Matter, Elements, and Materials

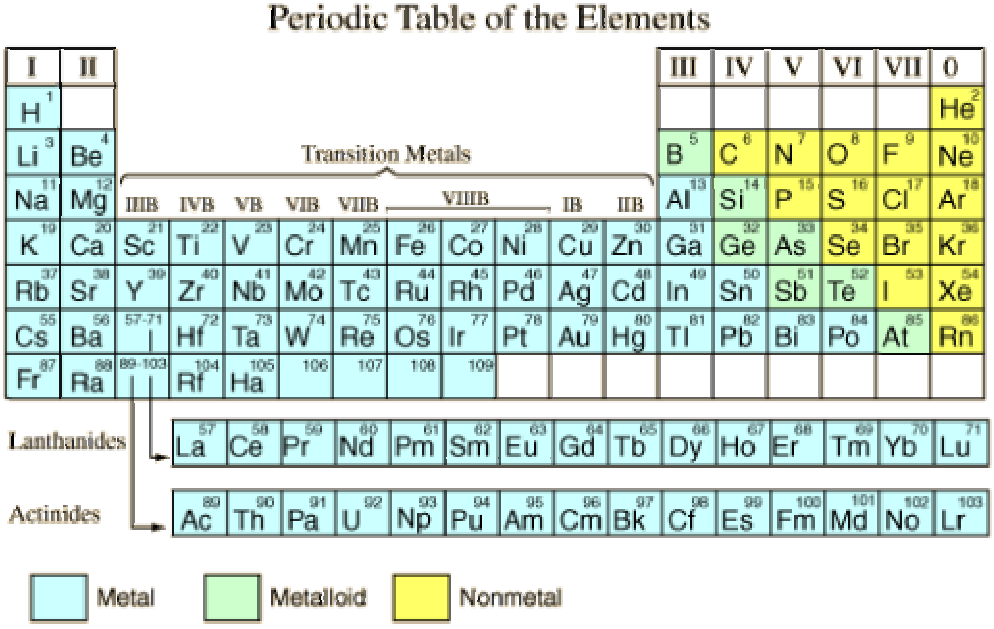
The use of materials is fundamental to the practice of civil engineering. In the past, civil engineering was the practice of creating large-scale systems for the good of society (civil was chosen as a modifier to be distinct from the only older type of engineer, military engineers). The physical components of these systems are built from materials, whether they are water supply, flood control, building, or highway systems. Hence, it is difficult to avoid the topic of materials if one practices civil engineering. The best choice and use of materials requires some understanding of materials, their properties, and behaviour.

1.1 Matter

Matter and radiant energy make up the physical universe. The term matter was derived from the Latin *materia*, meaning wood or other material. Matter can be said to be anything that has weight, occupies space, and is traveling at less than the speed of light. In civil engineering, the latter requirement is not often a concern.

Classification of matter, based on their properties or their structure, are used to group the many millions of material variations into manageable classes. From a chemist's point of view, the composition is very important, and matter is divided into three classes: **elements, compounds and mixtures**.

All natural matter is composed of some combination of the 92 natural **elements**. The elements are grouped as halides, metals, rare earths, etc. depending on their properties. It was found that elements had certain atomic properties that repeated and related to their physical properties. This information is summarized in the periodic table (Figure 1.1).



Periodic Table of the Elements

Transition Metals

I	II	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	III	IV	V	VI	VII	0
H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	57-71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	89-103	Rf 104	Ha 105	106	107	108	109									

Lanthanides	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Actinides	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

Metal

Metalloid

Nonmetal

Figure 1.1: Periodic Table

Several families of elements have been defined on the basis of the periodic table and their properties.

The **alkali metals**, found in group IA of the periodic table, are very reactive metals (they can react explosively) and hence do not occur freely in nature. (Their reactive nature is due to having only one electron in their outer shell). As with all metals, the alkali metals are malleable, ductile, and good conductors of both heat and electricity. Alkali metals tend to be softer than most other metals. Lithium, potassium, sodium and cesium are the most common elements in this group.

The second group, II, contains the **alkaline earth metals**. They are all quite reactive and are not found free in nature. Magnesium and calcium are common elements in this group.

The 38 elements in columns 3 through 12 of the periodic table are called the **transition metals**. As with all metals, they are ductile, malleable, and conduct electricity and heat. Important elements in this class are iron, cobalt, and nickel – these are the only elements known to produce a magnetic field.

Metalloids are the elements found along the stair-step line that distinguishes metals from non-metals. This line is drawn from between Boron and Aluminum to the border between Polonium and Astatine. The only exception to this is Aluminum. Metalloids have some properties of both metals and non-metals. Some of these elements, such as silicon, arsenic, and germanium, are semi-conductors, i.e., they conduct electricity under some conditions and not under others. This property makes them very useful for the electronic chip industry.

Non-metals are the elements in columns 14-16 (groups of the periodic table. Non-metals do not conduct electricity or heat very well. One unique aspect of these elements, which include hydrogen, carbon, nitrogen, and sulphur, is that they exist as either a gas or a solid at room temperatures.

Halogens are the five non-metallic elements in group VII. Halogen means "salt-former" and hence compounds containing halogens are called salts, such as table salt: Sodium Chloride.

The **noble gases** are found in the last column of the periodic table. These are essentially inert and unreactive, and exist as gases at room temperature.

The **rare earth** elements are the 30 elements found in group 3 and rows 6 and 7 of the periodic table. They are grouped as the lanthanide and actinide series. Many of these elements are man-made in nuclear reactions, include uranium, plutonium, curium, etc.

The most common elements on Earth, based on their percentage of the weight of the crust, are listed in Table 1. Of course, abundance does not equate to readily available. One example is aluminum, a very common element but always found in combination with other elements, and hence very expensive to extract in the pure form. Just before the turn of the 19th Century, aluminum was so rare that it cost as much as silver, and was partly chosen for the pyramidal tip of the Washington Monument because of its precious status.

Table 1.1: Eight most common elements in the Earths crust [CRC Handbook]

Element	**% by mass of earth's crust**
Oxygen	46.1
Silicon	28.2
Aluminum	8.23
Iron	5.63
Calcium	4.15
Sodium	2.36
Magnesium	2.33
Potassium	2.09
Titanium	0.565
Hydrogen	0.14

Elements are usually further organized into **compounds**: substances made of the union of two or more elements in definite proportion by weight. For example, water is a compound of hydrogen and oxygen, and salt is a compound of sodium and chloride.

Two or more atoms, of the same or different elements, form **molecules** when they are held together with strong primary bonds. Therefore, nitrogen gas, which exists as N_2, is a molecule but not a compound, and water is a molecule and a compound. Some molecules are relatively small, such as helium and water vapour molecules, while others are very large and may be visible in a powerful optical microscope. **Polymers** are large or macro-molecules composed of many repeating units, each called a **mer**.

Different elements, compounds, or molecules may be simply placed together in the same volume, in which case a **mixture** is formed. A mixture has two distinct chemical entities (unlike water, which is formed of molecular units) which, unlike compounds, can be separated by mechanical means, e.g., distillation and centrifuging. **Homogenous mixtures** are ones in which the different components are uniformly dispersed as in a **solution**. Salt dissolved in water is a homogenous mixture, as is nitrogen and oxygen in the atmosphere. **Heterogeneous mixtures** have **phases**, usually defined as a homogenous part separated from other parts by a distinct boundary visible under a microscope.

Colloids are systems in which there are two or more **phases** of matter, with one (the **dispersed phase**) in the other (the **continuous phase**). At least one of the phases must have very small dimensions, i.e., in the range of 10^{-6} to 10^{-9} m. Colloids were originally defined to be particles that were invisible to a visible microscope (electron microscopes use much shorter wave lengths, and therefore can resolve particles down to as small as ten nanometers). Important sub-types of colloids are

- **sols**, dispersions of small solid particles in a liquid (eg., metallic paint),
- **emulsions** in which both phases are liquid (eg., mayonnaise),
- **gels**, a colloid that has coagulated to a rigid or jelly-like solid. (eg. gelatin and silica gel dessicant),
- **aerosols** (solids in gases) and
- **foams** (gases in liquids or solids).

1.1.1 Bonding

Atomic elements form molecules and compounds because of the forces of attraction between them. Forces between atoms at a very small scale may result in the formation of strong bonds, such as ionic, covalent, or metallic bonds. These bonding forces act over small distances; for example, many atomic bonds act over a distance of 0.1 to 0.3 nm (a nanometer is one billionth of a meter).

Van der Waal's forces are weaker forces that act over larger distances, perhaps as much as 100 nm, but are most significant at distances of less than 20 nm. In addition, atoms, compounds, and very small particles may be held together by electrostatic forces—relatively weak forces that can act over larger distances (several hundred nm). These latter "long range" forces play a bigger role in gels.

The course textbook has a good section on bonding that should be reviewed.

1.2 Material Classifications

The most common classes of engineering materials are metals, ceramics, polymers, and composites.

Ceramics are compounds formed from the combination of metallic and non-metallic elements. Common ceramic materials include glass, cement, and clay, all important materials for civil engineers. Ceramics tend to be non-reactive, hard, moderately to very strong, stiff, and brittle.

Metals are combinations of metallic elements, often in crystalline form. They have free electrons that can move readily through the crystals. This explains the thermal and electrical conductivity of metals, as well as their relatively high degree of reactivity (which explains corrosion). Metals are strong due to their bonding, and ductile due to their structure: these are ideal properties for many structural applications. Different types of metals may be alloyed to create phases within the solid body, or unique metallic compounds that have special properties.

Polymers are molecules based on carbon, hydrogen and other non-metallic elements. They are characterized by the large size of their molecules, and tend to have low density, low stiffness and strength, and sensitivity to temperature. A polymer may be composed of ten to tens of thousands of molecules in chains or repeating mer units. For example, polyethylene is a polymer made from chains of ethylene CH_2-CH_2-and so on. Natural polymers, in the form of wood, natural fibres (e.g., cotton), etc. have traditionally been very important.

Composites are materials made of more than one material type. These are increasingly important, as they allow materials engineers to design specific properties that take optimal advantage of different materials. Examples include reinforced concrete (steel and concrete), fiberglass (glass fibres in a polyester resin matrix), and wood-fibre reinforced cement. Concrete is a mixture of different ceramic elements, as are, strictly speaking, glass-reinforced cement composites. The latter is, however, generally considered a composite.

Another useful classifications of materials is **inorganic** and **organic**. Organic materials contain carbon, and are often created by or from lifeforms on Earth. For example, wood, bone, and cotton are all organic carbon based materials. Oil and natural gas, which are forms of carbon stored below the earth for the last 100 to 400 million years, are liquid and gaseous carbon compounds that joined with hydrogen to form hydrocarbons. These are compounds that are used for man-made organic materials such as most modern polymer plastics. In the past natural renewable sources of carbon were used to produce natural-sourced plastics such as Celluloid, gutta-percha, lac, Bakelite and Cellophane.

Plant or mineral is another traditional distinction between materials. Minerals are defined as substances that 1. occur naturally, 2. made of substances that were never alive (i.e., hence coal is not a mineral), 3. has an invariant chemical make-up (hence sand is not a mineral, but quartz is), and 4. the atoms are arranged in a regular crystalline pattern (the calcium in milk is not a mineral, since it is in solution).

Other classifications of convenience, such as semi-conductors, advanced materials, biomaterials, natural material, etc are made but these are usually not rigorous defined from a scientific point of view.

1.3 States of matter

Matter, as elements, compounds or molecules, typically exists in three states under normal ranges of temperature and pressure: **solid, liquid, and gas** as shown in Figure 1.2. **Plasma** and **adsorbed** compounds are also sometimes considered states. A plasma is a compound with its atoms stripped of their electrons, typically by very high temperatures. Adsorbed matter is gases or liquids that are loosely attached to the molecules of liquids or solids. The adsorbed state exists only at microscopic level with characteristics somewhere between liquid and vapor. These states are experienced everyday with water, which is a solid in ice cubes, a liquid in water, and a vapor in the humidity in air.

A gas consists of molecules with a high level of kinetic energy, i.e., the molecules are moving about randomly at a high speed. In fact, the root mean square velocity (V_{RMS}) of the molecules is a direct measure of the gas temperature and the partial pressure that the gas exerts.

As temperature increases, the molecules collide more often and more energetically with one another and with the sides of any container. These collisions are what cause pressure on the sides of a container. Since a gas molecule can move freely, gaseous matter offers almost no resistance to change in shape (friction) and very little resistance to a change in volume (compression). If we compress a gas, the number of molecules per unit volume increases but, provided the temperature remains the same, the velocity of the molecules will not change. However, because the same number of molecules are moving at the same speed but in a smaller container, the pressure increases as the rate of molecular collisions with the walls of their container. Even at high pressures, the space between molecules remains large relative to the size of the molecules.

If a sufficient amount of energy is removed from a gas, the strength of attraction between molecules will eventually become stronger than the kinetic energy of the moving molecules, and the gas will become a liquid. Similarly, if a gas is sufficiently compressed, the molecules are forced into close contact and a liquid forms. Liquid matter does not strongly resist forces that act to change its shape because the molecules are free to move with respect to each other. Liquids still have sufficient molecular repulsion to resist forces acting to change their volume. Hence, a liquid retains more shape and offers greater resistance to disturbance than a gas does—this is clearly the case with the water molecule since liquid water is much more viscous and difficult to compress than steam (or water vapor) is.

The removal of even more energy from a material slows the movement of molecules, and intra-molecular forces begin to dominate. A solid is formed when the molecules cease to move about freely. Molecules in a solid state remain in a fixed position but do continue to vibrate. When even this vibration ceases, the temperature of the material has reached absolute zero (-273 °C or -460 °F). Solids are characterized by their resistance to change in either shape or volume.

The relative forces of attraction between molecules and the kinetic energy of molecules with a certain velocity clearly varies with different types of molecules and with different mixes of molecules. For example, at one extreme tungsten becomes a liquid at 3370 °C (6100 °F) and at the other, helium becomes a gas at –269 °C (-450 °F).

The more energy in a solid, the more the molecules vibrate, and the more intensive the collisions with their neighbors. Therefore, solids are expected to expand with temperature. The kinetic theory of gases described above also leads to the expectation that heating a liquid or gas will cause it to expand. The vibrational or kinetic energy causes molecules to move farther apart from each other, and the same number of hot molecules will therefore occupy more space than an equal number of colder molecules.

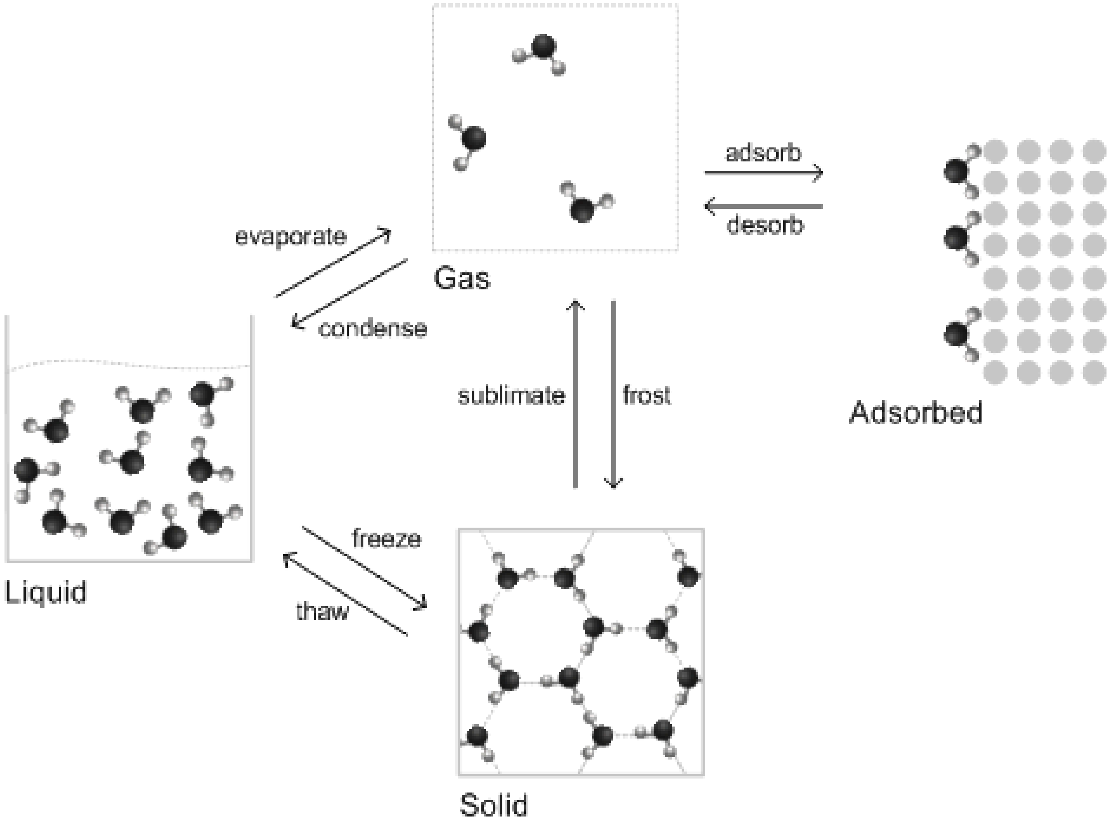


Figure 1.2: States and state changes

The adsorbed state

Many molecules and atoms can exist in the adsorbed state. Vapor molecules close to solid molecules can be attracted by the complementary polar nature of some solid material molecules, or they can induce polarity in the solid molecules by the dispersion and induction effect. If a molecule is attached to the surface with these weak van der Waals or hydrogen bonding forces, it is said to be adsorbed. All types of organic chemicals, especially volatile organic compounds (VOC) can be bound to the surface of materials and in their open pore structure. Many materials "off-gas" these compounds over time or when the temperature increases, and create the "chemical" smell of new plastics and new cars.

Adsorbents are materials that have the ability to adsorb gases. Virtually all materials are *desiccants*, i.e., they attract and hold water vapor. Wood, natural fibers, brick, and concrete have a moderate ability to hold water vapor. However, the term desiccant is normally reserved for materials with a very high affinity for water such as those used to remove moisture from the air in HVAC systems and equipment. The term *hygroscopic* is often used to describe those materials that exhibit a moderate affinity. Many porous building materials are hygroscopic, and they can store significant amounts of moisture as adsorbed water vapor on their very large internal surface areas.

Because the mobility of the vapor molecule is reduced by the attraction to the surface on which it is adsorbed, the behavior of adsorbed molecules is different from their behavior in either the pure liquid or vapor states. For example, adsorbed water does not freeze until temperatures are very low because the reorganization of the molecules into an ice crystal form is not the lowest energy state for adsorbed water. However, after several layers of adsorbed water molecules accumulate, subsequent layers begin to behave more like liquid water.

Molecules that are bonded to other solid molecules are said to be chemically bound. These *bound molecules* are not part of the adsorbed state, and typically require much more energy (i.e., heat) to remove. Such chemically bound water molecules can form hydrates, as in gypsum (which is 21% water by weight), and the considerable energy required to break these bonds explains why gypsum has such high fire resistance.

State changes

Matter can change from one state to another, even within a material layer, and these state changes can greatly affect building enclosure behavior. Each state-change process is given a name.

As noted earlier, the energy used to increase the velocity or vibrations of molecules is called sensible energy or sensible heat (because one can sense an increase in temperature in the material). The sensible energy required to raise a unit mass of material one unit of temperature is called *the specific heat capacity* of the material. The specific heat capacity is a function of temperature and pressure for many gases, but it can be assumed to be constant over limited temperature ranges.

Vaporization is the general term that describes the process by which liquid water changes to vapor. Vaporization can occur at the air-water surface, where it is called *evaporation*. Or it can occur within the mass of the liquid water and move to the surface in bubbles, where it is called *boiling*. Boiling occurs when the saturation vapor pressure is greater than the atmospheric pressure (at 100 °C for standard atmospheric pressure). Evaporation, in contrast, can occur at any temperature. Boiling will occur at a lower temperature on a mountain top because the atmospheric pressure acting on the surface of the water is lower than at sea level. When vaporization occurs at temperatures below zero (or more precisely, from ice), it is called *sublimation*.

Condensation is the process by which water vapor changes to liquid. If water vapor changes directly to the solid state without passing through the liquid phase, the process is called *frosting*.

When materials change their state, additional energy is required to reorganize the molecules into the new state. For example, there is a significant difference in total energy content between a gas and a liquid. A state change therefore releases or absorbs a material-specific amount of energy called latent energy or *latent heat*. Depending on the state change, the latent energy required to change a unit mass of material from one state to another is called the *heat of fusion* (from solid to liquid) or the *heat of vaporization* (from liquid to gas)

Water's heat of vaporization, the energy to evaporate one gram of water, is 2250 J at100 °C (212 °F) and 2500 J at 0 °C (32 °F). Condensation of one gram of water vapor releases the same amount of energy. If water's heat of fusion (the energy required to change ice to water (333 J/g)) and the heat of vaporization (2250 J/g at 0 °C (32 °F)) are provided, the ice will change state directly to vapor at 0 °C (32 °F).

1.4 Heat and energy

Heat, as described above, is a measure of the vibratory energy stored in matter. The greater the rate of vibration, the greater the heat content. The relationship of heat content to temperature is the most straightforward for ideal gases—the root mean square velocity of the individual gas molecules is a direct measure of the temperature.

The energy used to increase the velocity or vibrations of molecules is called *sensible energy* (because one can sense an increase in temperature in the material). The sensible energy required to raise a unit mass of material one unit of temperature is called the *specific heat capacity* of the material. The specific heat capacity is a strong function of temperature and pressure for many gases, but it can be assumed to be constant over limited ranges of temperature.

When materials undergo a change of state, additional energy is required to reorganize the molecules into the new state. There is a significant difference in total energy content between a gas and a liquid at the same temperature, for instance. A state change therefore gives off or takes up a material-specific amount of energy called *latent energy*. Depending on the state change, the latent energy required to change a unit mass of material from one state to another is called the *heat of fusion* (from solid to liquid) or *heat of vaporization* (from liquid to gas).

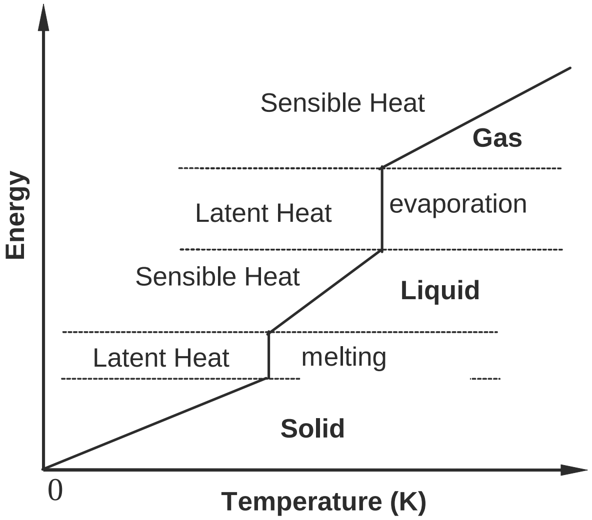


Figure 1.3: Simplified energy-temperature relation for a typical material

Chemical energy is the energy stored in the bonds that join atoms into larger units. This energy can be converted to heat energy only by breaking some of the bonds. Energy of this form is critical to the operation of our modern energy consumptive society.

For example, the combination of oxygen and hydrogen in the presence of a flame converts chemical energy to heat energy in the reaction $O_2 + 2\ H_2 \Rightarrow 2\ H_2O$ + heat. This is a very clear flame, and may be invisible since all flames are seen by the particulate products of incomplete combustion (which form soot in the worst case, and yellow flames in the intermediate).

It might be interesting to note here that hydrogen is not a very convenient form of energy, although it is a very concentrated form. The small size of the molecule means that leakage is difficult to avoid, and storage must be at very high pressures (10 to 100 MPa) or low temperatures (less than -200 C). An alternate method stores H atoms in loose bonds to metals (called metal hydrides), which can be forced to give up their hydrogen slowly when heated. This method has the drawback of weight, volume and expense. The lack of convenience of liquid hydrogen is not as important for NASA, who uses it for many of the largest rockets such as the Shuttle.

The addition of a small amount of carbon to hydrogen results in methane, or swamp gas, CH_4. The combustion of methane has the following reaction: $2O_2 + CH_4 \Rightarrow C0_2 + 2\ H_2O$ +heat. Methane can be simply generated by the anerobic decomposition of most carbon matter in the presence of water, and can be more easily stored than hydrogen, although still under pressure. Adding more carbon creates methanol, or C_3H_8. This has sufficient molecular weight to be a liquid at room temperature (it is an alcohol, but don’t drink it), and enough energy in its molecular bonds that it is used in race cars as fuel.

The carbon in methane and methanol (and ethanol, ethane, etc) all come from the atmosphere and are returned to it. That is, they are carbon neutral and do not add to CO_2 pollution. Oil and gas, on the other hand, are based on carbon stored a long time ago, and hence result in a net increase in atmospheric carbon dioxide and thus are implicated in climate change.

1.5 The nature of porous materials

Although most materials appear solid to the eye, many common building materials, e.g., wood, brick, gypsum, stone and concrete, are actually quite porous. Porosity is defined as the volume of air in a macroscopic sample of the material divided by the macroscopic volume. Apparently solid and heavy materials such as concrete and brick can be as much as 50% air by volume. Materials such as metals and some plastics have very little to almost no porosity.

One simple view of porous materials is to consider them made of a large number of small solid perfectly spherical and equal sized particles packed cubically as shown in Figure 1.4. The spaces between the particles create the pores in this idealized porous material. As the particles become smaller, the surface area increases (Figure 1.5).

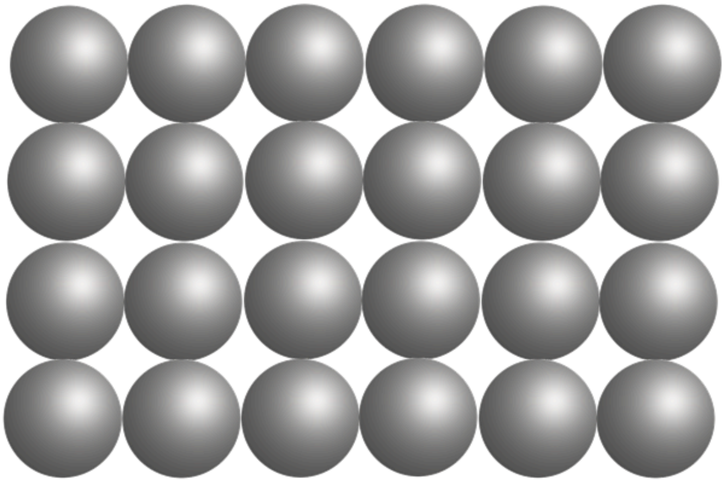


Figure 1.4: Cubical packing of spherical particles

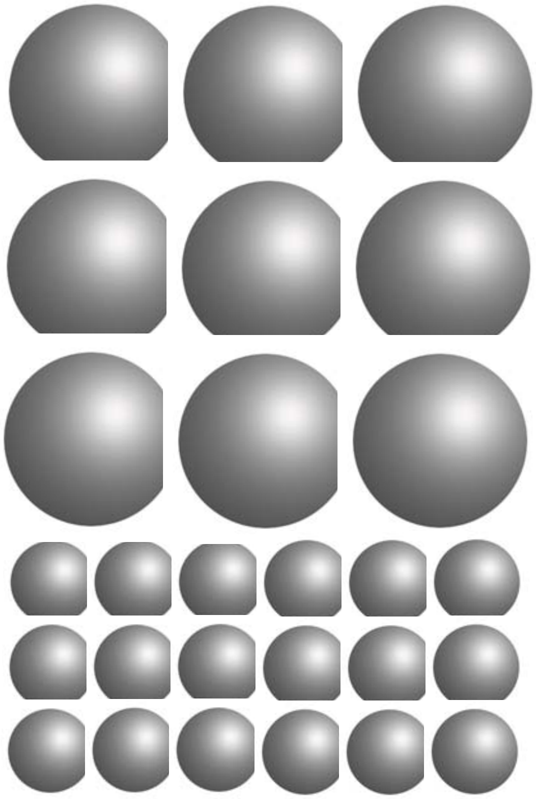


Figure 1.5: Influence of particle size on surface area

Figure 1.6 plots particle size versus surface area under the simple assumption. It can be seen from the figure that some materials have very large internal surface areas. For example, brick typically has an internal surface area of from 0.1 to 5 m^2/g [Arnott and Litvan, 1988], and cured cement gel has internal surfaces totaling at least 10 to 100 m^2/g [Sereda, 1970].

Real materials are composed of a wide variety of particle shapes and sizes of course. Hence, the pores would be expected to be very irregular in shape. Scanning electron photographs confirm that pores are in fact highly irregular and that the solid components are agglomerations of crystals and fibres. These facts mean that real materials will have an even greater surface area and a wide range of pore sizes. Nevertheless, on an average basis, experimental results show that the cylindrical capillary pore model is a useful and reasonable model for most moisture physics. All of the theory that flows presumes that cylindrical pores are involved.

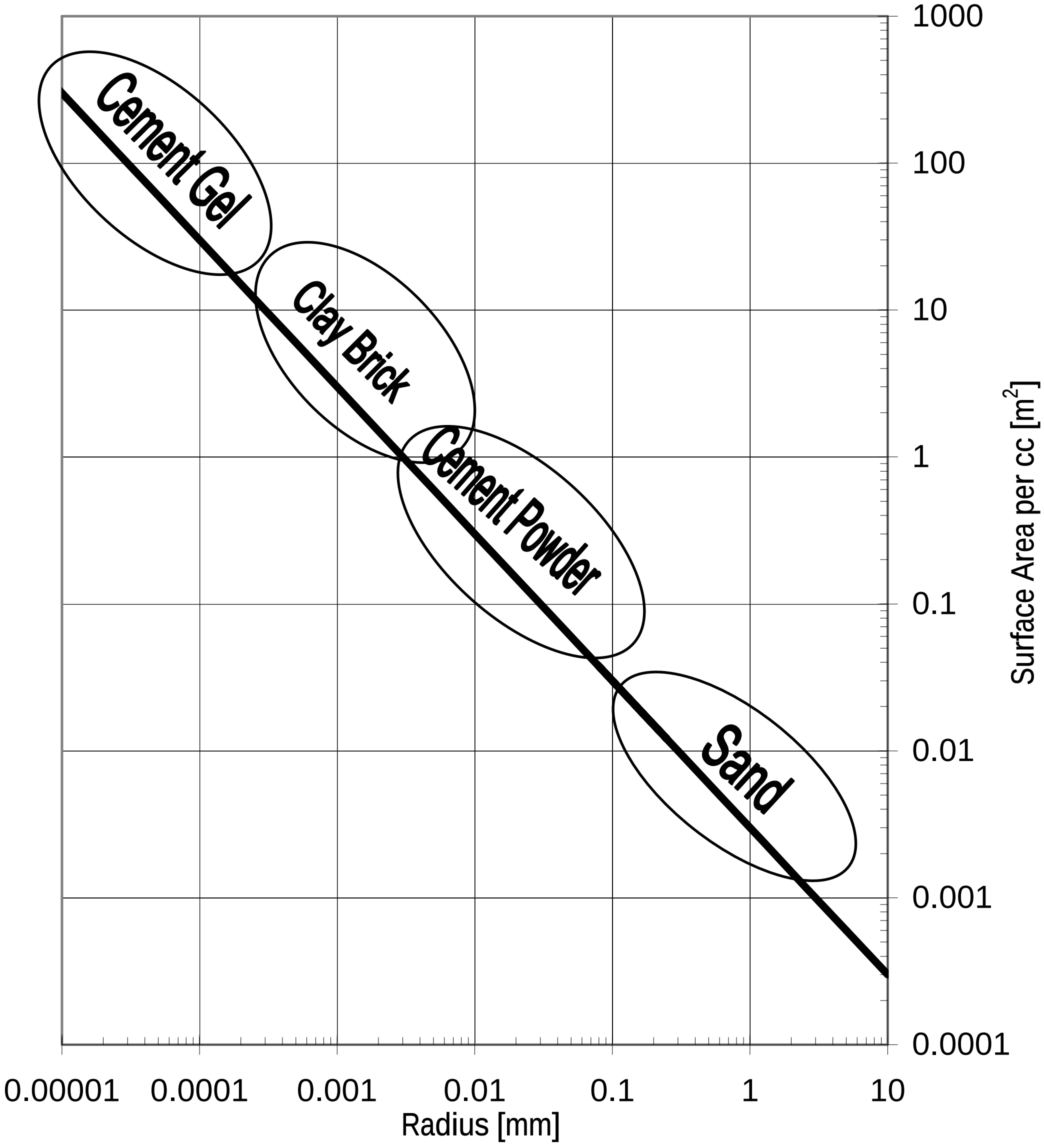


Figure 1.6: Surface area versus particle size

The larger the percentage of volume occupied by small pores, the larger the internal surface area. Because of their large internal volume and surface area, some porous building materials can store their own weight in water (or ice) in their internal pore volume with one-quarter of this amount as adsorbed water vapor on the pore walls at high relative humidities (**Error! Not a valid bookmark self-reference.**).

Table 1.2: Moisture contents of some common building materials

Material	**Density (Dry)** kg/m^3	**Open Porosity (%)**	**MC @ ≅95%RH (M%)**	w_{cap} **(M%)**
Concrete	2200	15-18	4-5	6-8
Brick	1600-2100	11-40	3-8	6-20
Cement Mortar	1800-1900	20-30	5-7	14-20
Softwood	400-600	50-80	20-30	100-200
Fibreboard	240-380	60-80	20-25	100-200
Wood chipboard	700	50-70	15-20	100-150
Expanded polystyrene	32	95	5	> 300
Gypsum (exterior)	1000	70	10	50-100

Note: these values are approximate and from a variety of sources [e.g., Whitley *et al*, 1977; Kumaran, 1996; Lohmeyer, 1996; Pel, 1996; Kuenzel, 1994]

The total porosity, ψ_T, of a completely dry porous material comprised of solid materials and air is normally defined as the ratio of the total air volume (V_a) to the total volume of the material sample (V_T) or that fraction of the porous volume that is not solid. In terms of fractions, X_i is the volume fraction of the *i*th component of the total non-solid volume. The total non-solid volume in a porous material can usefully be divided into the volume fraction of pores that are:

- open, interconnected, and with access to the exterior, X_O,
- dead-end pores connected to exterior X_D, (a subset of X_O), and
- closed or sealed pores with no access to the exterior, X_C.

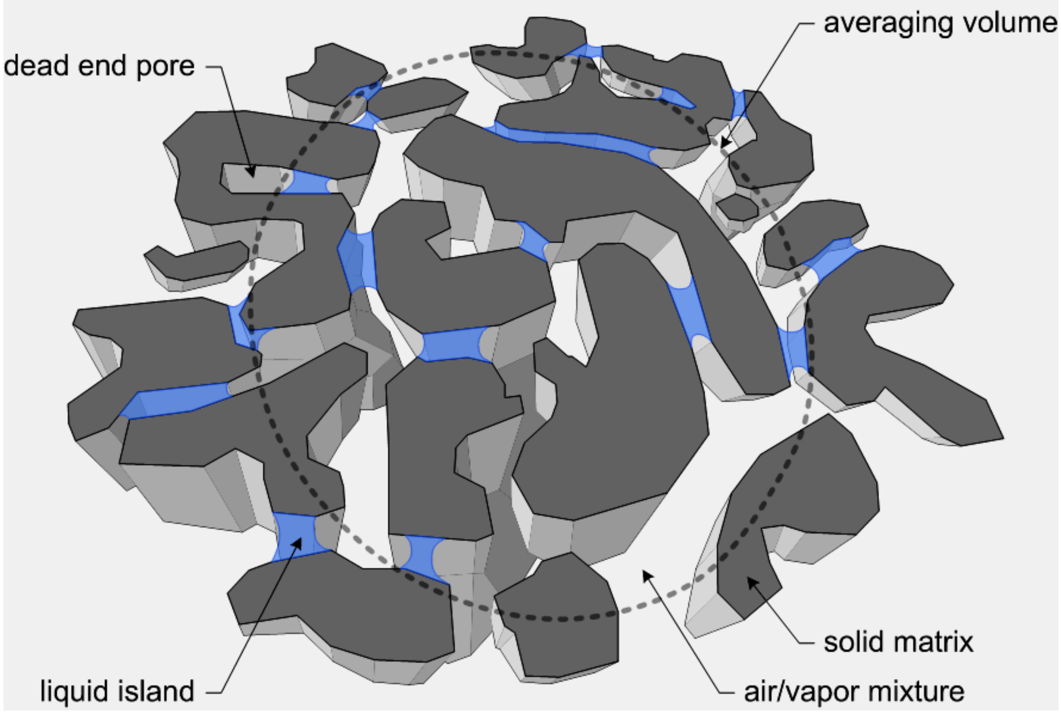


Figure 1.7: Porous Media Definitions

In the assessment of moisture storage, it is the open porosity, $\psi_O = X_O \cdot \psi_T$, that is of interest. The larger the percentage of volume occupied by small pores, the larger the internal surface area. Because of their large internal volume and surface area, some porous building materials can store their own weight in water (or ice) in their internal pore volume with one-quarter of this amount as adsorbed water vapor on the pore walls at high relative humidities (Error! **Not a valid bookmark self-reference.).**

Table 1.2 summarises the range of open porosity that can be expected for a number of building materials.

With respect to liquid moisture transport, an effective porosity $\psi_{eff} = (XO - X_D) \cdot \psi_T$, is used to reflect the fact that dead end pores do not participate in the flow of liquid water through the material.

There are no experimental methods that can accurately and definitively define each of the porosity fractions. However, the open porosity can be approximately measured by various means, including mercury intrusion porisimetery, helium and nitrogen gas adsorption, and vacuum saturation [Haynes, 1973]. Most methods cannot identify closed pores and sometimes fail to measure very small pores (e.g., less than a few nanometers). Another problem arises when measuring materials whose pore structures change with water content because of shrinkage, swelling, or chemical bonding (e.g., wood, gypsum and some plastics).

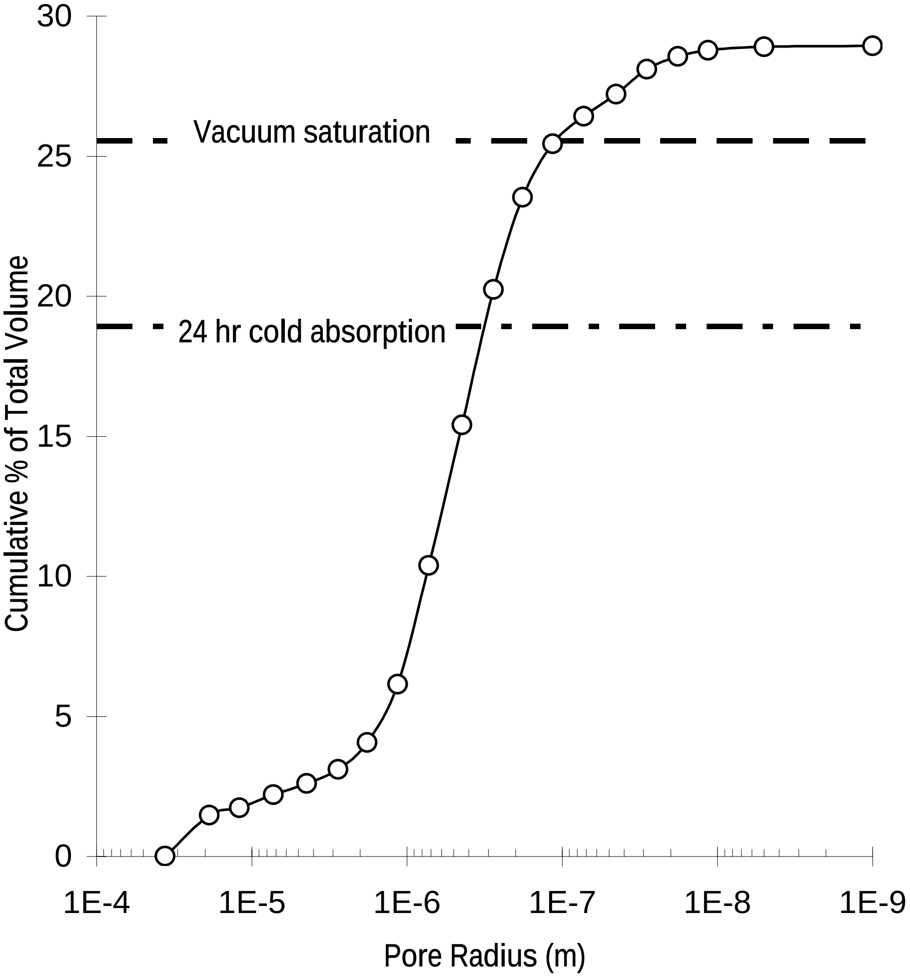


Figure 1.8: Pore size distribution of a representative clay brick [Arnott 1990]
Note: A water molecule is approximately 3 x 10^{-10} m in diameter

The pore size distribution for a representative clay brick is shown in Figure 1.8 as calculated from mercury intrusion testing [Arnott, 1990; Litvan, 1975]. The cumulative percentage of total volume intruded for each of the pore radius ranges is plotted along with the percentage of water absorbed during a vacuum saturation test (25.5% total volume or 88.3% of accessible pore space), and the 24 hour cold water immersion test (18.9% of total volume or 65.4% of accessible pore space). The total open porosity (ψ_O) was 28.9%. Hence, as shown by others [Peake and Ford, 1982], vacuum saturation and immersion may give different results than mercury porisimetry.

Silica

A good place to start looking at materials is to start with natural materials such as silica. Silica, SiO_2, is found in nature in the pure form in quartz. Small impurities