PROPERTIES OF LEAD

Lead has the advantages of low melting temperature and extreme malleability, which allow easy casting, shaping and joining of lead articles. Besides this lead is slow to corrode and there are many examples of lead articles which have lasted for centuries. Lead is relatively abundant. Lead concentrates can be easily extracted from the ore and winning the metal from the concentrate does not need much energy. This reflects also in a fairly low price compared with other non-ferrous metals. Lead can be recycled as a secondary raw material from lead-acid batteries, from metallic scrap and from several composite consumer products in conjunction with existing recycling loops, for example for steel, zinc and copper, at moderate costs.

However, compared with other metals, lead has extremely low strength, exacerbated by its creep and fatigue behaviour. Thus it is unsuitable for applications that require even moderate strength. (Some of its mechanical properties are closer to those of higher strength plastics than most metals.)

Lead is rarely used in its pure form, as small alloying additions considerably increase its strength. For applications requiring higher strengths, composites such as lead clad steel can be used.

The very high density of lead lends itself to some quite different applications, such as shielding against sound, vibrations and radiation, for example as protection for users of computer and TV screens. For these purposes lead is used in metallic form or as lead compounds in lead glasses.

Some compounds of lead have their own useful properties, particularly in relation to colour and glass-forming ability.

2.1   PHYSICAL PROPERTIES

2.1.1   GENERAL PROPERTIES

Freshly cast lead is silvery in colour, but quickly turns dull grey to bluish grey, as the metal at the surface oxidises in the presence of air.

Lead possesses the general physical properties of metals: it is a conductor of electricity and heat (though not as good a conductor as some other metals, such as copper and aluminium), has a metallic lustre, albeit a dull one, and has high density. It has a very low melting point, compared with most other metals, of 327°C. This is useful for ease of casting and joining lead, and also influences some of its mechanical properties, which are described later.

Several different isotopes of lead exist in nature. Their relative concentrations in different mineral deposits can vary; this can be used as a diagnostic tool in identifying sources of lead in soils and sediments.

The physical properties of lead are compared with those of other metals and materials in Tables 2.1(a) and 2.1(b).

2.1.2   DENSITY

Lead has a particularly high density, 11.3g cm^{-3} compared with many other metals (e.g. iron 7.8g cm^{-3}, copper 8.9g cm^{-3}, aluminium 2.7g cm^{-3}. Lead owes its high density to two factors:

● its high atomic number, and hence high relative atomic mass of 207,
● the metal atoms (or, more precisely, ions) are arranged in a dense, close packed structure (face centred cubic structure).

It should be noted that lead is not the densest element: other denser metals include: gold (19.3g cm^{-3}), platinum (21.5g cm^{-3}), tungsten (19.3g cm^{-3}), tantalum (16.6g cm^{-3}) and mercury (13.6g cm^{-3}). Three metals with similar densities to lead are molybdenum (10.2g cm^{-3}), silver (10.5g cm^{-3}) and palladium (12.0g cm^{-3}).

The high density of lead has important bearings on other properties, particularly attenuation of X-rays, gamma rays and sound waves.

2.1.3   ATTENUATION OF X-RAYS AND GAMMA RADIATION

When X-rays or gamma rays pass through matter, they become attenuated; i.e. their intensity diminishes with distance travelled. There is a huge range in the effectiveness of materials at shielding radiation, but they are described by the following equation:

$$I_x / I_o = A. \exp -(\mu . \rho . x)$$

where I_o is the original intensity of radiation

          I_x is the reduced intensity after passing through a thickness x of shielding material

          A   is a constant

          µ   is the mass attenuation coefficient of the shielding material (which varies with wavelength of radiation)

          ρ   is the density of the shielding material.

This equation shows that the ratio of radiation transmitted to original radiation (I_x/I_o) varies inversely and exponentially with the wavelength of the radiation and the density of the shielding material (i.e. as the wavelength of the radiation increases and the shielding material becomes more dense, the amount of radiation transmitted will decrease.)

Lead has a high mass attenuation coefficient, particularly for higher energy X-rays (as have other elements of high atomic number) and high density, so it makes an excellent shielding material. (CRC Handbook of Chemistry and Physics, 1996-7).

2.1.4   RESISTANCE TO IRRADIATION BY THERMAL NEUTRONS

Lead has a very small neutron capture cross section (the only metals with lower values are magnesium and beryllium). In consequence it does not absorb neutrons and therefore does not become radioactive and unstable (although any impurities in the lead can absorb neutrons and thus transmutate).

2.1.5   ATTENUATION OF SOUND

When sound waves pass through matter they become attenuated, that is, their intensity reduces with distance travelled. Sound attenuation is a complex subject, with different processes (and, therefore, different material properties) being important over different ranges of frequencies. However, for many practical applications, mass per unit area is one of the most important factors in calculating the effectiveness of a solid barrier in sound-proofing. As lead is dense, a relatively thin layer of lead can attenuate sound more effectively than a much thicker layer of other less dense sound-proofing materials. The softness of lead also avoids resonant effects.

2.2   MECHANICAL PROPERTIES

Under low loads, all solid materials deform slightly, then return to their original shape when the load is released. This is termed elastic deformation, and is reversible.

At higher stresses, brittle materials fracture and ductile ones (some metals, some polymers) are plastically deformed, i.e. can be stretched, bent etc. and do not return to their original shape when the load is released.

2.2.1   DUCTILITY

Lead is very ductile (or malleable), that is, it can be plastically deformed, and large deformations are possible before the material breaks. In most metals, only very limited deformation is possible before the metal becomes hard and brittle. At this stage, it is necessary to anneal the metal, i.e. leave it to soak in an oven at a suitable temperature (usually a few hundred degrees C) for a suitable time (often around a couple of hours). This softens the metal by allowing processes of stress relief, recovery and sometimes recrystallisation, to occur within the metal. The softened metal can then be further deformed, and the sequence can be repeated.

Lead behaves quite differently to most other metals, because it melts at a much lower temperature. Because its melting temperature is much closer to the temperature at which it is used (normal room or outdoor temperature), some of these recovery processes can occur within the metal spontaneously. This allows extensive deformation before fracture, without the need to anneal the metal. This ability to hammer lead into desired shape is extremely useful for numerous applications, as will be described later.

2.2.2   TENSILE STRENGTH

The tensile strength of pure lead is quoted as 12-17 MPa, which is very much lower than that of the other common metals (mild steel is about 15 times stronger; copper ("as cast") 10 times stronger; aluminium ("as cast") about 6 times stronger.) Even less strong materials (soft pine, plastics) have slightly higher strengths than lead (see Table 2.2). However, as lead slowly deforms with time under a static load, it is necessary to specify the exact testing conditions. This phenomenon, termed "creep", is described below. As with other metals, the strength of lead can be considerably improved by small additions of alloying elements. Antimony, tin and copper are commonly used (see Table 2.3).

2.2.3   CREEP BEHAVIOUR

Creep is the slow plastic deformation of materials under a constant stress. In metals, it can occur at even low temperatures, but the effect is extremely small and only important for the most sensitive applications. This phenomenon is more important at higher temperatures (relative to the melting point),

since displacement of the metal atoms (more precisely, ions) can more readily occur.

Lead is subject to creep at normal temperatures, since its melting temperature is relatively low. This creep can occur at low stresses, leading eventually to failure well below the tensile strength.

The long term "creep strength" of metals is difficult to measure, as tests of many years are required. However, studies have found that creep can occur in lead (of 99.99% purity) at stresses as low as 0.7 MPa (though by a very small amount, elongation of 0.06% after 500 days at 30°C; double the stress produced a 2% extension in the same period (Blasket and Boxall, 1990)). Extrapolation from other tests shows that, under normal conditions, no appreciable creep will be expected at stresses below 1.72 MPa (or if in compression, 2.75 MPa) for 99.9% pure lead (LDA technical notes 1992). Differences in results are assumed to be because of differences in temperature and other test conditions.

Processing conditions and some alloying additions influence the creep behaviour of lead; small additions of copper (widely used for lead sheet) and also silver can improve creep resistance.

2.2.4   FATIGUE

This phenomenon is the failure of metals, after repeated loading cycles, at stresses below the normal tensile strength of the material. It occurs because of the growth of tiny cracks within the material: stresses at the crack tip are much higher than across the bulk of the specimen. It can be caused by mechanical loading and even cycles of thermal expansion. Lead, like many other materials, is subject to fatigue. As with creep behaviour, fatigue resistance can be improved by certain alloying additions, most importantly copper.

2.2.5   FINAL COMMENT

For any application, the proposed design must predict the service conditions which the components will experience. Because of the particular mechanical properties of lead, it is important to comply with the standards set out for the specific building or architectural applications.

2.3   CHEMICAL PROPERTIES

2.3.1   EXTRACTION OF LEAD FROM ITS ORE

The most common ore of lead is galena, lead sulphide (PbS). Extraction of metallic lead from this compound is relatively easy:

1.   roast the sulphide in air, to convert to the oxide
        e.g. $2PbS + 3O_2 => 2PbO + 2SO_2$

2.   heat the oxide in the presence of a reducing agent (such as charcoal, coal)
        e.g. $2PbO + C => 2Pb + CO_2$

On primitive hearths, such as a pile of charcoal and lead ore, the lead on the surface (open to the air), quickly becomes oxidised. This newly formed lead oxide can react with lead sulphide underneath in a double decomposition reaction to yield lead metal:

$$2PbO + PbS => 3Pb + SO_2$$
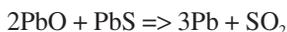
The removal of silver and other impurities from lead is also relatively easy, though separate refining stages are required for removing different impurities. These processes are described in more detail in Chapter 4 - Industry Profile.

Thus, metallic lead of high purity can be obtained with simple technologies, requiring much lower temperatures than the preparation of many other metals, including copper and iron. This is undoubtedly an important reason why lead has been known and used since ancient times.

2.3.2   CORROSION OF LEAD

Contrary to popular opinion, lead is not a completely inert metal, though it is not very reactive. In general, it is less reactive than iron and tin, but more reactive than copper. Under some conditions, lead can slowly dissolve in water (over a period of many years), consuming oxygen and displacing hydrogen.

The corrosion of lead is usually very slow, because many of its compounds can form protective barriers on the surface of the metal. Lead generally displays good durability when exposed to air and to many aqueous solutions, even in some fairly hostile environments. However, even small amounts of corrosion are important in the case of lead, not just because the metal article can lose its integrity and fail, which is the prime concern to the design engineer, but because even low concentrations of lead dissolved in drinking water, or ingested by other routes, can potentially be harmful to health, as discussed in detail in Chapter 6.

Lead in air
In moist air, lead quickly tarnishes, forming a thin layer of lead oxide on the surface. This can further react with carbon dioxide in the air to form lead

carbonate. This surface layer provides a high degree of protection against further reaction under normal atmospheric conditions.

Lead in water
Corrosion of lead in water, as with other metals, is an electrochemical reaction. Some parts of the surface act as anodes (positive electrodes), while other parts act as cathodes (negative electrodes).
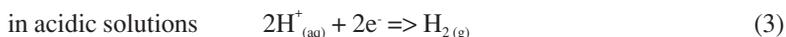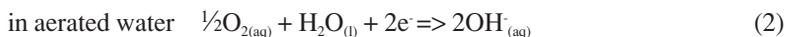
Anodic reaction
The metal dissolves into aqueous metal ions, and electrons are generated.

$$Pb_{(s)} => Pb^{2+}_{(aq)} + 2e^- \quad\quad (1)$$

Cathodic reaction
In highly concentrated metal salt solutions, metal can be deposited on the cathode, as in electroplating. However, under normal circumstances this does not occur, and cathodic reactions involve water and oxygen. There are two alternative reactions, which are important:

in aerated water $\quad \frac{1}{2}O_{2(aq)} + H_2O_{(l)} + 2e^- => 2OH^-_{(aq)} \quad\quad (2)$

in acidic solutions $\quad\quad 2H^+_{(aq)} + 2e^- => H_{2\,(g)} \quad\quad (3)$

Both reactions (2) and (3) can occur together. However reaction (2) is generally more rapid than reaction (3), and accounts for most of the corrosion. So, if the water is de-aerated, the corrosion rate greatly reduces by a factor of about ten. Unfortunately, normal waters are almost always aerated.

The rate of reaction (3) on exposed metal surfaces will be greater in more acidic solutions (having lower pH) as the concentration of hydrogen ions is greater. Both an anodic and a cathodic reaction must happen simultaneously. If either is blocked, then the whole reaction stops. The dissolution of lead in water is called plumbosolvency. Whether or not it occurs depends upon the composition of the water and other factors, described below.

Control of corrosion reactions
In practice, the corrosion of lead is often controlled by its reaction products (lead salts) building up on the surface of the metal. Many of these salts have very low solubilities in water, particularly lead sulphate, carbonate and chromate. If they form a barrier which covers the whole surface, and the barrier is not damaged, the rate of corrosion is greatly reduced.

Table 2. 4 lists the solubility of some lead compounds in water. Most lead salts have low solubilities, and thus have the potential to form protective layers on the

surface. This property gives lead particularly good resistance to sulphuric, phosphoric and chromic acids, making it extremely useful in the chemical and other industries. Notable exceptions are lead acetate, nitrate and chloride which are very soluble and do not offer protection.

It must be stressed that the pH (measure of acidity or alkalinity of a solution) and the presence of other species, can greatly affect the solubility of these products. Lead sulphate is even more insoluble in aqueous sulphuric acid than in water, whereas lead carbonate can be dissolved in both acid and alkaline solutions; the oxides of lead are more soluble in some acids.

Thus, the rate of dissolution of lead depends upon the exact composition of the water to which it is exposed, including dissolved gases and minerals. The hardness of the water is a very important factor, as lead can slowly dissolve in soft water, but generally does not dissolve in hard water. Temperature and rate of flow of solutions can also influence corrosion rates.

Lead alloys will generally have higher corrosion rates than pure lead, because inhomogeneity of composition encourages some areas to act as local anodes or cathodes.

Rates of surface attack by a wide range of natural and industrial waters, including seawater, are quoted as lying between 2 and 20µm per year (Blaskett and Boxall, 1990). This corresponds to a mass loss of 20 to 230gm^{-2} exposed area per year (allowing for the high uncertainty level in these figures). The risk of lead dissolving in certain environments, such as in drinking water and soil, will be discussed in more detail in Chapters 6 and 7.

2.4   PROPERTIES OF SOME COMPOUNDS OF LEAD

Many lead compounds have strong colours, from white to yellow to red and black, most of which do not alter on prolonged exposure to sunlight. The compounds are also relatively stable, and so have found use in paints and other colourants.

Lead oxide is a good glass former and can be mixed in all proportions with ordinary silicate glasses. It improves the appearance of silicate glasses, increases their density, and lowers their melting temperature.

The reactions of lead oxide in dilute sulphuric acid are fundamental to the operation of a lead-acid battery. This is discussed in detail in Chapter 3.2.1.

TABLE 2.1(a) Physical Properties of Lead and a Selection of other Metals and Materials

	Pb	Cu	Fe	Al	Zn	Sn
density (g cm^{-3})	**11.34**	8.96	7.87	2.70	7.14	7.3
melting point (°C)	**327.5**	1084	1536	660	419.5	231.9
boiling point (°C)	**1750**	2560	2860	2520	911	2270
atomic number	**82**	29	26	13	30	50
atomic weight	**207.19**	63.54	55.85	26.98	65.37	118.69
mean specific heat capacity at 100°C (Jkg^{-1}K^{-1})	**129.8**	386	456	917	394	226
thermal conductivity (at ambient temp) (Wm^{-1}K^{-1})	**34.9**	397	78.2	238	119.5	73.2
coefficient of thermal expansion 0-100°C (10^{-6}).K^{-1}	**29.0**	17.0	12.1	23.5	31	23.5
electrical resistivity at 20°C, (μ ohm cm)	**20.6**	1.69	10.1	2.67	5.96	12.6

TABLE 2.1(b)

	Pb	Polymers			Ceramic	Glass	
		HDPE	PP	uPVC	porcelain	soda glass	leaded glass
density (g cm^{-3})	**11.34**	0.94-0.96	0.90-0.91	1.3-1.4	2.3	2.5	3-4
melting point (°C)	**327.5**	130	60			1200-1500	
mean specific heat capacity at 100°C (Jkg^{-1}K^{-1})	**129.8**		1920	840-1170	~750	~700	
thermal conductivity at ambient temperatures (Wm^{-1}K^{-1})	**34.9**	0.45-0.52	0.12	0.12-0.17	1.5-2.5	0.85 (light flint)	0.55 (dense flint)
coefficient of thermal expansion 0-100°C (10^{-6}) K^{-1}	**29.0**	100-200	60-100	70-80	2-6	7.5	

(adapted from Smithells, 1992 and Kaye and Laby, 1995)

Pb - lead; Cu - copper; Fe - iron; Al - aluminium; Zn - zinc; Sn - tin
HDPE - high density polyethylene; PP - polypropylene; uPVC - unplasticised PVC

TABLE 2.2   Tensile Strengths of Lead and some other Metals and Materials
(All figures are for pure metals in the as cast condition unless otherwise stated. The strength of most metals is higher (approximately doubled) in rolled condition, and also much increased by alloying additions.)

	Pb	Cu	Fe	Al	Zn (rolled)	Sn	soft solder
UTS (MNm^{-2})	**12-17**	120-170	100-230	90-100	110-150	20-35	55-75

	Pb	glass	leather belt	pine spruce, along grain	oak	HDPE	PP	PVC
UTS (MNm^{-2})	**12-17**	30-90	30-50	20-50	60-110	20-36	28-40	50

Explanatory note: UTS is the ultimate tensile strength of the material, that is, the stress at which the material breaks. It is usually measured in special testing apparatus. Exact values of properties may vary with different testing conditions.

Results of tensile tests on lead, at 20°C, tested at a speed of 0.5mm/min, found the strength was 13.2 MNm^{-2}; testing at a higher speed of 25mm/min gave a measured strength of 11.5 MNm^{-2}.

For metals, strength is very sensitive to such factors as: temperature, material preparation, rate of cooling, any deformation or further heat treatment, the presence of impurities (even in trace amounts); for glass, the amount of handling has a marked effect (decreasing strength); polymers are sensitive to variables in manufacturing process, and degrade after exposure to heat and ultra-violet radiation (Kaye and Laby, 1995).

Note: the creep strength of pure lead, which allows for slow deformation, is much lower, taken as around 1.5-3MNm^{-2}.

TABLE 2.3   Strengthening Effect of adding Antimony to Lead

Antimony content %	Tensile strength (MNm^{-2})
0	17.25
1	23.46
2	29.00
4	39.05
6	47.20
8	51.20
10	52.92
11	52.58
12	57.61

(Blaskett and Boxall, 1990)

TABLE 2.4 Solubility of some Compounds of Lead in Water and other Solutions

Compound	Chemical formula	Solubility in Water (g/100ml)	Temperature (°C)	Soluble in other solutions?
lead acetate	$Pb(C_2H_3O_2)_2$	44.3	20	yes
lead bromide	$PbBr_2$	0.844	20	in acid, KBr
lead carbonate	$PbCO_3$	0.00011	20	in acid, alkali
basic lead carbonate	$PbCO_3$ $2Pb(OH)_2$	insoluble	-	
lead chlorate	$Pb(ClO_3)_2$	151.3	18	
lead chloride	$PbCl_2$	0.99	20	in ammonium salts, slightly in dilute HCl, and ammonia
lead chromate	$PbCrO_4$	0.0000058	25	in acid, alkali
lead fluoride	PbF_2	0.064	18	in HNO_3
lead hydroxide	$Pb(OH)_2$	0.0155	18	
lead iodide	PbI_2	0.063	18	in alkali, KI
lead nitrate	$Pb(NO_3)_2$	56.5	18	in aq. alcohol, NH_3, alkali
lead oxalate	PbC_2O_4	0.000166	18	
lead oxide: litharge	PbO	0.0017	18	in HNO_3, alkali, ammonium chloride
red lead oxide	Pb_3O_4	insoluble	-	in hot HCl, acetic acid
lead dioxide	PbO_2	insoluble	-	in dilute HCl, slightly in acetic acid
lead ortho-phosphate	$Pb_3(PO_4)_2$	0.000014	18	
lead sulphate	$PbSO_4$	0.00425	25	very low solubility in sulphuric acid; dissolves in other acids and ammonium salts
lead sulphide	PbS	0.01244	18	in acid, not in alkali
lead sulphite	$PbSO_3$	insoluble	-	

(adapted from Kaye and Laby, 1995 and Blaskett and Boxall, 1990)