classified as traditional and modern. The traditional building materials are generally the naturally occurring substances such as earth (e.g., clay, sand), stone and rocks, lime, and wood logs. Whereas, modern building materials include many artificial or manufactured synthetic and composite products such as bricks, lightweight concrete blocks, concrete, metals, glass, ceramics, plastics, and petroleum-based paints. The manufacture of building materials is an established industry, and the use of these materials is generally segmented into specific specialty trades such as concrete, masonry, carpentry, plumbing, roofing, electrical, mechanical, insulation, and HVAC (heating, ventilation, and air conditioning). In the countries like the USA, in order to work in these trades, one has to get certified by passing the Law and Business and the Trade Examinations.

For a material to be considered suitable for construction, it should have some essential engineering properties. These properties are broadly classified as follows:

1. Physical properties
2. Mechanical properties
3. Thermal properties
4. Chemical properties
5. Optical properties
6. Acoustical properties
7. Physiochemical properties
8. Metallurgical properties

These properties of building materials are responsible for its quality and capacity and will be useful while deciding the use of the material in different applications. Physical and mechanical properties, such as strength, porosity, etc., are generally considered while selecting a material for a particular use. Chemical properties are considered when the material is used in aggressive environments. Some of these properties are discussed in Sections 1.4–1.7. Before using the materials, they should be tested and evaluated to ascertain whether the properties assumed in the design are actually available. For this purpose, samples are taken randomly (the number of samples tested is based on statistical analysis) and tested. The test methods, required equipment, and selection criteria are discussed in Chapter 25.

1.4 Physical Properties

The physical properties generally include the shape, size, density/bulk density, specific gravity, and porosity of the material.

Density (ρ) *Density* of a homogeneous material is defined as the mass per unit volume and expressed in kg/m^3. Density is also called the unit weight of substance.

$$\rho = \frac{m}{V} \tag{1.1}$$

where m = mass (kg) and V = volume (m^3).

Bulk density (ρ_b) This is defined as the mass per unit volume of material in its natural state (including pores and voids), and expressed in kg/m^3. It is calculated as:

$$\rho_b = \frac{m}{V_b} \tag{1.2}$$

where m = mass of specimen (kg) and V_b = volume of specimen in its natural state (m^3).

For most of the materials, bulk density will be less than their densities; however, for liquids and materials like glass and dense stone materials, density and bulk density will not differ much. Bulk density represents the degree of compactness of material. Bulk density of a material depends upon the packing of particles, particle shape and size, moisture content, and grading. For example, in coarse aggregates, a higher bulk density indicates fewer voids that are to be filled by sand and cement in concrete.

Properties like strength and heat conductivity are greatly affected by their bulk density. Density and bulk density of some building materials are compared in Table 1.2.

Table 1.2 Comparison of density and bulk density of some building materials

Material	Density (kg/m^3)	Bulk density (kg/m^3)
Brick	1920–2400	1600–1800
Granite	2600–2900	2500–2700
Wood (teak)	1500–1600	630–720
Steel	7750–8050	7850
Concrete	2400	2080–2400

Density index (ρ_0) This is the ratio of bulk density of a material to its density and is expressed as:

$$\rho_0 = \frac{\text{Bulk density}}{\text{density}} = \frac{\rho_b}{\rho} \tag{1.3}$$

It indicates the degree to which the volume of a material is filled with solid matter. For natural building materials, ρ_0 will be less than 1.0 because natural materials are not absolutely dense.

Specific weight (γ) This is also called *unit weigh.* This is the weight per unit volume of material in kN/m^3, and is expressed as:

$$\gamma = \rho g \tag{1.4}$$

where, ρ = density of the material (kg/m^3) and g = acceleration due to gravity (m/s^2).

Unit weight is used to determine the dead load of a structure in structural design. The unit weight of water is 9.81 kN/m^3 at 4°C.

Specific gravity or relative density (G_s) This is the ratio of the density of a substance to the density of a reference substance, and is a dimensionless quantity. The reference substance is usually specified as water at 4°C. At this temperature, the density of water will be the highest at 981 kg/m^3 (approximately taken as 1000 kg/m^3). Hence, the specific gravity may be expressed as:

$$G_s = \frac{\gamma_s}{\gamma_w} = \frac{\rho_s g}{\rho_w g} = \frac{\rho_s}{\rho_w} \tag{1.5}$$

True or absolute specific gravity (G_a) When both the permeable and impermeable voids are excluded to determine the true volume of solids, the specific gravity is called true or absolute specific gravity and can be expressed as:

$$G_a = \frac{(\rho_s)_a}{\rho_w} \tag{1.6}$$

The absolute specific gravity is not much used in practical applications.

Porosity (n) This is a measure of the void or empty spaces in a material, and is expressed as a ratio of the volume of voids (V_v) to the total volume (V), between 0 and 1, or as a percentage between 0 and 100%.

$$n = \frac{V_v}{V} \tag{1.7}$$

Porous materials absorb more moisture. Porosity influences many properties like thermal conductivity, strength, bulk density, and durability. Porosity reduces the resistance to freezing, thawing, and abrasion. Rocks usually have porosity of less than 20%. Dense materials, which have low porosity, have to be used when high mechanical strength is required, whereas walls of buildings are commonly built with materials like bricks, which have considerable porosity.

Void ratio (e) This is defined as the ratio of volume of voids (V_v) to the volume of solids (V_s) in the material.

$$e = \frac{V_v}{V_s} \tag{1.8}$$

The following relationship exists between void ratio and the porosity.

$$n = \frac{e}{1+e} \tag{1.9}$$

Durability This is the ability of a material to perform its required function over a lengthy period under normal conditions of use without excessive expenditure on maintenance or repair.

It has to be noted that the strength and durability are two separate aspects: neither guarantees the other. Durability may be affected by a number of parameters. For example, the durability of reinforced concrete is affected by the following (Subramanian, 2013):

1. Environment
2. Temperature or humidity gradients
3. Abrasion and chemical attack
4. Permeability of concrete to the ingress of water, oxygen, carbon dioxide, chloride, sulphate and other deleterious substances

5. Alkali-aggregate reaction (chemical attack within the concrete)
6. Chemical decomposition of hydrated cement
7. Corrosion of reinforcement
8. Concrete cover to the embedded steel
9. The quality and type of constituent materials
10. Cement content and water/cement ratio
11. Degree of compaction and curing of concrete
12. Shape and size of member
13. The presence of cracks

1.5 Mechanical Properties

The important mechanical properties of building materials are strength (compressive, tensile, bending, and impact), elasticity, plasticity, ductility, hardness, toughness, malleability, brittleness, fatigue, impact strength, abrasion resistance, creep resistance, and stiffness/flexibility.

Strength This is the ability of a material to resist stresses caused by the external forces (i.e., tension, compression, bending, torsion, and impact), without failure or fracture. It is of importance to note that materials such as stones and concrete have high compressive strength but low tensile, bending, and impact strengths (about 1/5 to 1/50th of compressive strength).

Ultimate strength This is the minimum guaranteed ultimate tensile strength at which a metal would fail, is obtained from a tensile test on a standard specimen, as described in Section 25.20.1 of Chapter 25. The stress–strain curve obtained from this test for various materials is shown in Fig. 1.1.

Compressive strength Compressive strength of concrete is found by testing standard cylinders (150 mm diameter and 300 mm long) or cubes (150 mm size) in compression testing machines, usually on the 28th day of casting them—cylinders have lower resistance than cubes of the same cross-sectional area. Properties such as modulus of elasticity, tensile strength, shear strength, and bond strength are usually expressed in terms of the compressive strength (see Subramanian, 2013, for more details).

Bending strength Tests of building strength on concrete are performed on small beams supported at their ends and subjected to one or two concentrated loads, which are gradually increased until failure takes place.

Hardness This is a measure of the resistance of the material to indentations and scratching. Several methods are available to determine the hardness of steel and other metals. In all these methods, an ‘indenter’ is forced on the surface of the specimen. On removal, the size of indentation is measured using a microscope. Based on the size of the indentation, the hardness of the specimen is determined.

Elasticity This is the ability of a material to regain its original shape and size after removal of the external load. Ideally, elastic materials obey the Hooke’s law, which states that, within elastic limits, stress is directly proportional to strain. The ratio of unit stress to unit deformation is termed as the *modulus of elasticity*. A large value of it represents a material with very small deformation.

Plasticity This is the ability of a material to change its shape under load without cracking and retain its shape after the load is removed. Some of the examples of plastic materials are steel, copper, and hot bitumen.

Ductility This is the ability of a material (such as a metal or reinforced concrete) to undergo plastic deformation without fracture and is required for materials to resist earthquake loads. The lack of ductility is often termed as *brittleness*. Cast iron, stone, and brick and plain concrete are comparatively brittle materials. *Malleability* is a similar property, and is the ability of material to deform under pressure (compressive stress), without rupture. If malleable, a material may be flattened by hammering or rolling. Copper is the most malleable building material.

Creep This is defined as the deformation of structure under sustained load. More materials will creep or flow to some extent and eventually fail under a sustained stress less than the short-time ultimate strength. For example, when load is applied on a concrete specimen, it shows an instantaneous deformation followed by a slow increase of deformation over a period of time. Creep and long-time strength, at atmospheric temperatures, must sometimes be taken into account while designing the members of nonferrous metals and while selecting allowable stresses for wood, plastics, and concrete.

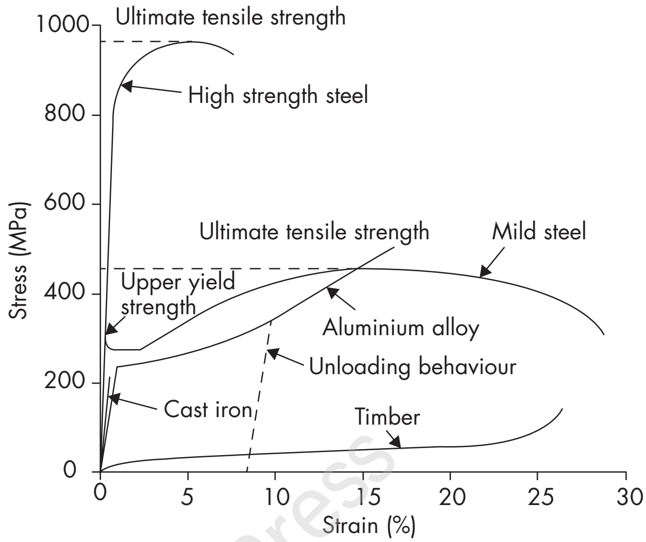


Fig. 1.1 Typical tensile stress–strain curves for some structural materials

Stiffness This is a measure of the resistance offered by a member to deformation ($k = F/d$), and has a unit of Newton per meter (N/m). Stiff materials have high modulus of elasticity, hence, will result in small deformations for a given load. Stiffness is the reverse of flexibility.

Fatigue strength This is the highest stress that a material can withstand for a given number of cycles without breaking. A material has a tendency to fail at a lesser stress level when subjected to repeated loading, such as those occurring in steel bridges and cranes. Welding details also affect the fatigue strength.

Impact strength This is the capacity of the material to withstand a suddenly applied load, and expressed in terms of energy. It is often measured with the Izod impact strength test or the Charpy impact test, both of which measure the impact energy required to fracture a sample. It thus indicates the *toughness* of the material, which is the ability of a material to absorb energy when impacted. Stainless steels and titanium alloys are tough, whereas glass and ceramics are very *fragile* (opposite of tough). Hardness and toughness have an inverse relationship. For a particular solid, the toughness decreases when hardness increases.

1.6 Thermal Properties

The important thermal properties are thermal conductivity, thermal capacity, and fire resistance.

Thermal conductivity This is also called heat conductivity. This is the ability of a material to conduct heat, and is measured in Watts per metre-Kelvin [W/(m·K)]. It is influenced by the nature of material, its structure, porosity, character of pores, moisture content, and mean temperature at which heat exchange takes place. Higher the thermal conductivity, faster will be the heat transfer—it is usually measured by the *U*-value. Materials with large size pores have high heat conductivity because the air inside the pores enhances heat transfer. Moist materials have higher heat conductivity than dry materials. The lower the *U*-value of a material, the better will be its ability to resist heat conduction. This property is important while selecting insulating materials for walls of heated buildings, which should have negligible thermal conductivity. The reciprocal of thermal conductivity is called thermal resistivity. Designated as *R* (*R*-value), thermal resistance indicates how effective any material is as an insulator. A higher *R*-value indicates a better insulating performance. It has to be noted that $U = 1/R$ and $R = 1/U$.

Thermal capacity This may be defined as the ability of a material to store heat per unit volume, and is measured by the product of density and specific heat, with units of Joule per Kelvin (J/K). When a material shows greater thermal capacity, it shows that it can store more heat in a given volume for every degree of increase in temperature. Specific heat is a measure of the amount of heat required to raise the temperature of given mass of material by 1° [measured in J/(kg·K)]. It takes less energy input to raise the temperature of a low specific heat material than that of a high specific heat material. For example, it requires one calorie of heat energy to increase the temperature of water by 1°C. As water has a high heat capacity, it is sometimes used as thermal mass in buildings. Generally, materials with higher thermal capacity can reduce heat flow from the outside to the inside of buildings by storing the heat within the material. Thus, by using a material of adequate thermal capacity, the heat (produced by the Sun) entering a wall during the daytime could be stored within the wall itself for several hours, and conveniently made to flow out during the cool night hours. Table 1.3 shows the typical thermal properties of some building materials.

Table 1.3 Thermal properties of some building materials

Material	Modulus of elasticity, E (GPa)	Poisson's ratio	Coefficient of thermal expansion, α ($\times 10^{-6}$/°C)	Thermal conductivity, λ_a (W/mK)	Specific heat capacity, c_a (J/kg · K)
Aluminium alloys	72	0.33	23.5	56–205	900
Concrete (M30)	27.4	0.15–0.25	11	0.8–1.40	840–880
Copper	118	0.33	17.6	385	386
Glass	70	0.24	9.0	0.8–1.0	840
Iron (grey cast)	90	0.26	12.1	79.5	448
Structural steel	200–207	0.30	11–12	54	425
Stainless steel	193	0.30	16	14.6	450

Fire resistance This is the ability of a material to resist the action of high temperature without any appreciable deformation and loss of strength. While a fire-resistant material is one that is designed to resist burning and withstand heat, fire-retardant materials are designed to burn slowly. Some examples of fire-retardant materials are: fire-retardant treated wood, brick, concrete, mineral wool, gypsum boards, and intumescent paint. Steel suffers considerable deformation and loss of strength under the action of high temperature. *Refractoriness* denotes the ability of a material to withstand the prolonged action of high temperature of about 1580°C without melting or losing shape.

1.7 Other Properties

Chemical properties include corrosion resistance, chemical composition, acidity, or alkalinity. Optical properties include the colour, light reflection, and light transmission. Acoustical properties comprise sound absorption, transmission, and reflection. Physiochemical properties include hygroscopicity and water absorption. Useful in construction, metallurgical properties are metal fusibility, weldability, hardening, and tempering. Some of these properties are briefly described here.

Chemical resistance This is the capacity of any material to resist the deteriorating action of substance such as harmful acids, alkalis, seawater, and gases. For example, natural stones such as limestone, marble, and dolomite are affected even by weak acids, wood has low resistance to acids and alkalis, and bitumen disintegrates due to alkaline liquids.

Hygroscopicity It is the property of a material to absorb water vapour from air, resulting in volume change (shrinkage or swelling). It is influenced by air temperature and relative humidity, and types, number and size of pores. Wood, concrete, brick, plaster, and several engineering polymers are hygroscopic, including nylon, polycarbonate, cellulose, and poly (methyl methacrylate). Hydrophobic materials are the opposites of hygroscopic materials and repel water; their typical examples include glass, metals, and plastics.

Water absorption This denotes the ability of the material to absorb and retain water. It is expressed as percentage in weight or of the volume of dry material:

$$W_w = \frac{M_1 - M}{M} \times 100 \tag{1.10a}$$

$$W_v = \frac{M_1 - M}{V} \times 100 \tag{1.10b}$$

where M_1 = mass of saturated material (g), M = mass of dry material (g), and V = volume of material including the pores (mm^3). Water absorption by volume is always less than 100%, whereas that by the weight of porous material may exceed 100%.

The properties of building materials can change considerably when saturated. The water resistance of a material is expressed by the coefficient of softening, which is the ratio of compressive strength in water-saturated condition to that in dry condition. For example, the coefficient of softening for clay is zero, as it soaks readily in water. However, for materials like glass and metals, which are not affected by water, it is taken as one. In locations exposed to moisture (like roofing or foundations), materials with the coefficient of softening less than 0.8 should not be used.

Corrosion resistance Formation of rust (iron oxide) in metals, when they are subjected to atmosphere, is called *corrosion*, and is a recurring problem in steel structures and steel reinforcements. To mitigate corrosion in steel structures, several methods are applied such as treatment of the environment to render it non-corrosive, coating/painting systems (surface preparation, such as sand blasting, plays an important role in the durability), galvanizing, thermal (metal) spraying, cathodic protection, and use of corrosion-resistant structural steels (e.g., weathering steel and stainless steel). For reinforcements in concrete, cathodic protection, corrosion-inhibiting admixtures, or the use of thermo-mechanically treated corrosion-resistant steel bars (TMT-CRS bars), fusion-bonded epoxy-coated rebars, galvanized rebars, stainless steel rebars, fibre-reinforced polymer bars, and basalt bars may be used.

Metallurgical, acoustical, and optical properties are discussed in detail in the relevant chapters. Properties of some materials used in building construction are given in Table 1.4.

Table 1.4 Properties of some materials used in building construction

Material	Density, kg/m^3	Stiffness (E), GPa	Poisson's ratio	Strength[1], MPa	Fracture toughness, $MN/m^{3/2}$
Clay bricks	1480–2400	14–18	–	5–110 (compression)	0.6
Timber[2]	170–980 (dry)	3–21	0.25–0.49	10–80 (tension) 15–90 (compression)	7–13
Structural steel	7850	195–205	0.3	235–960	50–100
Cast iron	6900–7800	170	0.26	220–1000	20–50
High strength steel	7850	205	0.3	500–1900	50–125
Aluminium alloys	2700	70	0.33	80–505	25–35

(Contd)

Table 1.4 (*Contd*)

Material	Density, kg/m³	Stiffness (E), GPa	Poisson's ratio	Strength[1], MPa	Fracture toughness, MN/m$^{3/2}$
Concrete (M20–M100)	1800–2500	22–50	0.15–0.25	2–12 (tension) 20–100 (compression)	0.8–1.2
Glass	2500	70	0.24	40–70[3]	0.8
Rubber	830–910	0.1–1	0.5	15–30	–
Polyethylene (high-density)	960	1.1	0.4–0.45	20–30	2.5
Glass fibre composite	1400–2000	6–50	–	40–1250[4]	7–23
Carbon fibre composite	1500–1600	70–200	–	600–2000[4]	6–80
Epoxy resin	1100–1400	2.6–3	–	30–100	0.5–1

1. In tension unless stated, yield or proof strength for metals, ultimate strength for other materials
2. Based on tests on small specimens, loaded parallel to grain
3. Modulus of rupture
4. In the longitudinal direction

1.8 Sustainable Materials

The definition of sustainability, suggested by the then Prime Minister of Norway, Gro Bruntland, in 1987, is *meeting the needs of the present without compromising the ability of future generations to meet their needs*. Sustainability is thus is a realization that today's population is merely borrowing resources and environmental conditions from future generations. The greatest threats to the sustainable development on earth are as follows:

1. Population growth and urbanization
2. Energy use and global warming
3. Excessive waste generation and the subsequent pollution of soil, air, and water
4. Transportation in cities
5. Limited supply of resources

Many of them are interrelated and discussed in the work of Subramanian (2016).

The materials we use for construction affect the environment. Their production and transportation deplete natural resources, consume considerable energy, and pollute the environment. Several building materials, and the energy needed to produce them, are becoming scarce. If the present trends continue, some of the common raw materials and energy sources (like oil and natural gas) will be exhausted within about the next century. As per www.msci.org, the grades of mined copper and iron ore are declining and the natural reserves of lead, molybdenum, chromium, nickel, copper, zinc, tin, and radium are depleting. There is an urgent need to use alternate materials—for example, using M-sand in the place of natural sand—to preserve natural resources.

A reclassification of all building materials and products based on sustainability, and to meet criteria pertaining to personal health and health of environment, is necessary. Traditional materials like clay, lime, and stone are still abound, and timber (especially softwoods) can be replenished by properly managed forestation. In addition, these materials can be easily reused or recycled; they produce little or no pollution and are reabsorbed into the natural cycles of environment, when they are discarded. Recycling materials like steel and aluminium also preserves the natural resources and saves considerable energy.

1.8.1 Healthy Materials

In order to satisfy the criteria of being healthy to human beings, Pearson (1998) has suggested the following:

1. The materials should be clean and should not contain pollutants or toxins, emit no biologically harmful vapours, dust, particles or be odours either during manufacture or usage. They should also be resistant to bacteria, viruses, moulds, and other harmful microorganisms.
2. They should not be radioactive and must not emit any harmful levels of radiation.
3. They should not be electromagnetic and should not allow the conduction or built-up of static electricity or emit harmful electric fields of any type.
4. They should have good sound-reduction properties and should not themselves produce any noise.

1.8.2 Ecological Materials

For materials to be environment friendly, they should satisfy the following criteria (Pearson, 1998):

1. They should be renewable and abundant, and coming from diverse natural sources. Their production should have a low impact on the environment.
2. They should be non-polluting and should not emit harmful vapours, particles, or toxins into the environment, either during manufacture or usage.
3. They should be energy efficient, and use low energy in production, transport and should generally be available locally (see also Section 1.8).
4. They should be durable and easy to maintain and repair—additionally, it is better if they are tried and tested over several generations, as in the case of natural materials.
5. They should produce less waste during production and be capable of being reused and recycled, so that the vast amount of energy spent on processing raw materials could be saved.

Fig 1.2 Green Seal and EU Ecolabel

Many countries now have a system of labelling environment-friendly products. In the USA, since 1989, a non-profit organization called Green Seal identifies products and services that have less impact on our health and environment and awards a 'Green Seal' as shown in Fig. 1.2 (www.greenseal.org). Similar 28 international eco-labelling programmes exist, including Germany's Blue Angel, the European Union's Ecolabel, and the Nordic Swan, and all are members of the Global Eco-labelling Network (GEN).

1.9 Green Building Rating Systems

To promote the design and construction practices that reduce the negative environmental impacts of buildings and improve occupant health and well-being, the US Green Building Council (USGBC), a Washington D.C.-based non-profit coalition of building industry leaders, developed the LEED® green building rating system in 1993. In the USA and in a number of other countries around the world, LEED® certification is the recognized standard for measuring building sustainability. Similar assessment systems are available in other countries also. Some of these are

1. the British green building rating system developed by Building Research Establishment (BRE) in 1992 called the Building Research Establishment Environmental Assessment Method (BREEAM),
2. Griha in India (info@grihaindia.org),

3. the comprehensive Assessment System for Building Environmental Efficiency (CASBEE) of Japan,
4. Green Star of Australia, and
5. Green Globes, which is a web-based, interactive learning tool developed from BREEAM to the needs of US commercial buildings.

All these systems are designed to encourage the construction of green buildings, which will minimize the disruption of local ecosystems; ensure the efficient use of water, energy, and other natural resources; and ensure a healthy indoor environment. However, they differ in terminology, structure, assessment of performance, points assigned to different performance criteria, and documentation required for the certification. These systems, while voluntary in nature, continue to gain recognition. It is interesting to note that adoption of these systems also results in economic incentives, as owners and renters are increasingly demanding facilities with high green building ratings.

1.9.1 LEED-NC

From 1994 to 2009, LEED® grew from one standard for new construction to a comprehensive system of six interrelated standards covering all aspects of the development and construction process: LEED-NC, for New Construction; LEED-EB, for Existing Buildings; LEED-CI, for Commercial Interiors; LEED-H, for Homes; LEED-CS, for Core and Shell projects; and LEED-ND for Neighbourhood Development (Kibert, 2005). LEED-NC, which was originally developed for office buildings but is now being used for all types of buildings except single family homes, is briefly discussed here.

LEED-NC 2009 is structured with eight prerequisites and a maximum of 110 points. These points are divided into the following seven major categories:

1. Energy and atmosphere (35 maximum points)
2. Indoor environmental quality (15 points)
3. Sustainable sites (26 points)
4. Materials and resources (14 points)
5. Water efficiency (10 points)
6. Innovation and design process (6 points)
7. Regional priority (4 points)

A building is LEED® certified if it obtains at least 40–49 points. Silver, gold, and platinum levels are awarded for 50–59, 60–79, and greater than 80 points, respectively (see Table 1.5). Note that LEED is continuously evolving and improving. The recent update to the rating system LEED-NC 4.0 was launched in 2014. LEED-NC 4.0 has the following six main credit categories (Subramanian, 2017):

1. Location & Transportation (LT)
2. Sustainable Sites (SS)
3. Water Efficiency (WE)
4. Energy & Atmosphere (EA)
5. Materials & Resources (MR)
6. Indoor Environmental Quality (EQ)
7. Innovation and Design Process
8. Regional Priority

Table 1.5 Overview of LEED-V4 categories and credits

Integrative Process: 1 Possible Point	
Location and Transportation: 16 Possible Points	Required
Credit 1 Sensitive Land Protection	1
Credit 2 High Priority Site	2
Credit 3 Surrounding Density and Diverse Uses	5
Credit 4 Access to Quality Transit	5
Credit 5 Bicycle Facilities	1
Credit 6 Reduced Parking Footprint	1
Credit 7 Green Vehicles	1

(*Contd*)

Table 1.5 (*Contd*)

Sustainable Sites: 10 Possible Points	
Prerequisite 1 Construction Activity: Pollution Prevention	Required
Credit 1 Site Assessment	1
Credit 2 Site Development - Protect or Restore Habitat	2
Credit 3 Open Space	1
Credit 4 Rainwater Management	3
Credit 5 Heat Island Reduction	2
Credit 6 Light Pollution Reduction	1
Water Efficiency: 11 Possible Points	
Prerequisite 1 Outdoor Water Use Reduction	Required
Prerequisite 2 Indoor Water Use Reduction	Required
Prerequisite 3 Building-Level Water Metering	Required
Credit 1 Outdoor Water Use Reduction	2
Credit 2 Indoor Water Use Reduction	6
Credit 3 Cooling Tower Water Use	2
Credit 4 Water Metering	1
Energy and Atmosphere: 33 Possible Points	
Prerequisite 1 Fundamental Commissioning and Verification	Required
Prerequisite 2 Minimum Energy Performance	Required
Prerequisite 3 Building-level Energy Metering	Required
Prerequisite 4 Fundamental Refrigerant Management	Required
Credit 1 Enhanced Commissioning	6
Credit 2 Optimize Energy Performance	18
Credit 3 Advanced Energy Metering	1
Credit 4 Demand Response	2
Credit 5 Renewable Energy Production	3
Credit 6 Enhanced Refrigerant Management	1
Credit 6 Green Power and Carbon Offsets	2
Materials and Resources: 13 Possible Points	
Prerequisite 1 Storage & Collection of Recyclables	Required
Prerequisite 2 Construction & Demolition Waste Management Planning	Required
Credit 1 Building Life-Cycle Impact Reduction	5
Credit 2 Building Product Disclosure & Optimization - Environmental Product Declarations	2
Credit 3 Building Product Disclosure and Optimization - Sourcing of Raw Materials	2
Credit 4 Building Product Disclosure & Optimization - Material Ingredients	2
Credit 5 Construction & Demolition Waste Management	2
Indoor Environmental Quality: 15 Possible Points	
Prerequisite 1 Minimum IAQ Performance	Required
Prerequisite 2 Environmental Tobacco Smoke (ETS) Control	Required

(*Contd*)

Table 1.5 (*Contd*)

Credit 1 Enhanced Indoor Air Quality Strategies	2
Credit 2 Low-emitting Materials	3
Credit 3 Construction Indoor Air Quality Management Plan	1
Credit 4 Indoor Air Quality Assessment	2
Credit 5 Thermal Comfort	1
Credit 6 Interior Lighting	2
Credit 7 Daylight	3
Credit 8 Quality Views	1
Credit 9 Acoustic Performance	1
Innovation and Design Process: 6 Possible Points	
Credit 1 Innovation in Design	5
Credit 2 LEED® Accredited Professional	1
Regional Priority: 4 Possible Points	
Credit 1 Regional Priority	1–4
Project Total: 100 base points; 6 possible Innovation in Design and 4 Regional Priority points	
Certified: 40–49 Points; *Silver:* 50–59 Points; *Gold:* 60–79 Points; *Platinum:* > 80 Points	

(*Source*: www.usgbc.org)

Figure 1.3 shows the views of a LEED Platinum certified building in Rockville, MD, USA.

Fig. 1.3 Views of the LEED Platinum certified building in Rockville, MD, USA

A part of the Confederation of Indian Industry (CII), the Indian Green Building Council's (IGBC) Green Building rating systems were launched in 2003. CII–Sohrabji Godrej Green Business Centre building in Hyderabad was the first to receive the prestigious Platinum rated green building rating in India (see Fig. 1.4). Since then, the rating systems have been successfully applied to more than 4025 buildings, with a foot-print of 4.50 billion square feet. It is given under the following 16 different categories (https://igbc.in):

1. IGBC Green New Buildings
2. IGBC Existing Buildings
3. IGBC Green Homes
4. IGBC Green Residential Societies
5. IGBC Green Healthcare
6. IGBC Green Schools
7. IGBC Green Factory Buildings
8. IGBC Green Data Centres
9. IGBC Green Campus
10. IGBC Green Villages

11. IGBC Green Townships
12. IGBC Green Cities
13. IGBC Green SEZ
14. IGBC Green Landscapes
15. IGBC Green Mass Rapid Transit System
16. IGBC Green Existing Mass Rapid Transit System

The task of selecting building materials and products, for a high-performance green building, is the most difficult and challenging task for any design team. Several tools are available for this process and one best tool is the *life-cycle assessment* (LCA). LCA provides information about the resources, emissions, and other impacts resulting from the life cycle of material use. Hence, one must consider the impact of the material from extraction to disposal. One such LCA programme is Building for Environmental and Economic Sustainability software (BEES-NIST). Ideally, the material cycle should be a closed looped and waste free. Thus, the following rules apply while selecting the materials for green construction:

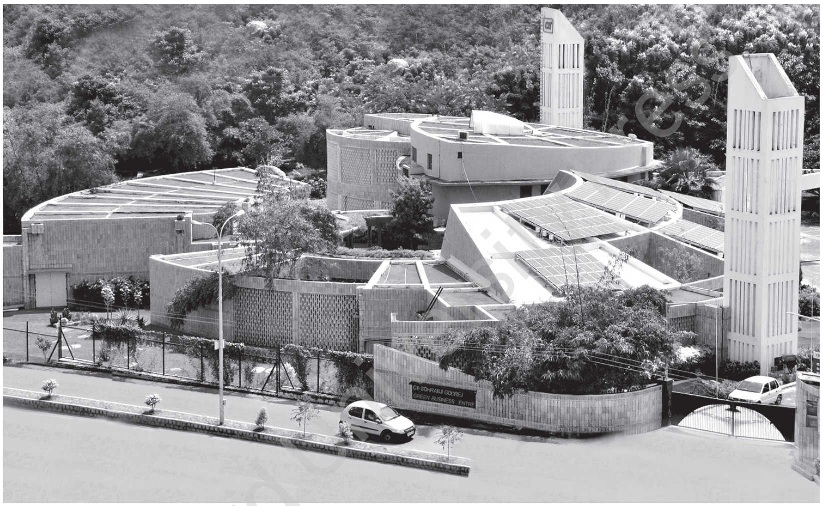


Fig. 1.4 Platinum-rated CII–Sohrabji Godrej Green Business Centre, Hyderabad (*Source*: CII–IGBC)

1. They should consume least energy to manufacture.
2. They should not involve long-distance transportation (for the raw materials as well as finished product).
3. The natural resources and raw materials do not affect the environment.
4. They must be easy to recycle and safe to dispose in landfills.
5. Materials should be harmless in production and use.
6. Materials dissipated from recycling must be harmless.
7. They should have long life and durability.
8. Buildings must be de-constructible.
9. Building components must be easy to disassemble.

It may be difficult to identify a material that obeys all the aforementioned rules. Especially, the last rule of disassembly has not been considered in traditional building materials, except prefabricated steel structures. Disassembly also discourages the use of composite materials. It has been shown that by using concrete, one can earn 37–62 LEED® points (see Table 1.6).

Table 1.6 Summary of possible points to increase LEED ratings of buildings

Category	Total number of points	Points earned using concrete
Sustainable sites	26	12
Water efficiency	10	10
Energy and atmosphere	35	1–19
Materials and resources	14	9
Indoor environmental quality	15	2
Innovation credits	6	2–6
Regional priority	4	1–4
Total	**110**	**37–62**

(*Source*: Adapted from RMC-Guide, 2010)

Green buildings adopt various strategies for water management: using low flow or ultra-low flow plumbing fixtures, electronic controls and fixtures, substitution of alternative water sources (rainwater, reclaimed water, and grey water) for potable water, rainwater harvesting, xeriscaping, and use of other technologies and approaches that result in the reduction of potable water consumption (Kibert, 2005).

1.10 Embodied Energy and Energy Efficiency

Energy from fossil fuels is becoming scarce and the amount used in the production and transportation is high. As mentioned earlier, the best materials are those which are energy efficient (using low energy in production, transport, and use), need minimum processing and are available locally. *Embodied energy* refers to the total energy consumed in the acquisition and processing of materials, including manufacturing, transportation, and final installation. Products with greater embodied energy usually have higher environmental impact due to the greenhouse gas emissions associated with their energy consumption. However, a true indicator of environmental impact will be obtained, only when the embodied energy is divided by the number of times the product is used or recycled. Thus, aluminium may have low embodied energy per time in use, as it is very durable. Similarly, recycled aluminium and steel have less than 10–20% of embodied energy, compared to original steel or aluminium made from ores.

Typical embodied energy of some common building materials is shown in Table 1.7. From this, it is seen that the embodied energy of locally grown and reclaimed timber is low (Haseltine, 1975). Clay used as adobe or unbaked brick is another example of material requiring low energy. In contrast, synthetic and processed products such as plastics, aluminium, steel, glass, and oven-fired bricks and clay tiles, have higher embodied energy (Pearson, 1998). In addition, the materials used should be good energy conservers with high insulation value that should retain heat in winter and keep the building cool in summer.

Table 1.7 Embodied energy of common building materials (http://www.yourhome.gov.au)

Material	Embodied energy (MJ/kg)
Very high energy	
Aluminium	227.0
Carpet (synthetic)	148.0
Polystyrene insulation	117.0
Synthetic rubber	110.0

(*Contd*)

Table 1.7 (*Contd*)

Material	Embodied energy (MJ/kg)
Very high energy	
Linoleum	116.0
Stainless steel	100+
Plastics (general)	90.0
PVC (polyvinyl chloride)	80.0
Copper	70–100
Acrylic paint	61.5
Zinc	51.0
High energy	
Steel	32.0
Galvanized steel	38.0
Hardboard	24.2
Glass	12.7
Glue-laminated timber	11.0
Plywood	10.4
Cement	5.6
Steel (recycled)	8.9
Aluminium (recycled)	8.1
Particleboard	8.0
Medium energy	
Autoclaved aerated concrete (AAC)	3.6
Kiln dried sawn softwood	3.4
Lime	3-5
Gypsum plaster	2.9
Clay bricks and tiles	2.5
Lumber	2.5
Kiln dried sawn hardwood	2.0
Precast steam-cured concrete	2.0
Concrete (30 MPa)	1.3
Concrete blocks	1.5
Low energy	
Stabilized earth	0.7
Fly ash, rice husk ash (RHA), volcanic ash	<0.5
Sand, aggregate	0.1

These figures should be used with caution because:

1. The actual embodied energy of a material manufactured and used in one location may be very different from the same material transported by road to another location.
2. Though materials like stainless steel have high embodied energy value, they are recycled many times, reducing their life cycle impact.

As discussed in Section 1.8, it is not enough to consider the energy requirement of material during the production stage; *a life-cycle assessment approach* is necessary to determine its environmental impact. Thus, all stages in the life of a product should be analysed, that is, raw material acquisition, manufacture, transportation, installation, use, recycling, and waste management. There is also a *Life-cycle Cost Analysis* (LCCA), which deals with the cost impact of a product or material, but does not deal with the environmental impact. Both have important roles to play in sustainability assessment of a material/product.

1.11 Comparison of some Major Building Materials

Though the various building materials are covered individually in the subsequent chapters, the four major building materials, which are used extensively, are briefly discussed here.

Masonry Masonry may be defined as the work done by masons using individual units, which are often laid in and bound together by mortar; the term masonry can also refer to the units themselves. The common materials of masonry construction are brick, stone, concrete block, glass block, and cob (made of soil, water, straw, and sometimes with lime).

Some important features include:

1. Different types of bricks and concrete blocks exist (see Chapter 3). The process of manufacturing of bricks from clay involves preparation of clay, moulding, and then drying and burning of bricks in kilns, at temperature of about 1100°C, to give them their final hardness and appearance.
2. The vertical shaft brick kiln (VSBK) technology, which consumes less fuel and energy and emits lower suspended particulate matter (SPM), as compared with Bull's Trench Kiln (BTK), is suitable for medium sized kilns. VSBK technology was introduced during 1996; at present, there are more than 40 operational VSBKs in India (www.teriin.org).
3. Masonry is mainly used for load bearing walls and walls taking in-plane or transverse loads. It is durable, fire resistant, and aesthetically pleasing. It can be used for buildings with moderate heights, that is, up to 20 storeys. (Unfortunately, the bricks produced in India do not have uniform quality and the bricks produced in south India have low strength. Hence, buildings with load-bearing brick masonry are built only up to three to four floors).

Reinforced and prestressed concrete Concrete is a composite material made of two or more sizes of aggregates (generally with gravel and sand), with a binding medium of Portland cement and water. After mixing, it is placed into moulds (called formwork) with proper compaction, and after proper curing, the cement hydrates and eventually hardens into a stone-like material. The following are some of its features:

1. As concrete is weak in tension, it is usually strengthened with steel bars (known as reinforcement or rebars). This strengthened concrete is called as *reinforced concrete* or RCC.
2. Currently, concrete is the predominant building material in India and several other countries. Reinforced concrete framed or shear wall construction, if properly poured and cured, is very durable and fire resistant.
3. Since reinforced concrete can be cast to any required shape, it is used for a variety of constructions including tall buildings and floors and foundation of all types of buildings.
4. Substitution of cement by several wastes such as fly ash, ground-granulated blast furnace slag, silica fume, reactive rice-husk ash, etc., can lead to significant reductions in the amount of cement needed to make concrete, hence reduces emissions of CO_2 and consumption of energy and raw materials, and results in reduced landfill/disposal burdens.

5. Recent advancements such as self-compacting concrete (SCC), though having more binder content, reduce manpower, as SCC is easier to place even in congested structural members, has reduced noise level, and is environment friendly.

Prestressed concrete is a concrete in which high strength reinforcing steel bars are stretched and anchored to compress it, thus increasing its resistance to stress. It is used for floor construction of large span structures and in buildings, bridges, and towers.

Some of the shortcomings are as follows:

1. In India, though concrete is used extensively in all types of construction, except by a small number of big companies, quality control is not exercised during mixing of concrete.
2. Moreover, the curing of concrete is mostly ignored or not done properly for the code prescribed duration.
3. In addition, the steel reinforcements (especially the smaller diameter rods) available in the market are produced by re-rollers and do not possess the required ductility and strength.
4. Since concrete can be mixed and poured to any required shape, it is misused by several small contractors, who do not give much importance to design or detailing.

The aforementioned factors have led to the deterioration of several concrete structures all over the country and resulted in the failure of several concrete structures in the recent earthquakes. Since prestressed concrete is used in major constructions, as well as used by major contracting companies, the quality of prestressed concrete in India is up to the standards.

Structural steel Most metals used for construction purposes are alloys. For example, structural steel is a primary alloy of iron and carbon (0.10–0.25%). The properties of steel vary widely, depending on its alloying elements. Some of its features are as follows:

1. Steel is made using the basic oxygen steel making (BOS) process or the electric arc method.
2. Raw materials such as iron ore, scrap steel, coke, limestone, and dolomite are charged in a blast furnace, and heated up to 1600°C, and oxygen of greater than 99.5% purity is blown into the mix.
3. The liquid steel is solidified into large blocks called ingots and then rolled into semi-finished products and then into plates, structural shapes, bars, etc.
4. The main advantages of steel are strength, speed of erection, prefabrication, and demountability.
5. They are used in load-bearing frames in buildings, and as members in trusses, bridges, and space frames. Steel, however, requires fire and corrosion protection.
6. Steel is also used in conjunction with concrete in composite constructions and in combined frame and shear-wall constructions.
7. In many cases, the fabrication of steel members is done in the workshop and the members are then transported to the site and assembled.
8. Tolerances specified for steel fabrication and erections are small compared to reinforced concrete structures.
9. Different steel sections are joined by welding or bolting. Welding or tightening of high strength friction grip bolts requires proper training.
10. Due to these factors, steel structures are often handled by trained persons and assembled with proper care, resulting in structures with better quality.
11. Compared with concrete, steel offers much better compressive and tensile strength, and enables lighter constructions. Unlike masonry or reinforced concrete, steel can be easily recycled.

Wood This imparts natural, human warmth that steel and concrete lack. Due to this, wood has long been used for housing (up to three floors) and for historical structures in western countries such as the

USA, the UK, Germany, France, and Japan where there is cold climate. However, with the development of wood composites—thin, pressed sheets—combined with joints and steel frames have changed the scene. Glued laminated wood has been used in a number of large span structures. Prominent wood composite structures are Tacoma Dome and North Michigan University stadium in the United States and Odate Jukai Dome in Japan. All these domes have diameters in the range of 160–180 m. Since wood is a natural product, it is environment friendly, though the resins used in glued laminated wood many contain harmful chemicals. However, not all woods can be used for constructions and quality wood is in short supply in India and hence wood is used in India only for doors and windows. (Nowadays, even they are replaced with aluminium, steel, ferrocement, or plastic doors and windows.)

Important structural properties of steel, concrete, and wood are compared in Table 1.8.

Table 1.8 Important properties of steel, concrete, and wood

Item	Mild steel	Concrete* M20 grade	Wood
Unit mass, kg/m^3	7850 (100)	2400 (31)#	290–900 (4–11)
Maximum stress in MPa			
Compression	250 (100)	20 (8)	5.2–23+ (2–9)
Tension	250 (100)	3.13 (1)	2.5–13.8 (1–5)
Shear	144 (100)	2.8 (1.9)	0.6–2.6 (0.4–1.8)
Young's modulus, MPa	2×10^5 (100)	22,360 (11)	4600–18,000 (2–9)
Coefficient of linear expansion $\times 10^{-6}$/°C	12	10 to 14	4.5
Poisson's ratio	0.3	0.20	0.20

* Characteristic compressive strength of 150 mm cubes at 28 days
+ Parallel to grain
# Relative value when compared to steel

1.12 Alternative Building Materials

A number of industrial, agricultural, and mining wastes are used in the production of alternative building materials (Venkatarama Reddy, 2004). The industrial wastes include: fly ash, phosphogypsum, blast furnace slag, silica fume, alumina red mud, slate and marble waste, glass powder, paper-mill pulp, sludge, and discarded tires. Fly ash is used in the production of Portland-pozzolana cement, lime-fly ash bricks, fly ash-lime-gypsum (Fal-G) concrete, fly ash-lime cellular concrete, and sintered fly ash lightweight aggregate. However, the response by the Indian building community to the use of fly ash is poor, as only 5% of generated fly ash is used in India. It has to be noted that not all the available fly ash is suitable for use in concrete and other products.

Calcium silicate bricks are manufactured from a mixture of sand and/or siliceous waste and a small portion of lime, which is mechanically pressed and autoclaved. These bricks can also solve the problem of waste disposal.

The agricultural wastes that could be used in building products such as roofing units, thermal insulating materials, and walling boards are bagasse, jute stalks, groundnut hulls, hemp, flax, reed, natural wool, expanded cork, and straw bales. Rice husk ash, saw dust, cork granules, and coconut kernel are used as substitutes in concrete.

In addition, several substitutes for teak, rosewood, and white cedar, such as secondary species of timber, poly-vinyl chloride (PVC), mild steel and galvanized steel, aluminium, precast concrete, ferrocement, particle boards, fibre boards, fibre glass, and glass reinforced gypsum composite boards, have been tried. The use of some of these waste products and other substitutes as building materials are discussed in the respective chapters (3, 5–7, 9, and 11).

1.13 Building Codes and By-Laws

A building code contains a set of rules that knowledgeable people recommend for others to follow. It is not a law, but can be adopted into law. National building codes contain administrative regulations, development control rules, and general building requirements; fire safety requirements, stipulation regarding materials, structural design and construction, building and plumbing services, landscape development, guidelines for sustainability, asset and facility management, and other aspects of buildings to ensure safety and health for people living in or around buildings (see SP 7-2016, SP 21:2005, SP 41-1987, IS 3362:1977, IS 3792:1978, and IS 6060:1971). They are mandatory in nature and serve to protect buildings against fire, earthquake, noise, structural failures, and other hazards (IS 1641:1988, IS 1950:1962, and IS 2526:1963). Building by-laws usually contain provisions for parking, peripheral open spaces including set-backs, disaster management, and fire safety. They may also contain green building and sustainability provisions, rainwater harvesting, wastewater reuse, and recycle and installation of solar roof-top photovoltaic (PV) norms. Recent by-laws also have guidelines for mitigating electromagnetic radiations (Model Building Bye-Laws, 2016).

In addition, the Energy Conservation Building Code (ECBC) was launched by the Ministry of Power, Government of India in May 2007, as a first step towards promoting energy efficiency in the building sector (ECBC, 2006). The ECBC provides design norms for:

1. Building envelope, including thermal performance requirements for walls, roofs, and windows;
2. Lighting system, including day lighting, and lamps and luminary performance requirements;
3. HVAC system, including energy performance of chillers and air distribution systems;
4. Electrical system; and
5. Water heating and pumping systems, including requirements for solar hot-water systems.

SUMMARY

- The major requirement of any building is to shelter its occupants from the environment and offer a pleasant, comfortable, and healthy indoor environment.
- Building materials are categorized based on the source of availability as natural (e.g., clay, sand, stone, lime, and wood logs) and manufactured (e.g., concrete, metals, glass, ceramics, and plastics).
- The different properties which are of concern are physical, mechanical, thermal, chemical, optical, acoustical, physiochemical, and metallurgical.
- The physical properties include the shape, size, density/bulk density, specific gravity, and porosity of the material.
- The important mechanical properties are strength, elasticity, plasticity, ductility, hardness, toughness, malleability, brittleness, fatigue, impact strength, abrasion resistance, creep resistance, and stiffness/flexibility.
- Production and transportation of building materials deplete natural resources, consume considerable energy, and pollute the environment. Several materials are also becoming scarce.
- In order to have sustainable development, it is important to preserve these materials, by reducing their use (by using alternative materials), recycling them after use, or reusing them. In addition, the materials used should be environment friendly and not affect the health of the occupants. A number of industrial, agricultural, and mining wastes are now used to provide alternative building materials.
- Several rating systems have been developed, such as LEED, BREEAM, Green Globes, and CASBEE. For a building to be LEED® certified, it should obtain at least 40–49 points.
- Embodied energy is the total energy consumed in the mining, manufacturing, transportation, and final installation. Products with greater embodied energy have higher environmental impact.
- A building code, like the NBC of India, contains a set of rules that should be followed to have better functioning.

EXERCISES

Multiple-choice Questions

1. Density of concrete is about
   (a) 2000 kg/m^3 (c) 3200 kg/m^3
   (b) 2400 kg/m^3 (d) 7000 kg/m^3
2. The modulus of elasticity of steel is about
   (a) 150 GPa (c) 220 GPa
   (b) 200 GPa (d) 240 GPa
3. Match the following:
   (a) BREEAM (i) The USA
   (b) LEED (ii) India
   (c) CASBEE (iii) Australia
   (d) Green Star (iv) Japan
   (e) IGBC (v) The UK
4. As per LEED-NC, the combination of energy and atmosphere has the following possible points:
   (a) 26 (c) 35
   (b) 10 (d) 5
5. As per LEED-NC, sustainable sites has the following possible points:
   (a) 26 (c) 35
   (b) 10 (d) 5
6. To get a Gold rating in LEED-NC, one has to obtain the following points:
   (a) 40–49 (c) 60–79
   (b) 50–59 (d) 80–100
7. To get a Silver rating in LEED-NC, one has to obtain the following points:
   (a) 40–49 (c) 60–79
   (b) 50–59 (d) 80–100
8. Which of the following materials has the maximum value of embodied energy?
   (a) Steel (c) Aluminium
   (b) Copper (d) Zinc
9. Which of the following materials has the lowest value of embodied energy?
   (a) Recycled steel
   (b) Concrete
   (c) Recycled aluminium
   (d) Cement

Review Questions

1. What are the functions of a building?
2. How are building materials classified?
3. How are the properties of building materials classified?
4. List and define the different physical properties of building materials.
5. Define the following:
   (a) Density (c) Density index (e) Porosity
   (b) Bulk density (d) Specific weight (f) Void ratio
6. List the mechanical properties of building materials.
7. What are the thermal properties of materials?
8. What are the chemical, optical, acoustical, physiochemical, and metallurgical properties of materials?
9. What are the factors influencing the choice of a building material?
10. Write short notes on the following:
    (a) Ductility (d) Fire-resistant and fire-retarding materials
    (b) Thermal conductivity (e) Corrosion resistance
    (c) Selection of building materials (f) Durability
11. Define sustainability. Why is it important to consider sustainability while selecting a building material?
12. When is a product or material considered sustainable? Illustrate with an example.
13. What are healthy materials?
14. When are materials considered as ecological materials?
15. List any three green-labelling systems.
16. Name any three green building rating systems
17. Describe the LEED-NC rating system briefly.
18. What is embodied energy? Is it the true indicator of environmental impact?

19. Briefly describe four important building materials.
20. What are the alternative or substitute building materials. Name five such materials and describe two of them briefly.
21. Why is it important to have standards for building materials?

ANSWERS

Multiple-choice Questions

1. (b)	**2.** (b)	**3.** (a)–(v), (b)–(i), (c)–(iv), (d)–(iii), (e)–(ii)
4. (c)	**5.** (a)	**6.** (c)
7. (b)	**8.** (c)	**9.** (b)