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Introduction to materials science for structural designers

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Chapter 5
Introduction to materials science for structural designers

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5.1. Introduction

Materials are one of the instruments structural engineers use to design and create structures. Besides the obvious aesthetic aspect of material selection, there is a functional aspect related to the use of materials to fulfil structural needs in the design of structural elements. The structural element needs to meet requirements for displacement, strength and safety. This translates into minimum properties for the material in terms of

- Young’s modulus
- tensile, compressive and shear stress
- fracture toughness (as a standard measure of structural material safety).

Although this can be reduced to mere numbers, as illustrated in Figure 5.1 for the major structural materials, an understanding of these numbers will help to make correct design choices. In addition, the twenty-first century structural designer has a responsibility to make choices that minimise eco-impact and as such this aspect also requires some understanding of eco properties.

5.2. An atomistic point of view of strength, stiffness, expansion, elongation and failure

The concept of the atom as the smallest, indivisible unit of a material was introduced by the Greek philosopher Democritus about 400 BCE. In the nineteenth century the English chemist John Dalton provided the essential proof for atomic structure. In a masonry wall, the properties of the wall are determined by the strength of the bricks and the strength of the connections between the bricks. In a material, the atom is effectively infinitely strong as it is indivisible, thus all properties are derived from the connections between the atoms, analogous to a masonry wall. The number of different types of atoms is limited; the periodic table of elements shows all types of atoms graphically.

The connections between atoms follows from the structure of the atom: an electrically positively charged core surrounded by negatively charged electrons in fixed orbitals, as shown in Figure 5.2. The electric forces of attraction and repulsion thus govern the connections between atoms or, as chemists call them, the chemical bonds that can be formed. There are three types of chemical bonds that can be formed, namely

- ionic bonds based on the exchange of electrons between atoms
- metallic bonds based on distributing ‘free’ electrons over the crystalline lattice of a number of metal atoms
- covalent bonds based on the sharing of electrons between atoms.

Figure 5.1 Plot of Young's modulus-to-weight against yield strength-to-weight ratios for common structural materials (produced by Ansys Granta Selector (2022R2) software)

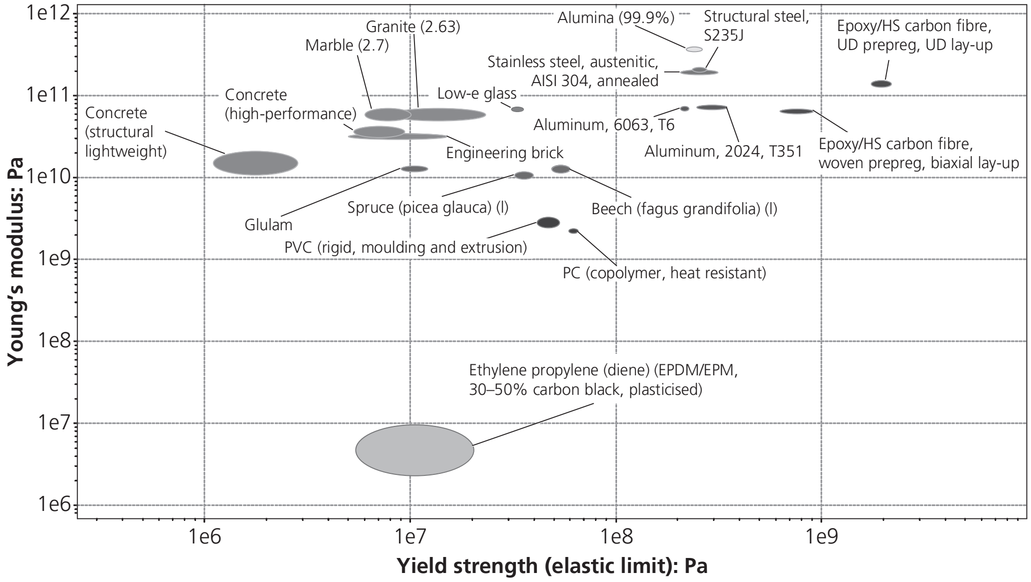
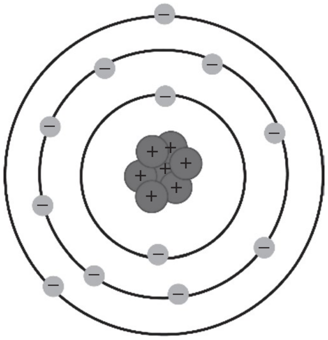
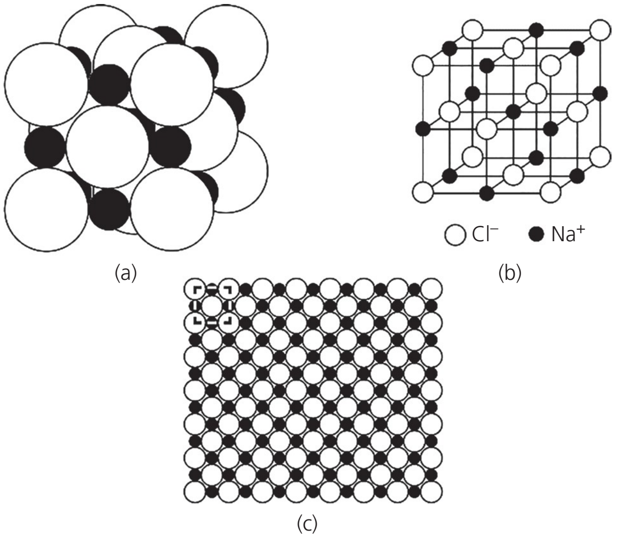


Figure 5.2 Atomic structure (Note: all author's own)



Electrostatic forces have two important properties: the force is proportional to the electric charge and inversely proportional to the square of the distance. The ionic bonded solid, shown in Figure 5.3, is easiest to understand. In this case sodium chloride is made by the sodium atom losing an electron and becoming a positive ion, and the chloride receiving the electron and becoming a negative ion. This requires the ions to arrange themselves in an ordered structure, called a crystal lattice. In this case the crystal lattice is simple cubic. The distance between opposite charges is the length of the rib of the cube and the distance between equal charges is $\sqrt{2}$ times the length of the rib. The attractive force is thus twice the repulsive force. If an external shear force is applied and the solid is deformed, the ions move. When the ions have moved enough that the attractive force is less than the repulsive force, the solid shears. This in essence explain why ceramics, which are ionically bonded solids, are dense, stiff and brittle.

Figure 5.3 Ionic bonded solid (Note: all author's own)



Metals have a different structure, as shown in Figure 5.4. The outer electrons of the atoms mix and form a cloud of electrons between the resulting positive ions; this is called the Cottrell cloud. The attraction is between the positive ions and the negative cloud. The attraction is thus not directional between ions. An important consequence of this is that the ions can move relative to each other without breaking the bond. This is the basis of plasticity in metals. This has the important result that metals are dense, stiff and (potentially) ductile.

Covalent structures are based on the concept of sharing electrons, as shown in Figure 5.5. This locks atom together at the bond, although they can rotate around the bond. This type of bonding is present in polymers and wood. Figure 5.5(b) shows the structure of polyethylene. The result of covalent bonding is a much more open structure where, per unit volume, there is less attractive force. The result is that polymers are less dense and not very stiff. Depending on the exact chemical formula they can be ductile or non-ductile.

Although atoms are usually pictured as static (Figure 5.2), in reality the electrons are moving. The kinetic energy inside the atom is related to the thermal energy (temperature). As the temperature

Figure 5.4 Metallic bond (Note: all author's own)

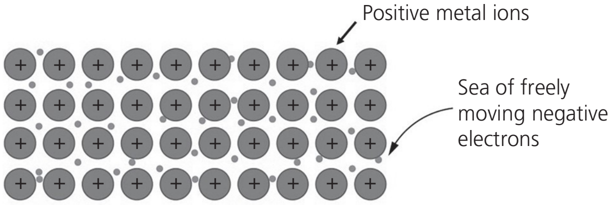
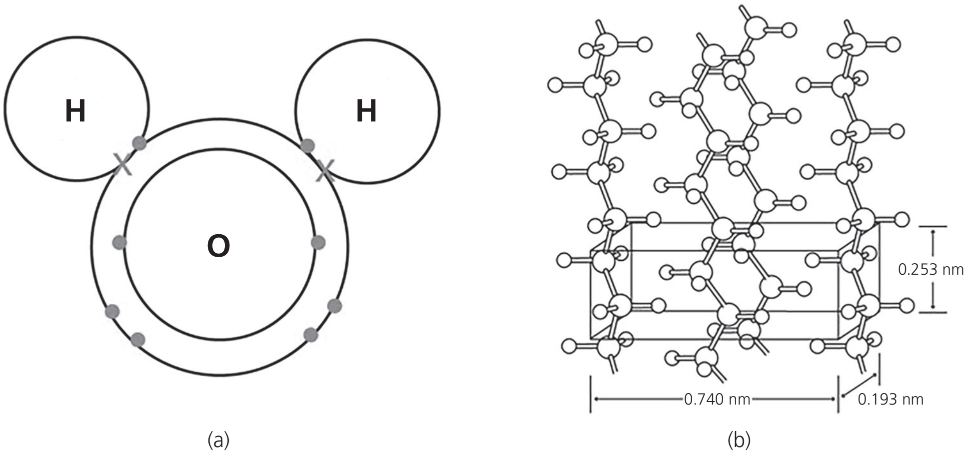


Figure 5.5 Covalent bonds: (a) the water atom and (b) the polyethylene structure (Note: all author's own)



increases, the kinetic energy increases and the atoms expand as the radius of the electron orbitals increases. This is the basis of thermal expansion. As a general rule, the thermal expansion of a solid is the same in absolute terms between 0 kelvin and the melting temperature. The thermal expansion of low melting solids (e.g. polymers and aluminium) is thus per degree kelvin higher than that of high melting solids (e.g. steel).

5.3. Eco-impact of structural materials

A direct eco-impact can occur at different points in the material production and use cycle, for example

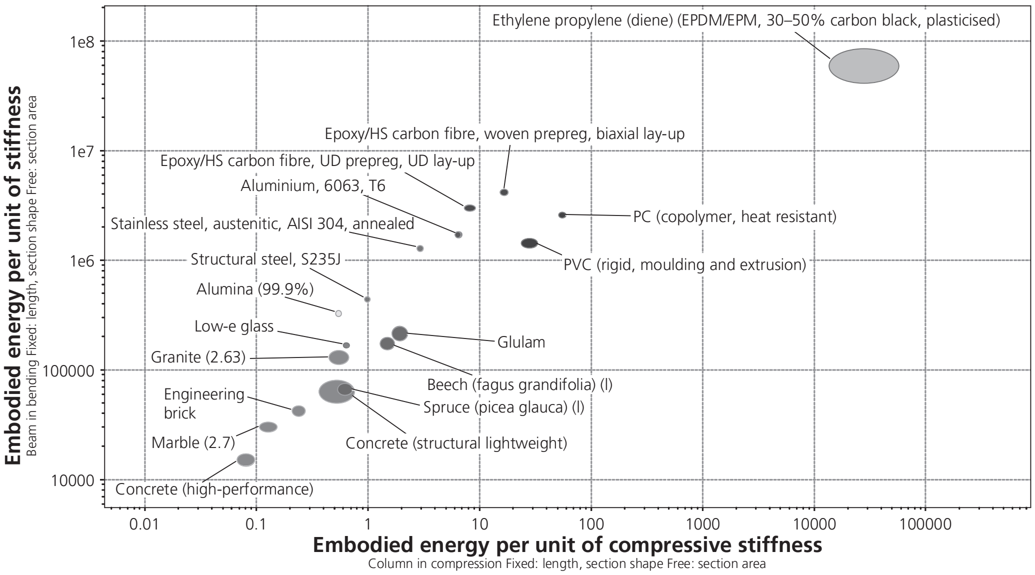
- damage when sourcing the raw material, pollution from mining
- pollution when processing the raw material
- pollution during use of the material (e.g. solvent release during painting)
- pollution at the disposal of the material (e.g. toxins released by combustion of the material).

These specific points can be remedied by proper preventative or restorative measures. If proper process controls are followed, the eco-impact can mostly be reduced to the following quantifiable parameters

- embodied energy: the energy required to produce 1 kg of material
- carbon dioxide (CO_2) released during production of 1 kg of material
- energy required for transport and in use
- carbon dioxide released for transport and in use
- energy gained or saved by re-use or recycling at the end-of-life stage.

These values can be quantified quite well and are based on reliable data, found for instance in the Ansys Granta Selector software. It should be noted that embodied energy and carbon dioxide released are not always related. In the production of steel, iron oxide (Fe_2O_3) is reduced by carbon in a blast furnace; thermal (embodied) energy and carbon dioxide production are in this case directly related. In the primary production of aluminium, aluminium oxide (Al_2O_3) is dissolved

Figure 5.6 Embodied energy per unit stiffness for bending against embodied energy per unit stiffness in compression (produced by Ansys Granta Selector (2022R2) software)



in cryolite and separated using electrolysis. This uses a lot of electricity, but if it is produced by a hydroelectric power plant, this does not release operational carbon dioxide. Thus, embodied energy and released carbon dioxide are separate parameters that need to be looked at properly to make an eco-impact calculation.

Moreover, absolute numbers are not indicative. Embodied energy should be looked at in terms of relative performance. Figure 5.6 shows the embodied energy per unit stiffness in bending (y-axis) plotted against the embodied energy per unit stiffness in compression (x-axis). The popularity of concrete is logical looking at the data, due to its high stiffness per unit embodied energy for use in compression.

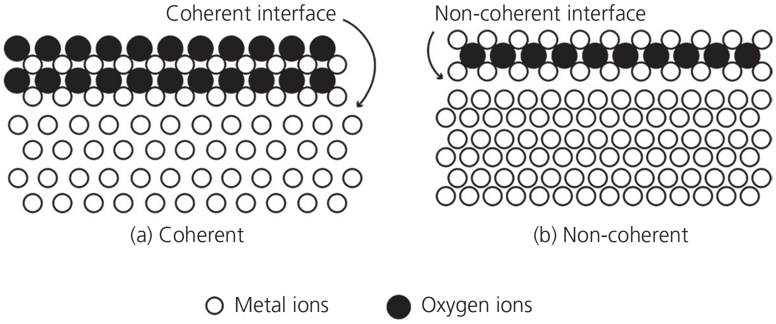
5.4. Metals

Except for silver, gold and platinum, metals are found in the earth's crust as minerals, mostly oxides. These minerals are also called ores. The metals are extracted from the ores by high temperature chemical reduction or electrolysis. Metals are not usually used in a pure form but mixed with other metals or non-metals to make an alloy. Metals are unique in that they can be made into high-strength elements, such as cables for suspension bridges or piano wire, or lower strength alloys which can be shaped into forms, such as I-profiles, which have a high stiffness-to-weight ratio and thus are efficient for bending- or buckling-sensitive applications.

Another critical aspect of metals is the high fracture toughness compared to ceramics, which allows smaller components to be joined into a single large structure, by riveting, bolts, adhesives or welding.

Metals can be shaped by casting, where the liquid metal is poured into a mould to make a component; by deformation, forcing the material into a shape; or by machining, where the volume which is not needed is removed from a solid block to make a shaped product.

Figure 5.7 Why steel rusts and stainless steel does not: (a) coherence; (b) non-coherence (Note: all author's own)



5.4.1 Corrosion

Corrosion is the electrochemical reaction of a metal with oxygen in the presence of water. In essence it is the metal reverting to the ore. Corrosion is considered a problem for steel, as it rusts, with the formed iron oxide dropping off the metal substrate. In contrast, many other technical metals, such as aluminium, stainless steel, titanium and copper alloys, seem to not corrode. The difference is in how the oxide connects to the metal, as shown in Figure 5.7. If the crystal lattice of the oxide is the same size as that of the metal, then the metal to metal oxide interface is coherent and the oxide sticks to the metal. If the crystal lattice of the oxide cannot fit onto the metal, then the interface is non-coherent and it cannot connect. The crystals of iron oxide (Fe_2O_3) and iron (Fe) do not fit together, so rust does not stick to the metal. By alloying iron with chromium and nickel, the crystal lattices are matched and the oxide sticks to the metal, creating 'stainless steel'. Metals with protective oxide coatings can be problematic to weld. Welding upsets the structure and the material of the heat-affected zone next to the weld can show corrosion even if the base metal does not.

The protective oxide layer does not protect the metal if contact with a more noble metal is made. The resulting contact corrosion attacks the metal which is lower in the electrochemical series, as shown in Figure 5.8.

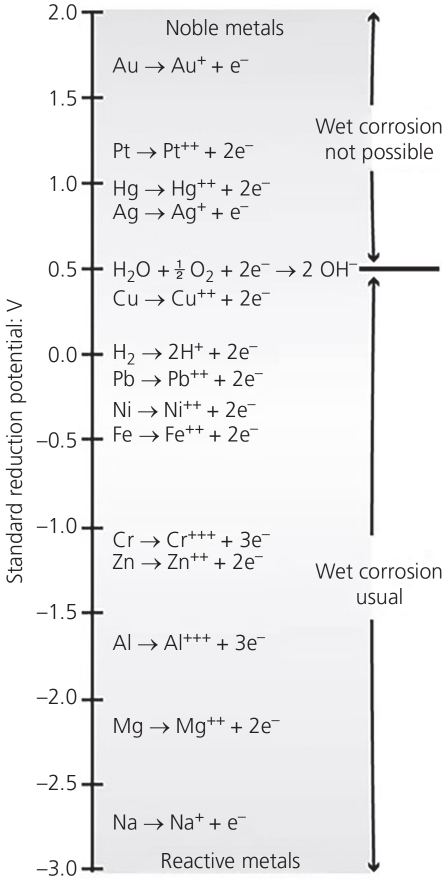
This principle can also be used to protect against corrosion. If steel is connected to zinc, the zinc corrodes preferentially, but does so slowly. Thus, a zinc coating or protective anode can protect a steel structure against corrosion.

Alternatively, preventing water and oxygen from contacting the metal can prevent corrosion. This can be done by creating a physical barrier by painting or powder coating.

5.4.2 Welding

Welding is connecting two pieces of metal by locally melting them and letting them solidify to create one piece. Usually this is done by locally heating the material using an electric current but can also be done using explosive force or friction. Proper welding is a connection that is air- and water-tight and can transfer tensile and shear forces.

Figure 5.8 Electrochemical series (Note: all author's own)



As welding locally melts the carefully created structure of the metal and lets it solidify without control, the properties of the weld are less than that of the mother material. Also, the volume next to the weld that is heated but not molten (the heat-affected zone) can show micro-structural changes and a decrease of properties. This affects strength and ductility, and also corrosion resistance.

5.4.3 Critical numbers for metals

Table 5.1 Global production of metals in 2022 (data from Ansys Granta Selector (2022R2) software)

Metal	Global production in tonnes, 2022	Global production in cubic metres, 2022
Steel	151 700 000	19 500 000
Stainless steel	58 600 000	7 300 000
Aluminium	47 000 000	17 400 000
Titanium	170 000	37 800

Table 5.2 Properties of metals (data from Ansys Granta Selector (2022R2) software)

	Low carbon steel	Stainless steel	Aluminium alloys	Titanium alloys
Young's modulus: GPa	210	190	70	115
Yield strength: MPa	230–360	250–1100	110–400	700–1000
Elongation to fracture: %	25–45	10–50	10–25	6–20
Fracture toughness: MPa$\sqrt{m}$	42–80	55–140	25–40	55–85
Density: kg/m^3	7800	7800	2700	4500
Thermal expansion coefficient: microstrain/K	12	14	24	9
Melting point: °C	1530	1440	500–640	1650

5.4.4 Steel

Steel is the most produced metal in the world in tonnes but aluminium is close in cubic metres. Primary production of steel is by reducing the minerals magnetite (Fe_3O_4) or haematite (Fe_2O_3) with carbon at high temperature. The high temperature is usually achieved by burning coke (heated purified coal) in a blast furnace. Primary steel production is thus a major contributor to global carbon dioxide production, estimated at 7–9% of the global total emissions from direct fuel usage.

Rough pig iron, containing some 4.5% carbon, produced in a blast furnace, is directly processed to steel by blowing oxygen over the liquid surface, oxidising the carbon to carbon dioxide. For structural steel the carbon percentage is reduced to about 0.1%.

In western countries primary steel production has dropped significantly in recent years with most steels works closing. Instead, steel is recycled by melting in an electric arc furnace followed by further processing.

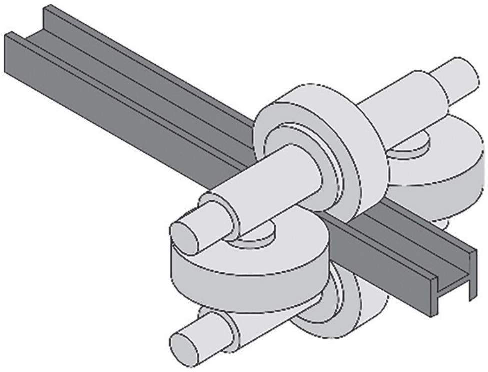
There are developments in producing steel using hydrogen, with one small experimental plant in Sweden. Changing over the industry will, however, take decades and increase the price of steel, although it would eliminate almost all the pollution of current primary steel production.

To save energy, continuous casting was introduced in the 1950s and is now the primary method used. In continuous casting the liquid steel produced by oxidising the pig iron is continuously poured into a water-cooled mould to produce a strip. This strip is then rolled into profiles or blocks at a temperature of about 1200°C. The rolling process is schematically shown in Figure 5.9 and is the basic process for producing steel profiles or plates. Rolling can only create open profiles with rounded interior corners. Closed profiles like hollow tubes are usually made by hot bending steel plate and welding the seam to make a closed section. High-strength seamless tubes can be forged but these are not usually used in the built environment due to cost.

5.4.5 Stainless steel

Stainless steel was invented in the early twentieth century by alloying normal steel with chromium and nickel to make it corrosion resistant. Adding the chromium and nickel changes the size of the crystal lattice so the metal and the oxide have a coherent interface.

Figure 5.9 Rolling mill set-up to produce an H-section profile (Note: all author's own)



It is usually made by melting high-quality recycled steel and adding chromium and nickel in an arc furnace. Recycling of stainless steel is at a high level. Some 50% of the demand for stainless steel is filled by using recycled material.

There are some 150 types of stainless steel, of which four are commonly used in architecture, namely AISI 304, 304L, 316 and 321. Type 304 is the basic stainless steel, containing 18% chromium and 8% nickel; 304L is a low carbon steel which is easier to weld; 316 has an addition of 2% molybdenum which increases the resistance to salt water corrosion; 321 has 19% chromium, 12% nickel and 0.7% titanium and is extremely resistant to all forms of corrosion. All four types can also be cast, for instance to make spiders for glass facades.

Stainless steel differs from normal steel in its slightly lower Young's modulus and higher fracture toughness. It is significantly more difficult to machine than normal steel and special drills and cutting tools are required. Welding of stainless steel requires special training and equipment.

5.4.6 Aluminium

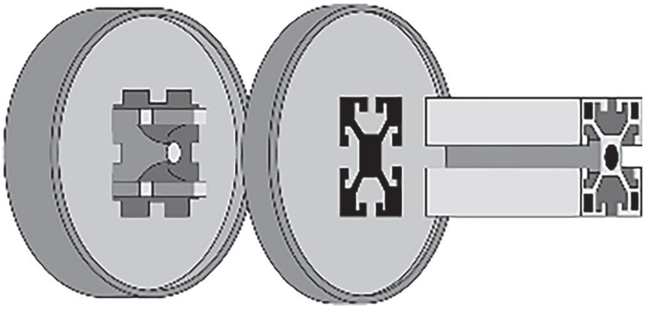
Aluminium was first produced industrially in 1856 using a chemical reduction process which made it very expensive. After the invention of electrolytic extraction in 1886 the material became much cheaper and widely used. There are hundreds of aluminium alloys which have been developed for many niche applications in aerospace and other engineering fields. These include specific casting alloys.

Aluminium has a number of critical properties, including

- the ability to be extruded, allowing the design of very efficient profiles
- low density compared to steel
- good resistance to normal atmospheric corrosion
- low melting point compared to steel, so easier and cheaper to recycle.

In extrusion a block of aluminium is pushed through a steel die at about 400°C to create a seamless profile. A die and profile are shown in Figure 5.10. The ability to make light, stiff profiles which

Figure 5.10 Extrusion die and resulting aluminium profile (Note: all author's own)



are corrosion resistant allows for weight-efficient bending and torsion structures. This makes aluminium alloys popular for vehicles. It is also highly useful for many domestic applications.

The low melting point makes aluminium alloys cheap to recycle. It is also the main problem in structural design in that the fire resistance is very low. There are no easy coating solutions to solve this. Aluminium alloys are thus used often in facades but rarely in the main load-bearing structures of buildings.

An important problem is that if steel contacts aluminium this leads to contact corrosion of the aluminium. So careful detailing, using a nylon or other non-conducting intermediary, is essential in a structure using both steel and aluminium to prevent electrical contact between the two.

5.4.7 Titanium

Titanium has the best strength-to-weight ratio of the technical metals. It is also very corrosion resistant. Titanium is made by a complex high-temperature reduction process which makes it very costly. Titanium alloys can be extruded, but this is more complicated and expensive than with aluminium alloys due to the higher temperatures involved.

Although appealing for many technical applications due to the high strength-to-weight ratio and corrosion resistance, titanium is too expensive to use as a structural material in buildings. It is occasionally used in facades due to the specific colour which appeals to some architects. The most famous example is the Guggenheim museum in Bilbao.

5.5. Ceramics

Ceramics are basically stony materials and as such are hard, stiff and brittle. They fall into five categories, namely

- technical ceramics
- non-technical ceramics
- natural stone
- glass
- concrete.

Technical ceramics are almost non-porous. An example would be a ceramic turbocharger for a high-performance car engine. These materials are used for high-temperature applications and are sintered from fine powders. They have no application in buildings due to the high cost and small size of the components.

Non-technical ceramics are made from clay and sand. A mixture of clay, sand and water is pressed into a form and allowed to dry, after which the form is baked. Brick is a typical example.

Natural stone is a ceramic in the physical and chemical sense. Suitable sites which have the right type of stone – for example, marble or sandstone – are identified. Blocks are cut out of the bedrock and processed into the shapes required. Historically, rough blocks of stone were used to make rubble walls and these were sometimes joined together with a lime-based mortar to make walls for buildings. Important for structural design is to remember that natural materials contain big flaw distributions and are thus unpredictable in terms of strength and that the compressive strength is much greater (as a rule of thumb 10×) than the tensile/bending strength.

Glass is the only stiff building material that can be transparent. It is also the only 'stony' material that is predominantly covalently bonded. There are several types of glass, but soda lime glass accounts for over 95% of global production. It is made by mixing fine sand, soda and lime. This is then melted and either cast into a mould or processed by deforming it while hot. Glass is usually considered an undercooled liquid, but this is not accurate from a modern materials science perspective. Glass is composed of a three dimensional (3D)-network of silicon and oxygen rings. In quartz (crystalline silicon oxide (SiO)), the rings are regular and contain the same number of atoms. In glass, the network is composed of irregular rings. This results in an amorphous (non-crystalline) structure. The addition of soda and lime helps to break up the regularity of the network, decreases the melting point and makes the hot glass easier to process. Properly made glass is inert and resists water very well, although it can be scratched by sand and other hard substances. It can also be etched by very alkaline substances, such as wet Portland cement concrete.

Most glass is currently made by the float glass process. In this process, liquid glass is poured onto a bath of liquid tin. This is drawn into a long ribbon which is cooled down slowly and then cut into sheets of 6×3.21 m. This is further processed by cutting into the smaller panes needed for windows, doors or other elements.

Glass is sensitive to defects and this results in a relatively high spread in the strength. The strength generally decreases over time due to accumulated damage. Tempering the glass helps to solve this problem. In tempering, the glass is heated to 620°C and then cooled by a jet of cold air. Due to differential shrinkage between the cooled surface and the hot core, a permanent compressive pre-stress is introduced into the glass surface. This prevents the flaws in the surface from feeling tension and thus prevents failure. Fully tempered glass is, however, sensitive to local impact loads and fragments. Heat-strengthened glass is cooled more slowly and has a lower compressive surface pre-stress. It is thus less strong in the engineering sense but much less sensitive to damage.

Sheets of tempered glass are often laminated with a rubber or plastic foil. This provides safety in that it prevents spallation of glass fragments. In certain cases, this can also provide structural safety, as is explained in Chapter 6 of the second book in this series *Structural Design of Buildings: Elemental Design* on structural glass.

5.5.1 Critical numbers for ceramics

Table 5.3 Properties of ceramics (data from Ansys Granta Selector (2022R2) software)

	Al_2N_3 technical ceramic	Bricks	Natural stone	Float glass	Concrete
Bending strength: MPa	280	10	5–40	30	1.5–3
Compressive strength: MPa	2200	50	30–400	400	15–50
Young's modulus: GPa	330	30	30–80	70	15–25
Fracture toughness: $MPa\sqrt{m}$	3	0.015	0.2–1	0.6	0.4
Density: kg/m^3	3300	2400	2400–2900	2450	2200-2600
Thermal expansion coefficient: microstrain/K	4.7	7	3–7	9.3	8–12
Melting point: °C	2450	1350	1200–1600	1050	930–1200

5.5.2 A note on masonry

Since ancient times walls have been built by stacking stones together. If the stones fit together perfectly this can be done without a binder. Usually stones and brick are irregular and a mortar is used to connect the stones. Lime mortars were used until the early twentieth century and cement mortars have been used mostly since then as these set much faster, allowing for a faster building process. However, lime mortars are more elastic, allowing for more thermal expansion and movement in earthquakes. The overall strength of a masonry wall depends on the strength of the stone and of the mortar.

5.5.3 Cement

There are two types of cement used to produce concrete: Portland cement and blast furnace slag cement. Portland cement is produced by heating limestone and clay in a kiln at 1400°C, producing a fine powder; 2–3% gypsum is added to slow down the chemical reaction with water. Blast furnace slag cement is produced by mixing ground blast furnace slag with 30% Portland cement. Functionally the two are identical except that the pure Portland cement concrete has a pH of 14 and the blast furnace slag cement has a pH of 12.

As the limestone has to be heated to make Portland cement, the embodied energy of Portland cement is some 50% higher than for blast furnace slag cement. However, the closing down of most blast furnaces for primary steel production has reduced the supply of blast furnace slag significantly in recent years.

Specialised sulfate-resistant cements exist and are only used where the (ground)water is contaminated with sulfates that would cause corrosion of the reinforcement if normal cement was used. The chemistry of curing of concrete is very complicated and cannot be explained briefly here.

5.5.4 Concrete

Concrete is a composite material composed of fine and coarse aggregate bonded together with a fluid cement (cement paste) that hardens (cures) over time. Concrete was invented by the Romans using volcanic ash to make the cement. It was used for rapid construction, such as for the Circus Maximus, and for underwater structures in harbours. Advanced use of concrete, using lightweight aggregates, is found in the dome of the Pantheon, which, after 2000 years, is still the largest unreinforced concrete dome structure in the world. After the fall of the western Roman empire, concrete was not used until the seventeenth century. Mass use of concrete started in 1849 when the French gardener Joseph Monier invented reinforced concrete to make large flowerpots. The Industrial Revolution led to rolled steel sections becoming available cheaply, allowing reinforced concrete to become the dominant material in the built environment; in 2020, 4.2 billion tonnes of cement were used to make 14 billion cubic metres of concrete worldwide.

To make 1 cubic metre of normal concrete, weighing 2.4 tonnes

- 250 kg of cement
- 700 kg of sand
- 1200 kg of gravel, crushed rock or other aggregate
- 150 litres of water

are mixed together.

The cement reacts with the water to bind everything together. Usually, more water is added than is needed for the chemical reaction, otherwise the concrete mix would be too thick to pour. Too much water, however, is deleterious to the strength of the concrete. The aggregate needs to be in a range of sizes so that there are no large holes. The sand fills in the smallest holes. The mixture needs to be mixed thoroughly and poured in a properly mixed condition. The tank on a concrete mixer truck rotates to ensure proper mixing. After pouring, the concrete is vibrated to remove air bubbles, which improves the properties and durability.

5.5.5 Admixtures for concrete

Admixtures can be added to liquid concrete to its change properties. The most important of these are

- accelerators that speed up the chemical reaction
- retarders that slow down the speed of the chemical reaction to prevent excessive heat build-up in large volumes of curing concrete
- (super)plasticisers that make the concrete easier to pour and reduce the amount of water needed, increasing the strength of the concrete
- silica fume to fill microscopic holes in the cement binder and increase the strength; this has to be combined with superplasticisers
- pigments to colour the concrete.

5.5.6 Reinforced concrete

Structural concrete is usually reinforced with steel. The steel reinforcement is placed inside the formwork, the liquid concrete is poured over it and, after setting, the concrete connects to the steel by friction. Steel reinforcement is usually contoured on the surface to increase the friction. If reinforced concrete is subjected to a bending load, the concrete cracks in the tension zone, after which the steel reinforcement in the tension zone carries the tensile load. Usually, steel reinforcement is only placed in zones which will be under tension. If the reinforced concrete is properly designed, the cracks in the concrete are small and do not influence the durability of the structure.

In *pre-tensioned concrete*, the steel reinforcement is put in tension before the concrete is poured over it. After curing, the pre-tension is removed and the steel contracts, putting the concrete in compression. This allows the pre-stressed component to be used in bending, keeping the concrete in compression. Thus, the concrete does not crack. Components made in this way can only be produced in a factory. The size is thus limited by available transport. As these components are factory-made, good quality control is possible, resulting in high-quality structural components. As curing conditions are controlled, production can be fast – usually one production cycle every 24 hours. The nature of pre-tensioning allows for this process to be used only in linear elements.

In *post-tensioned concrete*, greased steel cables in a protective sleeve are put in the formwork. After the concrete has cured, these cables are tensioned using a hydraulic ram and the ends of the cable are then fixed. This pre-stresses the concrete structure. Post-tensioning is done on the building site and can be used on large structures.

Occasionally, reinforced concrete structures are strengthened or repaired by bonding external carbon fibre reinforcement to the outside surface of the concrete using an epoxy resin.

5.5.7 Mechanics of concrete

If a block of concrete is put under compressive load, the aggregate carries and transfers the load, as shown in Figure 5.11. Contact between the aggregate is essential to transfer compressive load. This requires mixed graded aggregate of different sizes to ensure optimum force transfer. Having small, medium and large pieces of aggregate prevents holes and thus stress concentrations.

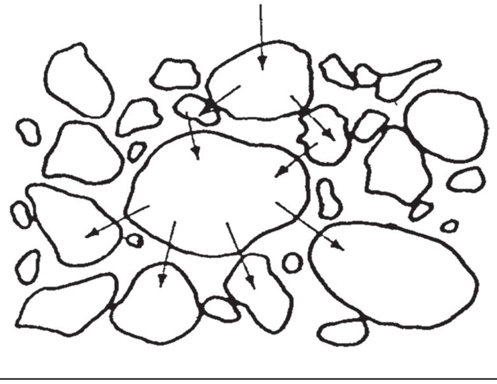
In tension, only the cement binder transfers the force, which explains why concrete is usually 10 times weaker in tension than in compression.

5.5.8 Corrosion in concrete

The steel in concrete is protected from corrosion by the high pH of the concrete. Concrete can react with atmospheric carbon dioxide in a process called carbonatation. During carbonatation the pH of the concrete drops and the reinforcement can then corrode. In the corrosion reaction, iron (Fe) changes to iron oxide (Fe_2O_3) which has a greater volume; this swelling can crack the concrete.

Carbonatation moves in a front from the outside to the inside of the concrete. If the concrete is porous and of low quality, this front is likely to move faster. Carbonatation is limited or avoided by

Figure 5.11 Internal load transfer in concrete (Note: all author's own)



using a concrete with the correct mix of graded aggregate, plasticiser and only the water required for the reaction with the cement. This reduces the porosity and thus the speed of the carbonatation front. Additionally, it is important that the distance from the concrete surface to the reinforcement, the cover layer, is thick enough.

5.5.9 Eco-impact of concrete

Although there is much press coverage about the impact of the concrete industry on the environment, as a material concrete has a relatively low eco-impact if used in compression or correctly used in bending. As the only part of the concrete that requires significant thermal energy is the Portland cement, compared to metals the embodied energy is relatively low.

There are developments to reduce the eco-impact of the concrete industry by using 3D-printing techniques to create more structurally efficient shapes, requiring less concrete. There are also developments to develop modified cements which have lower embodied energy. If these developments work, concrete will still be a major structural material well into the twenty-first century. A bigger problem is the supply of suitable sand and gravel, both of which are becoming scarce in many countries.

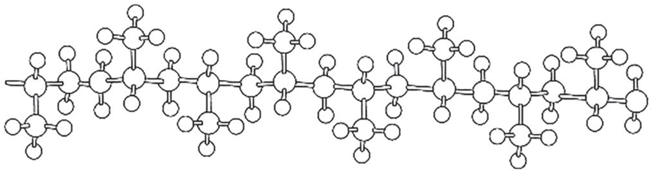
5.6. Polymers, composites and wood

Polymers can be divided into thermoplastic, thermosetting and rubber polymers. In all cases they are based on carbon chains, as illustrated in Figure 5.12. Thermoplastics are chains with no chemical bonds between the chains. They melt at temperatures of 150–300°C and can be deformed at lower temperatures. Thermoplastic essentially means it becomes plastically deformable at higher temperature. Thermosets are made by reacting small molecules together to make large 3D molecular networks. They set their structure at a higher temperature and cannot melt. Rubbers are thermoplastic chains which are formed into a network using sulfur bridges between the chains. The sulfur bridges are formed through vulcanisation. Thermoplastic polymers are weather-resistant and, with the right admixtures, UV-resistant. They are suitable for window frames due to their low thermal conductivity. The low Young's moduli, however, means thermoplastics require (glass fibre) reinforcement for structural use.

Today, thermosets are only used as adhesives; epoxies are a good example. Rubbers have no direct structural use but can be used for dampening elements as they can sustain large deformations and transfer the energy into heat. They are also critical as seals in facades and insulated glazing unit panels.

Composites are fibres of glass or another stiff material such as carbon, usually embedded in a thermosetting polymer. Essentially it combines the stiffness and strength of the fibres with the weather resistance of the thermosetting polymer. As the polymer is liquid until it sets, a considerable freedom of shape exists in manufacturing composites. The stiffness provided by the shape and by the fibres lead to durable components with a high strength-to-weight ratio. This makes them popular

Figure 5.12 Polymer chain (Note: all author's own)



in the aerospace and automotive industries. Increasing use is made of composites in bridges due to the low maintenance costs compared to steel. Modern composite elements do not require painting, which usually leads to a significantly lower overall lifecycle cost compared to steel.

Wood is a natural composite. Cellulose fibres are formed into tubes which are connected by the natural thermoplastic lignin. The tubes are used in trees to transport water from the roots to the crown where it is used for photosynthesis. After cutting down the tree, the wood needs to be dried to remove the liquid. After drying, the wood becomes much stronger and stiffer.

Wood thus combines both shape and fibre into a single material which, being mostly empty tube, is lightweight. Wood is thus a natural structural material with high stiffness and strength-to-weight ratio. The thermoplastic binder allows wood to be bent in a press after heating with steam.

There are two types of wood: soft wood and hard wood. Soft wood is derived from gymnoform (pine) trees, while hard wood is from angiosperm (leaf-bearing) trees. The terms soft and hard are relative. More important is that soft wood is less resistant to moisture and rot than hard wood.

Like all natural materials, wood has defects in its structure, such as knots. These lower the strength. In engineered woods, weak pieces are removed and the good pieces of wood are glued together to form large elements at high temperature and pressure. This allows for large structural elements. The production is outlined in Figure 5.13. However, the presence of the adhesive limits down-cycling and can prevent combustion of waste wood.

Figure 5.13 Production of engineered wood (Note: all author's own)

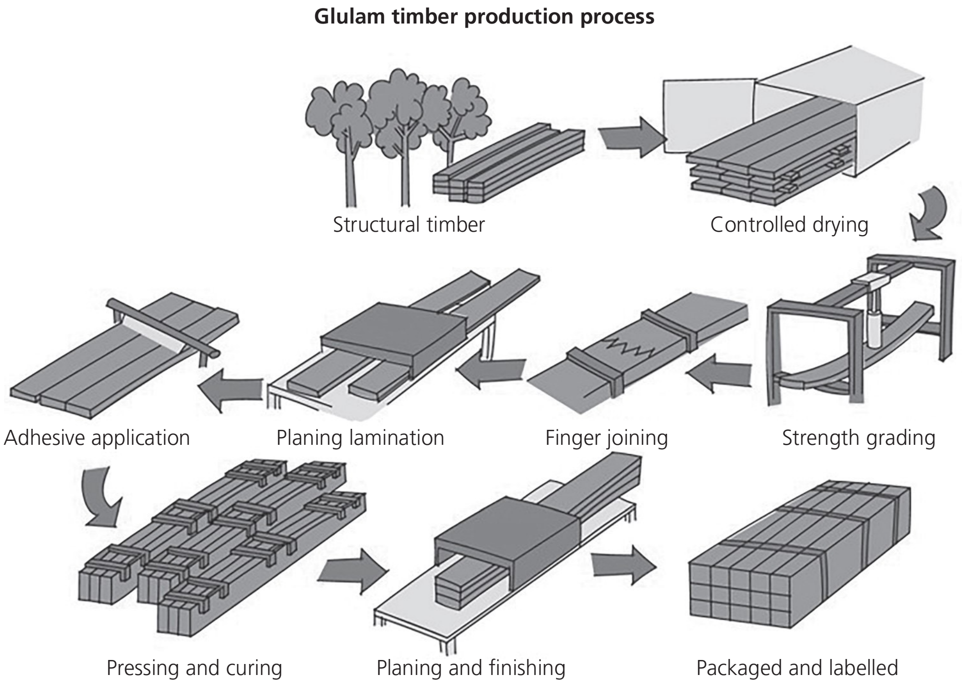


Table 5.4 Critical numbers for polymers, composites and timber (data from Ansys Granta Selector (2022R2) software)

	Thermoplastic polymer	Rubber	Composite	Timber
Bending strength: MPa	15–60	5–20	200–600	5–30
Compressive strength: MPa	15–80	5–30	200-600	8–80
Young's modulus: GPa	0.6–3	0.001–0.05	15–120	10–20
Fracture toughness: MPa$\sqrt{m}$	1–2.5	0.1–0.2	18–40	4–6
Density: kg/m^3	0.9–1.3	80–950	1700–2000	500–800
Thermal expansion coefficient: microstrain/K	100–200	200–300	8–30	2–10

As a natural material wood is subject to rotting processes. If the wood is not kept dry, mould will grow in the tubes and destroy the wood. Correct detailing is therefore essential to allow ventilation of wooden components. Correctly detailed wooden structures such as the Norwegian stave churches have lasted for centuries.

Both wood and composites are anisotropic materials. Properties such as Young's modulus and strength are dependent on the fibre direction. In engineered wood and composites, this is also a question of how the material/component is designed and the properties can be tailored to suit the need of the designer, although this requires specific knowledge and skills.

FURTHER READING

For a more fundamental look at different aspects of materials science

Smith W and Hashemi J (2005) *Foundations of Materials Science and Engineering*, 4th edn. McGraw Hill, Maidenhead, UK.

For a general overview of materials science

Callister WD and Rethwisch DG (2020) *Materials Science and Engineering: An Introduction*. Wiley, New York, NY, USA.

For materials selection

Ashby MF (2016) *Materials Selection in Mechanical Design*, 5th edn. Butterworth-Heinemann, Oxford, UK.

For eco-design

Ashby MF (2022) *Materials and Sustainable Development*, 2nd edn. Butterworth-Heinemann, Oxford, UK.

Wikipedia links for more in-depth explanations

Physical chemistry
https://en.wikipedia.org/wiki/Periodic_table (accessed 11/10/2023)
https://en.wikipedia.org/wiki/Bravais_lattice (accessed 11/10/2023)
https://en.wikipedia.org/wiki/Plasticity_(physics) (accessed 11/10/2023)

Metal working
https://en.wikipedia.org/wiki/Continuous_casting (accessed 11/10/2023)
https://en.wikipedia.org/wiki/Rolling_(metalworking) (accessed 11/10/2023)

Glass
https://en.wikipedia.org/wiki/Transparency_and_translucency (accessed 11/10/2023)
https://en.wikipedia.org/wiki/Float_glass (accessed 11/10/2023)
https://en.wikipedia.org/wiki/Tempered_glass (accessed 11/10/2023)

Concrete
https://en.wikipedia.org/wiki/Cement (accessed 11/10/2023)
https://en.wikipedia.org/wiki/Prestressed_concrete (accessed 11/10/2023)

Wood
https://en.wikipedia.org/wiki/Wood (accessed 11/10/2023)