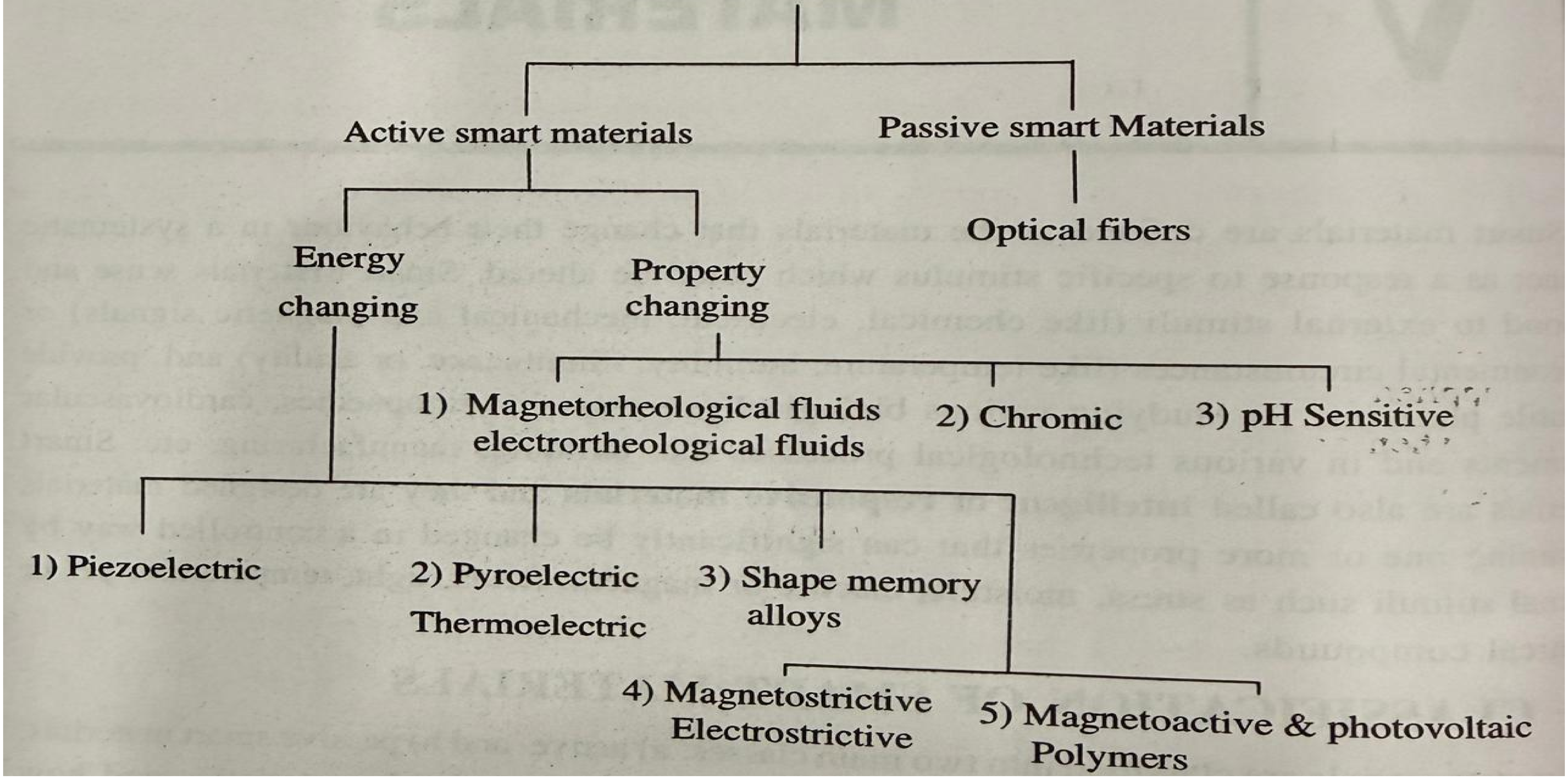
UNIT-5 ADVANCED MATERIALS

- **SMART MATERIALS**
- Smart materials are defined as the materials that change their behavior in a systematic manner as a response to specific stimulus which can be altered.
- They sense and respond to external stimuli like chemical, mechanical, electrical and magnetic signals or environmental circumstances like temperature, humidity, illuminance , acidity
- Helps for studying biological processes in orthopedics , cardiovascular treatments and in various technological processes like building, manufacturing etc.
- Also called as intelligent or responsive materials

SMART MATERIALS



Passive smart material:

- capable of transferring energy without transducing ,converting one form of energy or information into another
- Needs a power supply and not change their characteristics when exposed

to environmental conditions

optical fibres

Active smart material:

- Can transduce energy
- Two types

Energy changing smart materials: convert one form of energy into another (thermal,electrical,chemical,mechanical into another)

Ex: photo voltaic cells convert solar energy into electricity

Piezoelectric: convert mechanical into electrical energy and vice versa

Ex: quartz , aluminum nitride

Pyroelectric: generate electrical charges in response to temperature fluctuations ex:gallium nitride, cesium nitrate, aluminum nitride, and zinc oxide

Shape memory alloys : remembers its original shape and that when deformed returns to its predeformed shape when heated

Super elastic behaviour at high temperature

Ex:copper-aluminium-nickel and nickel-titanium

- Magnetostrictive: exhibit change in shape under the influence of magnetic field ex:cobalt, iron, nickel, iron-aluminum alloy
- Electrostrictive: exhibit a dimensional change upon upon applied electric field ex:lead magnesium niobate ,lead magnesium niobate--lead titanate
- Chromic:undergo various colour changes through alteration of electron density of a substance caused by the influence of external stimuli. Ex:spiropyrans, spironaphthoxazines, and silver chloride
- pH sensitive:change in volume when the pH of surrounding medium changes ex:Chitosan, Poly(acrylic acid)

- Electrorheological fluids:exhibit fast and reversible changes in their rheological properties under the influence of external electrical field

ex:hydrocarbon or silicon oil

- Magnetorheological fluids:under the influence of magnetic field ,it increases its viscocity to the point of becoming a viscoelastic solid

Ex:iron oxide, or nickel-based particles

- Magnetoactive polymers:respond to magnetic fields with large deformation or tunable mechanical properties.

Ex: carbonyl iron powders, iron (II, III) oxides

Photovoltaic polymers: produce electricity from sunlight by the photovoltaic effect.

Ex:polycrystalline silicon, monocrystalline silicon, amorphous silicon

Shape memory alloys:

- They exhibit a phase transition between two different crystalline structures.at specific temperatures.
- When heated above certain temperature , SMAs revert to their original shape due to this phase change.

Ex: Nickel-Titanium alloys (nitinol) ; Copper-Aluminum-Nickel alloys

Nitinol:

- It is a nickel-titanium alloy composed of 50-51% nickel and 49-50% titanium and a smart material known for its shape memory, super elastic properties.
- It is highly valuable in engineering and medical applications
- It responds to external stimuli like temperature or stress and reverts to predefined shape or exhibit elasticity

- It is prepared by melting high purity nickel and titanium using vacuum arc or an induction melting.
- Then it is casted into ingots under controlled conditions to minimize impurities.
- The alloy is shaped through hot and cold working ,then heat treated at 400-600 C to set its shape memory or super elastic properties

Properties:

- Tunable from 50 to 100 C based on Ni-Ti ratio and heat treatment
- Its young modulus is 30-40 Gpa(martensite state) 70-90 Gpa(austenite state)
- Its strain recovery is upto 8% in super elastic mode,full recovery in shape memory mode
- It has excellent corrosion resistance due to titanium oxide layer , ideal for biomedical and aerospace use.

Applications of SMAs

- Medical: used in making stents, guide wires, orthodontic arches, surgical tools due to biocompatibility and shape memory.
- Aerospace: used in actuators, deployable structures for light weight, adoptive components.
- Robotics: flexible actuators mimicking muscle behaviour
- Consumer goods: eye glass frames, self bending antennas and temperature responsive valves.

BIOSENSORS

BIOSENSORS

- Biosensors are devices used to detect and measure specific substances called analytes.
- The first biosensor was developed by Leland C. Clark in 1956 for oxygen detection.
- Today, biosensors are widely used in healthcare, environmental monitoring, and food safety.
- A common example is the glucometer, which helps diabetic patients monitor their blood glucose quickly and accurately.

Examples:

- Glucometer- Measures blood glucose
- Pulse Oximeter- Measures oxygen level and heart rate
- COVID-19 Test Kit- Detects viral antigens/antibodies
- Alcohol breath Analyzer- Estimates the blood alcohol level
- Air Quality Monitor- Detects air pollutants
- Food Safety Sensors- Detect pathogens and pesticides in food products
- Implantable Biosensors- Monitor body parameters continuously

A biosensor is an analytical device that combines a biological component with a detector to measure a specific substance in a sample.

Characteristics of Biosensors:

- Specificity: Detects only the target analyte.
- Sensitivity: Detects even low concentrations.
- Reproducibility: Gives consistent results.
- Rapid response: Quick detection and signal.
- Stability: Long-lasting and reliable.
- Portability: Small and easy to use.
- Cost-effective: Affordable for wide use.

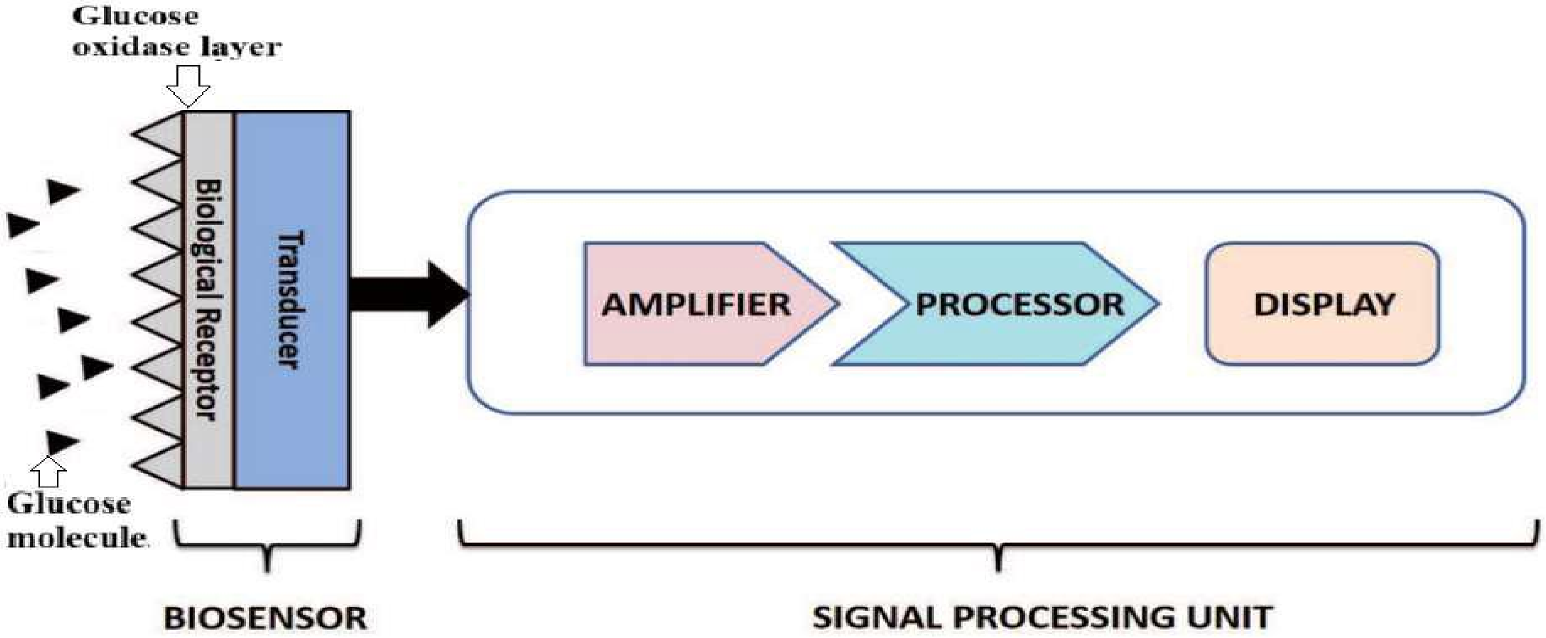
Types of Biosensors:

Based on the type of transducer, the biosensors are of following types-

- Amperometric biosensor: Measures the current produced by oxidation or reduction of the analyte.
- Potentiometric biosensor: Measures the change in electrode potential (voltage) due to the analyte.
- Conductometric biosensor: Measures the change in electrical conductivity of the solution caused by the analyte.
- Optical biosensor: Measures the change in light properties (absorbance/fluorescence) due to biological interaction.
- Piezoelectric biosensor: Measures the change in frequency of a crystal due to mass change on its surface.

Amperometric glucose monitor biosensor:

- An amperometric glucose biosensor determines the glucose concentration in blood by measuring the electric current produced during the enzymatic oxidation of glucose.
- It is widely used in diabetic monitoring, clinical diagnostics, and biomedical research



Working:

A glucose monitor operates through following steps-

Target Analyte
(Glucose in blood)
↓
Biological Recognition
(Glucose interacts specifically with the enzyme glucose oxidase immobilized on electrode surface)
↓
Physical or Chemical Change
(Enzymatic oxidation of glucose produces hydrogen peroxide which undergoes further oxidation to generate electrons)

$$\text{Glucose} + O_2 \xrightarrow{\text{Glucose oxidase}} \text{Gluconic acid} + H_2O_2$$

$$H_2O_2 \rightarrow 2H^+ + O_2 + 2e^-$$

↓
Transduction
(The electrode converts the electron flow into an electric current)
↓
Signal Processing
(The current is amplified and processed)
↓
Output
(Glucose concentration is displayed on the monitor)

Advantages of Amperometric Glucose Biosensor

- High sensitivity and accuracy
- Fast response time
- Requires small sample volume
- Portable and user-friendly
- Suitable for real-time monitoring

Limitations

- Enzyme activity decreases with temperature, pH variation, long-term use
- Interference from substances like ascorbic acid, uric acid.

CEMENT

Cement is described as a building material which possesses adhesive and cohesive properties to bind rigid masses like stones, bricks, building blocks etc. It possesses the property of setting and hardening when mixed with water to give a paste.

The essential constituents of cement used for constructional purposes are compounds of calcium (calcareous) and Al + Si (argillaceous), materials.

PortlandCement

William Aspdin (1824) is generally recognized as the father of the modern Portland cement industry, as he produced improved cement by heating a mixture of limestone and clay and crushing the resulting product to a fine powder.

Portland cement is most widely used non-metallic material of construction. It is also known as ‘magic powder’ and is a mixture of calcium silicates and calcium aluminates with small amount of gypsum.

The name Portland cement was used because this powder, on mixing with water, sets to give a hard, stone-like mass which resembles the Portland rock.

Raw materials required

a) **Calcareous materials:** CaO (such as Limestone, chalk, marl, etc.).
b) **Argillaceous materials:** Al_2O_3 and SiO_2 (such as Clay, shale, slate, aluminium ore-refuse etc).
c) **Gypsum:** ($CaSO_4.2H_2O$)

Composition of Portland cement

A good sample of Portland cement has the composition of

- Calcium oxide or lime (CaO) = 60 – 70%
- Silica (SiO_2) = 20 – 24%
- Alumina (Al_2O_3) = 5 – 7.5%
- Magnesia (MgO) = 2 – 3%
- Ferric oxide (Fe_2O_3) = 1 – 2.5%
- Sulphur trioxide (SO_3) = 1 – 1.5%
- Sodium oxide (Na_2O) = 1%
- Potassium oxide (K_2O) = 1%
- Gypsum ($CaSO_4.2H_2O$)

During the manufacture of Portland cement, great care should be taken, because

a) Excess lime in cement results in cracks during setting.
b) On the other hand if the lime content is less, the cement is low in strength and sets very soon.
c) Excess silica produces a slow hardening cement.
d) Excess of alumina even though hastens the setting, it weakens the cement.
e) If iron is not present in cement it will be white and hard to burn. The presence of iron imparts a grey colour and also strength to the cement.
f) Presence of excess of alkali oxides causes cement efflorescence.
g) If excess of sulphur trioxide is present, it will reduce the soundness of the cement. (Volume change that takes place when cement is hydrated is called soundness. If volume changes are less then cement is considered to be sound.

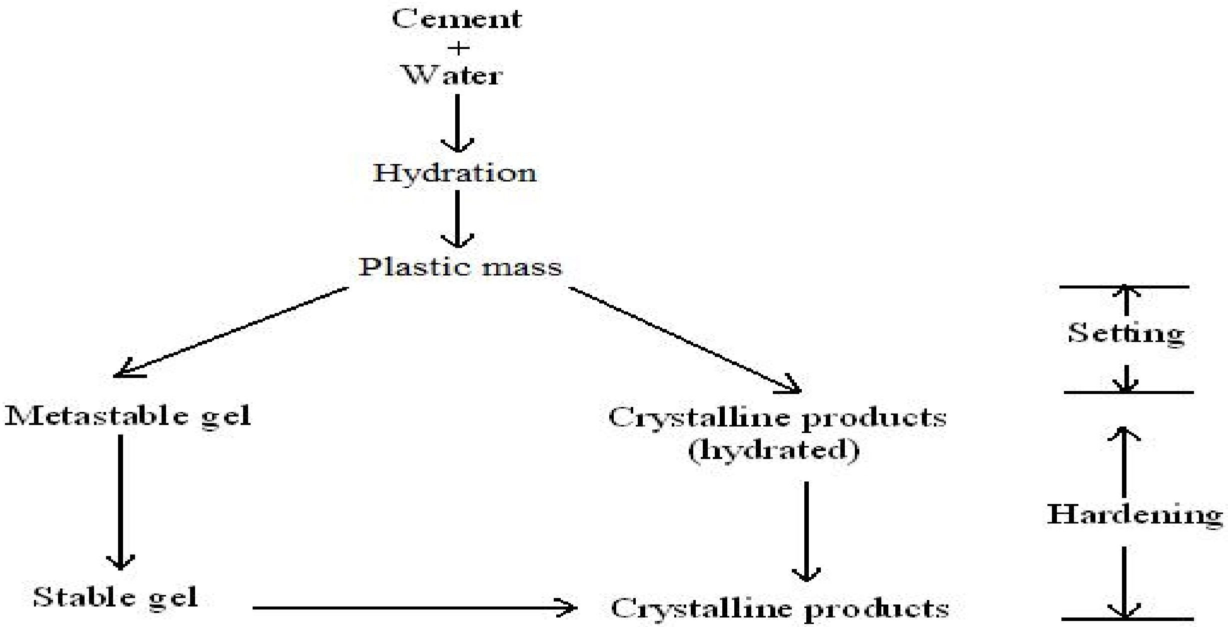
Gypsum helps to retard the setting action of cement. It enhances the initial setting time of cement.

Setting and hardening of cement

When water is added to the cement hydration of cement takes place and a plastic mass called cement paste is formed and then gel and crystalline products.

The process of solidification comprises of i.) Setting and then ii.) hardening

Setting is defined as stiffening of the original plastic mass, due to initial gel formation. Hardening is development of strength, due to crystallization.



Chemical reactions involved in Setting and hardening of cement:

i) Day-1:

When cement is mixed with water, at first, hydration of tricalcium aluminate take place rapidily(within 1 day)and the paste becomes quite rigid within a short time wish is known as intial set or flash set.

$$3CaO.Al_2O_3 + 6H_2O \rightarrow 3CaO.Al_2O_3.6H_2O + 880\ KJ/Kg$$

Tricalcium aluminate **hydrated tricalcium aluminate(crystalline)**

In order to retard the rapid hydration of C_3A, gypsum is added during grinding of cement clinkers.

Gypsum reacts with C_3A to give insoluble calcium sulpho aluminate complex, which does not possess hydrating property and retards early setting of cement.

$$C_3A+3CASO_4.2H_2O \longrightarrow C_3A.3CASO_4.2H_2O$$

ii) Day-2 to7:

Ater the hydration of C_3A,C_3S begins to hydrate to give tobermonite gel and crystalline $Ca(OH)_2$. This is responsible for the development of initial strength of cement. The hydration of C_3S gets completed within 7 days. It does not contribute much to the strength of cement.

$$2(3CaO.SiO_2) + 6H_2O \rightarrow \underbrace{3CaO.SiO_2.3H_2O}_{\textbf{Tobermonite gel}} + \underbrace{3Ca(OH)_2}_{\textbf{crystalline}} + 500KJ/kg$$

iii)Day-7 to 28:

Dicalcium silicate reacts with water very slowly and gets completed in 7 to 28 days.

The strength developed by cement paste at any time, depends upon the amount of gel formed and the extent of crystallization.

Initial setting of cement–paste is mainly due to hydration of tricalcium aluminate (C_3A) and gel formation of tetracalcium aluminoferrite.

$$3CaO.Al_2O_3 + 6H_2O \rightarrow 3CaO.Al_2O_3.6H_2O + 880\ KJ/Kg$$

Tricalcium aluminate **hydrated tricalcium aluminate(crystalline)**

$$4CaO.Al_2O_3.Fe_2O_3 + 7H_2O \rightarrow 3CaO.Al_2O_3.6H_2O + CaO.Fe_2O_3.H_2O + 420KJ/Kg$$

Crystal **gels**

These gels shrink with passage of time and leave some capillaries for the water to come in contact with C_3S and C_2S to undergo further hydration and hydrolysis reactions enabling the development of greater strength over a length of time.

Final setting and hardening of cement paste is due to the formation of tobermonite gel plus crystallization of calcium hydroxide and hydrated tricalcium aluminate.

$$2CaO.SiO_2 + xH_2O \rightarrow 2CaO.SiO_2.xH_2O$$

Gels

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3CaO.SiO_2.3H_2O + 3Ca(OH)_2$$

Tobermonite gel

PHASE RULE

- Important tool used for quantitative treatment of systems in equilibrium.
- Enables to predict the conditions that must be specified for a system to exhibit equilibrium
- Significant industrially and commercially , for steels, alloys , ceramics and semi conductors.
- Basis of separation procedures in petroleum industry, food formulations, preparation of cosmetics.
- Important tool to deal with behavior of heterogeneous systems.
- Helps in predicting the effect of temperature, pressure, and concentration on heterogeneous system in equilibrium.

- Explains the equilibrium between the various components existing in heterogeneous system.
- Applicable for heterogeneous systems in which the equilibrium depend on changes in temperature ,pressure an concentration and should not be effected by gravity, surface forces, electrical forces or magnetic forces.
- Phase rule equation F=C-P+2

where, F is no. of degrees of freedom or variables ; C is no.of components of system, P is no.of phases of system,

it relates the number of components and phases to the number of degrees of freedom of the system

Phase: A homogeneous , physically distinct and mechanically separable section of the system from other sections by different boundary surfaces

Ex: At freezing point, water exists in three phases

ice ↔ water ↔ water vapour

solid liquid gas

Component: The minimum number of chemical species that may be independently varied to indicate the composition of each phase

it can be either element or compound

Ex: water system

All 3 phases has the same composition H2O.the composition of each phase is expressed in terms of H2O.so this is a one component system

Degrees of freedom :The minimal number of independently specified variables such as composition, temperature and pressure that are necessary to fully define the state of the system.

- If F=0, the system is non-variant or invariant
- If F=1, univariant
- If F=2, bivariant

Ex: water system

Three phases are in equilibrium only at particular temperature and pressure.so zero variant

water↔vapour

To define the system,either T or P are required.so univariant

Phase diagram:

- Graphical representation of chemical equilibrium
- It illustrates the conditions of equilibrium between various phases of a substance
- Also called equilibrium diagram
- The phase diagram consists of
  - --regions or areas
  - --lines or curves
  - --point

One-component system: water

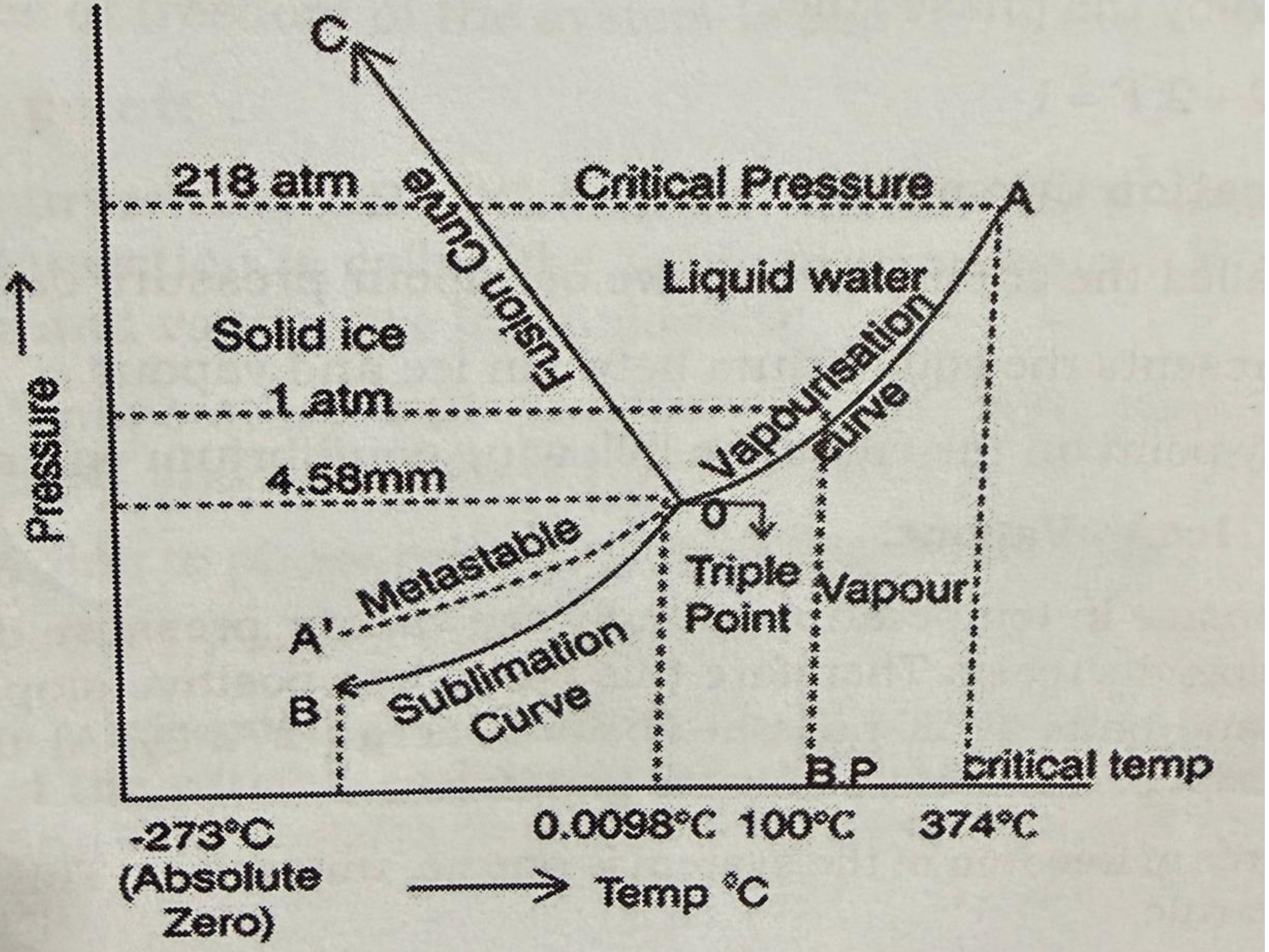
- Water exists in 3 phases – Solid ,Liquid,vapour
- Typical example for one component system
- It shows the following different equilibria

liquid ↔ vapour

solid ↔ vapour

solid ↔ liquid

- The number of these phases which can exist in equilibrium at any time depends on the conditions of T and P


C
218 atm
Critical Pressure
A
Fusion Curve
Liquid water
Solid ice
Vapourisation curve
1 atm
4.58mm
0
Metastable
Triple Point
Vapour
A'
Sublimation Curve
B
B.P
critical temp
Pressure
-273°C (Absolute Zero)
0.0098°C
100°C
374°C
Temp °C

curves	**areas**	**point**
OA=vaporization curve	AOB=vapor only	O=triple point
OB=sublimation curve	BOC=ice only	
OC=fusion curve	AOC=liquid only	
OA’ = metastable curve		

In water system, equilibrium involves two phases and shows the relation between solid , liquid and gaseous states of the substance as a function of T and P

Curves:

OA:

- Vaporization curve of water
- Represents equilibrium between liquid water and vapour
- At any point on the curve, liquid water↔ vapour
- From the phase rule :

  F= C-P+2 = 1-2+2 = 1 The curve has one degree of freedom i.e., univariant
- To describe the system at any time it is necessary to state either temperature or pressure .
- If we fix the temperature , the pressure will be fixed automatically . So the system is univariant.
- The critical temperature is 374C and critical vapor pressure is 218 atm
- Beyond point A, the two merge into each other and only vapor phase exists.

OB:

- Sublimation curve or vapor pressure curve of ice
- Represents equilibrium between ice and vapour
- At any point on the curve, ice ↔ vapour
- From the phase rule :

F= C-P+2 = 1-2+2 = 1 The curve has one degree of freedom i.e.,univariant

- The curve starts at ‘O’ and ends at B i.e., at absolute zero(-273 C)
- No vapor exists at this T and only ice is present

OC:

- Fusion curve or melting point curve of ice
- Represents equilibrium between ice and water
- At any point on the curve, ice↔ water
- From the phase rule :

$F= C-P+2 = 1-2+2 = 1$ The curve has one degree of freedom i.e., univariant

- This curve shows the effect of pressure on melting point of ice .
- The curve is slightly inclined towards the pressure axis .
- It indicates that the melting point of ice decreases with increase in pressure .
- So the fusion curve has a negative slope.

OA’:

- Metastable curve or vapor pressure curve of super cooled water
- It represents the liquid water and water vapour at metastable equilibrium .
- It is sometimes possible to cool water below it’s freezing point without turning into solid ice ,which is called super cooled water
- It is a very unstable condition
- Along OA’ the supercooled water is in metastable equilibrium with vapor. Super cooled water↔ vapour
- In presence of ice or any solid or by stirring, it changes into ice and the curve merges into OB.
- Degree of freedom is univariant

Triple point ‘O’ :

- The three curves OA , OB and OC meet at point O . This point is known as the TRIPLE POINT .
- At this point the three phases (solid , liquid and vapour) of water system remain in equilibrium with each other.
- The point has a definite temperature and pressure which is 0.0098C (273.16 K) at 4.58 mm pressure .
- Neither the temperature nor the pressure can be varied.
- This means that the point has no degree of freedom , the system is invariant .
- From the phase rule , $F=1-3+2=0$

Areas:

AOB – vapour phase

AOC – liquid phase

BOC – ice phase

- Single phases are capable of stable existence
- From the phase rule $F = C - P + 2 = 1 - 1 + 2 = 2$ Thus the phase areas have two degrees of freedom(bivariant)
- To define the system completely at any point in these areas both the temperature and pressure are necessary.

Two-component system:

- The three variables are to be specified in order to describe the state of phase.
- Graphical representation of three variables on a phase diagram (3D)

is difficult

- So represented 2D considering two variables and third one keeping constant
- If P is kept constant, the phase diagram is called isobaric
- If T is kept constant, isotherm
- If composition is kept constant, isopleths

Condensed system:

- For two component solid/liquid system ,the gas phase is absent and effect of pressure on equilibrium is very small.
- Only 2 variables,T and concentration are considered.
- Such a solid/liquid system with out gas phase is called condensed system.
- The degree of freedom is reduced to one and the phase rule equation is called condensed phase rule

$$F' = C-P+1$$

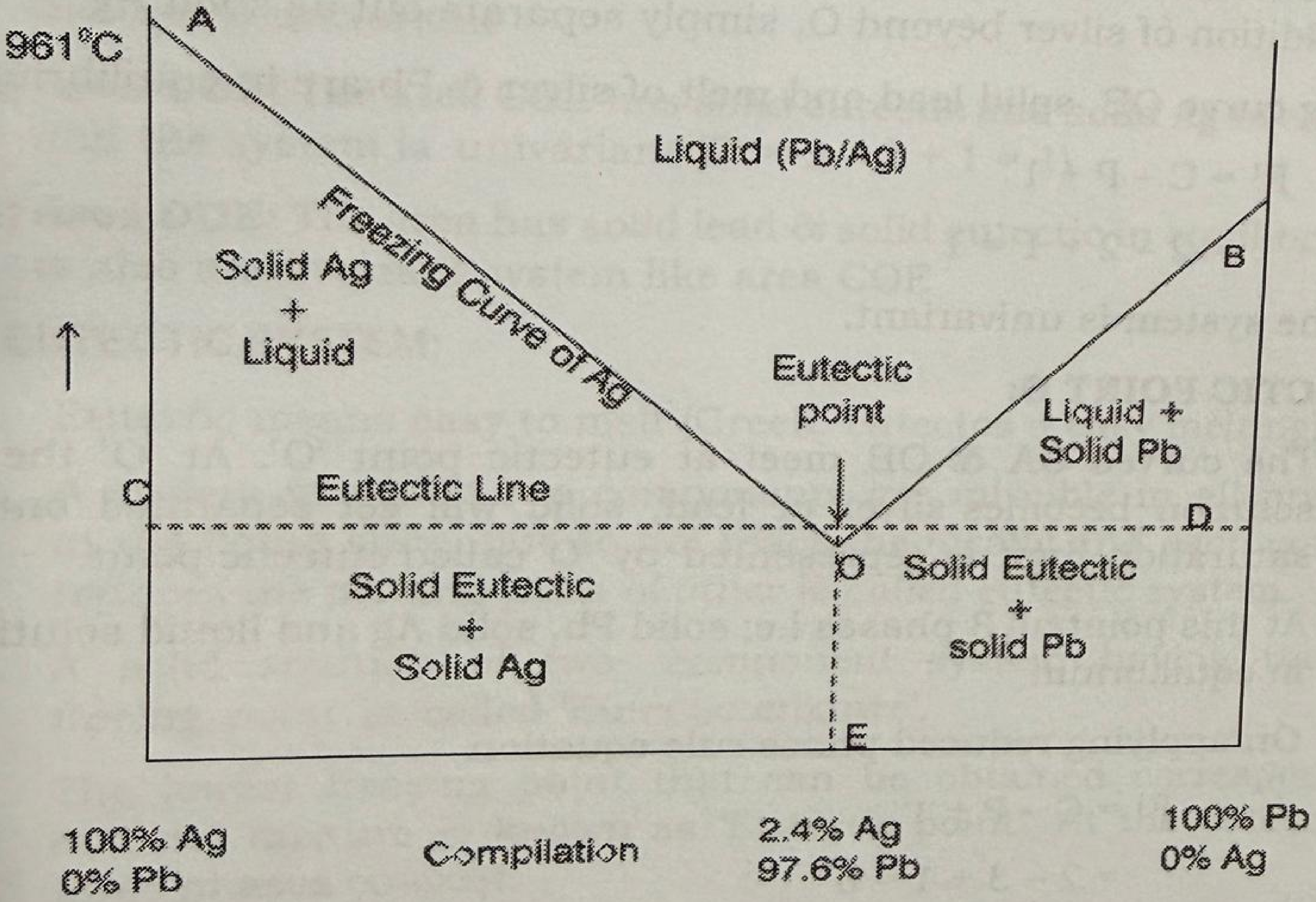
Type-A: when both components are completely miscible with one another in liquid state and they donot form any compound .on solidification,they give eutectic mixture. Ex:Ag-Pb

Type-B:the two components form a stable compound

Ex:Zn-Mg system

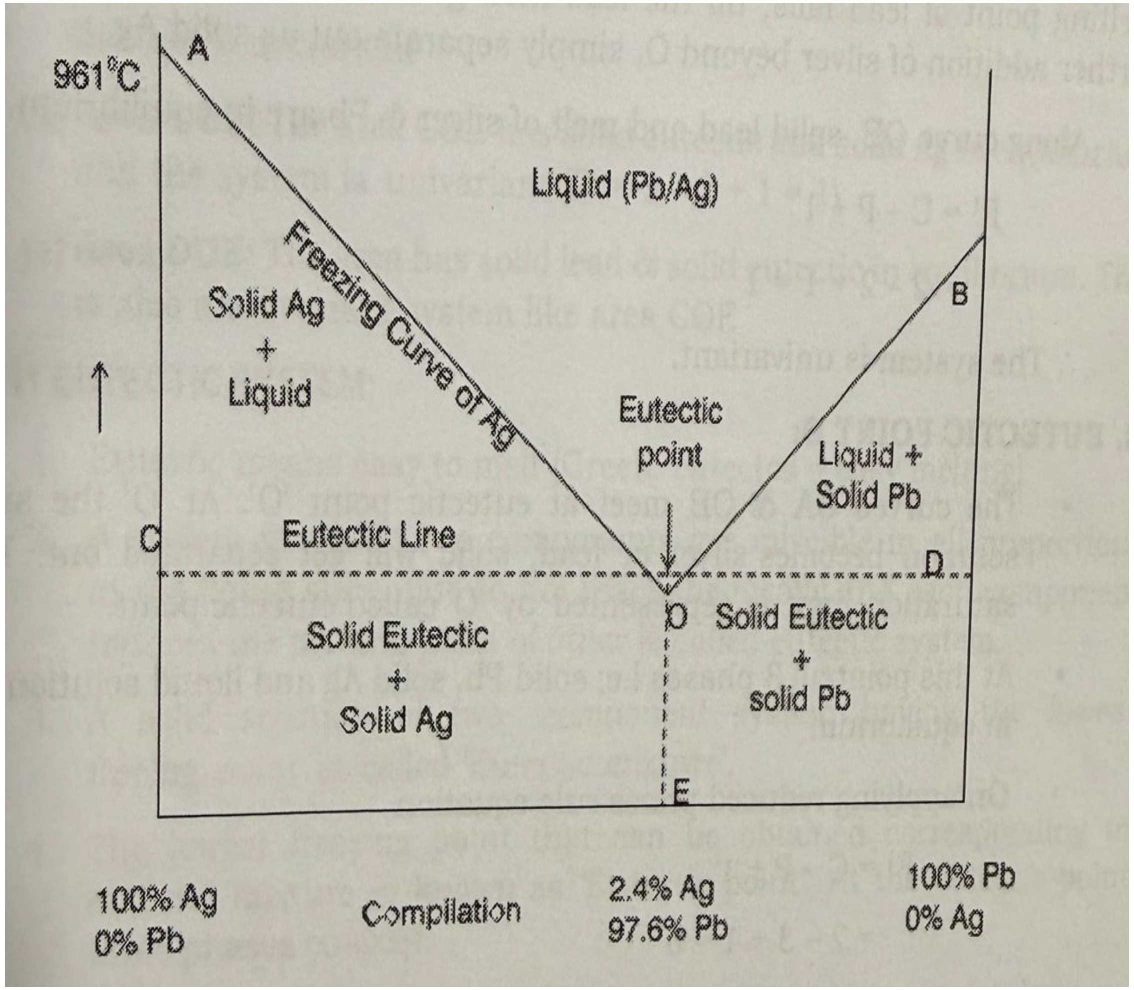
Silver-Lead system: two component system

- The four phases of silver-lead system are
  - Solid silver
  - Solid lead
  - Solution of silver & lead in molten state
  - vapour
- The B.P of Ag & Pb are very high and so vapour phase is absent.
- Hence this is considered as condensed system with three phases.
- Change of pressure have negligible impact on the system.(P is negligible in this system)
- The phase diagram is plotted between temperature and composition at a constant pressure of 1 atm.
- Hence the phase diagram is isobaric and the condensed phase rule is applied.


961°C
A
Liquid (Pb/Ag)
Freezing Curve of Ag
Solid Ag + Liquid
B
Eutectic point
Liquid + Solid Pb
C
Eutectic Line
D
O
Solid Eutectic + Solid Ag
Solid Eutectic + solid Pb
E
100% Ag 0% Pb
Compilation
2.4% Ag 97.6% Pb
100% Pb 0% Ag

The phase diagram consists of

- Two curves OA,OB
- Five areas AOB,BOD,AOC,COE & DOE
- Eutectic point ‘O’



Curves:

OA:

- Melting point or freezing point curve of Ag
- Point A represents the M.P of pure Ag(961 C)
- The M.P of Ag falls gradually by the addition of Pb till the silver melt gets saturated with lead.
- Any further addition of lead beyond ‘O’,will separate out as solid Pb.
- This saturation point ‘O’ is called eutectic point.
- Along OA , solid Ag ↔ melt of Ag & Pb
- P=2,C=2; F=C-P+1 = 1. so OA is univariant.
- Slight change of variable leads to disappearance of one of the phases.

OB:

- Freezing or melting point curve of Pb.
- Point B represents the M.P of pure Pb(327C)
- The M.P of Pb decreases by the addition of Ag , till the lead melt gets saturated with Ag.
- Further addition of Ag beyond O, will be separated out as solid Ag.
- Along OB , solid Pb ↔ melt of Ag & Pb
- P=2,C=2; F= C-P+1 = 2-2+1 =1 (univariant)

Eutectic Point O:

- At ‘O’, the silver solution becomes Ag or Pb.solid will be separated out.
- This saturation limit is called eutectic point O.
- At O, all 3 phases are in equilibrium.

  solid Pb ↔ solid Ag ↔ liquid solution
- From reduced phase rule equation, $F' = C - P + 1 = 2 - 3 + 1 = 0$
- So point O represents an invariant system.
- Any variation in one of the variables disturb the three phase equilibrium.
- At O, the temperature and composition of eutectic mixture are 303 C and 2.4%Ag + 97.6% Pb.
- It is the lowest freezing point of liquid mixture of two metals
- If the T is raised above eutectic T, the solid phases Ag & Pb disappear.
- If it is cooled below eutectic point , only solid Ag/Pb exists.

Areas:

AOB: It represents the homogeneous solution of Ag & Pb.

F’ = C-P+1 = 2-1+1 = 2 (bivariant)

AOC : It represents solid Ag & liquid melt in equilibrium

F’ = C-P+1 = 2-2+1 = 1 (univariant)

BOD: It has solid lead and liquid melt in equilibrium

F’ = C-P+1 = 2-2+1 = 1 (univariant)

COE: it has solid eutectic and solid Ag in equilibrium

F’ = C-P+1 = 2-2+1 = 1 (univariant)

DOE : it has solid lead and solid eutectic in equilibrium.

F’ = C-P+1 = 2-2+1 = 1 (univariant)

LUBRICANTS

- In all types of machines, the surfaces of moving or sliding or rolling parts rub against each other. This mutual rubbing of one part over the other leads to resistance of movement, which is termed as friction.
- Friction usually causes the wear and tear of the machinery, and since heat is generated in this process, it also reduces the efficiency of the machinery.
- Therefore to overcome the problems created due to friction we employ a substance coined as lubricant.
- Thus a lubricant may be defined as a substance which reduces the friction when introduced between two surfaces and the phenomenon is known as lubrication.

Characteristics of a good lubricant

Any substance which shows the process of lubrication must satisfy certain key functions. They are:

1. The lubricant should keep moving parts apart.
2. The foremost function of a lubricant is to reduce friction.
3. It should transfer heat and act as a coolant.
4. It should reduce the wear and tear as well as surface deformation caused due to rubbing action of two sliding surfaces.
5. It should prevent rust and corrosion and thereby reducing the maintenance and running cost of the machinery.
6. It should carry away contaminants and debris which would otherwise damage the surfaces of the machinery.
7. It should act as a seal.
8. It should also reduce the loss of energy in the form of heat.
9. It should reduce the expansion of metals due to liberation of frictional heat.

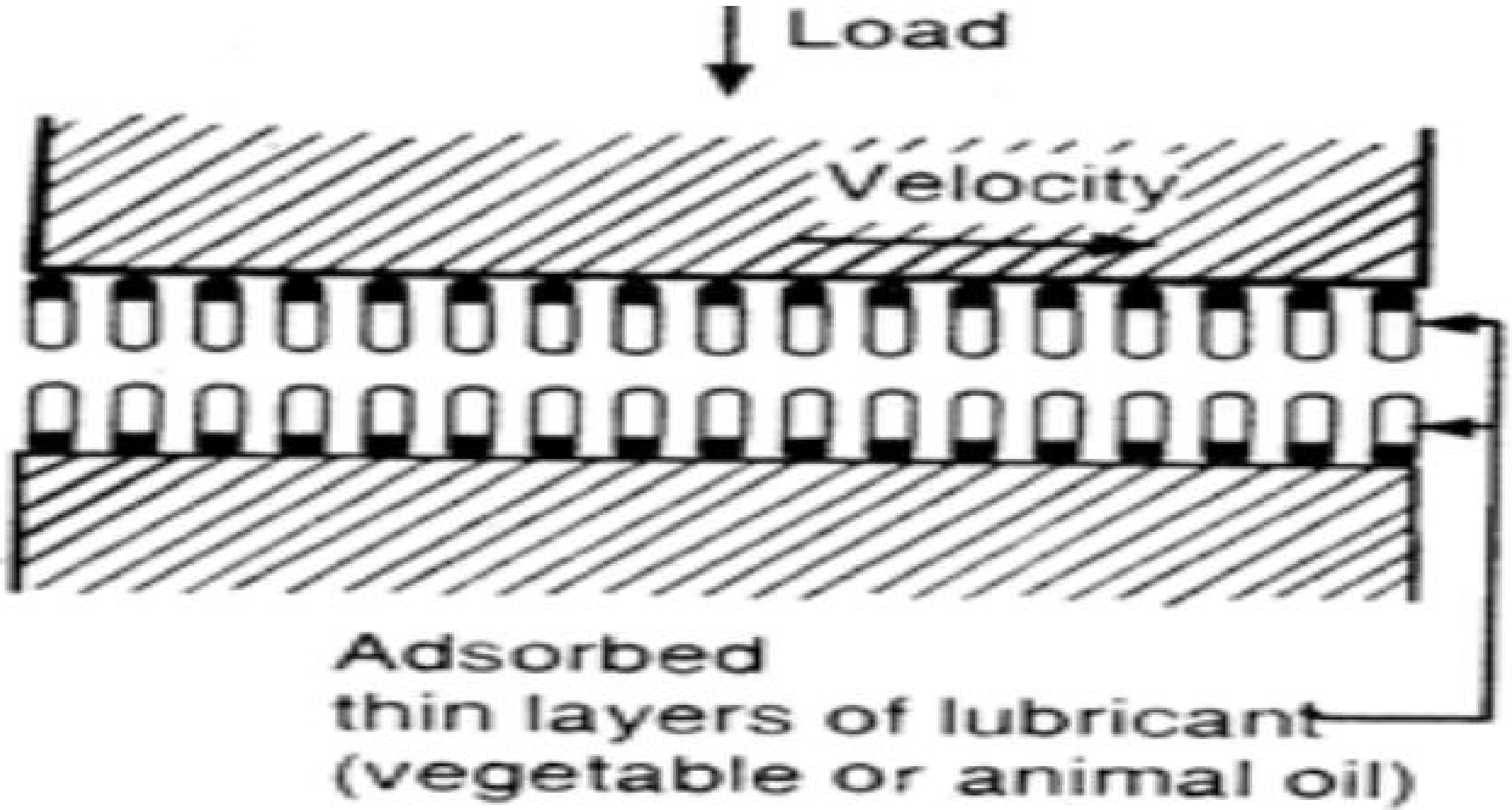
THIN FILM LUBRICATION OR BOUNDARY FILM LUBRICATION:

A thin layer lubricant is adsorbed on the metallic surfaces due to physical or chemical forces. This adsorbed layer helps to avoid a direct metal to metal contact between the rubbing surfaces. The load is carried away by the layer of the adsorbed lubricant on both the metal surfaces. This type of lubrication operates when a continuous film of lubricant cannot persist. The coefficient of friction in this case varies from 0.05 to 0.15.

The conditions of the lubricant which ought to be satisfied for boundary lubrication are:

1. Long hydrocarbon chains
2. Polar groups to promote wetting or spreading over the surface
3. High viscosity index
4. Good oiliness
5. Low pour point and oxidation
6. Active functional groups which can form chemical bonds with the metals or other surfaces
7. Resistance to heat, etc.
8. Solid lubricants, greases and oils with proper additives, function as lubricants in this type of lubrication.

Eg: graphite, MoS_2, mineral oils with additives of fatty acids or fatty oils and vegetable and animal oils and their soaps.



Boundary lubrication

The following are some of the important properties normally assessed for lubricating oils.

1. Viscosity:

Viscosity is the property of a fluid or liquid that determines its resistance to flow. A liquid in a state of steady flow on a surface may be supposed to consist of a series of parallel layers moving one above the other.

Any two layers will move with different velocities, top layer moves faster than the next lower layer, due to viscous drag i.e., internal friction.

. Consider two layers of a liquid separated by a distance, d and moving with a relative velocity difference, v. Then, force per unit area, F required to maintain this velocity difference is given by $F = \eta v/d$

where η is a constant of the liquid, called coefficient of viscosity. If $v = 1$ cm/sec, $d = 1$ cm, then $F = \eta$.

Hence, coefficient of viscosity (η) may be defined as “the force per unit area required to maintain a unit velocity gradient between two parallel layers”. The unit of viscosity is poise.

If a force of 1 dyne is required to maintain a relative velocity difference of 1 cm/sec between two parallel layers 1 cm apart, its coefficient of viscosity is 1 poise. A smaller corresponding unit is centipoises, which is equal to 1/100 of poise.

Viscosity is the most important single property of any lubricating oil, because it is the main determinant of the operating characteristics of the lubricant.

i) If the viscosity of the oil is too low, a liquid oil film cannot be maintained between two moving or sliding surfaces and consequently, excessive wear will take place. On the other hand,

ii) If the viscosity is too high, excessive friction will result.

Effect of temperature on viscosity:

Viscosity of liquids decreases with increase in temperature and consequently, the lubricating oils become thinner as the operating temperature increases.

Hence, viscosity of good lubricating oil should not change much with change in temperature, so that it can be used continuously, under varying conditions of temperature.

The rate at which the viscosity of oil changes with temperature is measured by an arbitrary scale, known as the “Viscosity-index” (V.I.).

If the viscosity of an oil falls rapidly as the temperature is raised, it has a low viscosity-index. On the other hand, if viscosity of oil is only slightly affected on raising the temperature, its viscosity-index is high.

1. Flash and Fire points:

- “The lowest temperature at which the lubricating oil gives off enough vapours that ignite for a moment, when a tiny flame is brought near it”
- while fire-point is “the lowest temperature at which the vapours of the oil burn continuously for at least 5 seconds, when a tiny flame is brought near it”.
- In most cases, the fire-points are 5 to 40^{o} higher than the flash-points.
- The flash and fire-points do not have any relation with the lubricating property of the oil, but these are important when oil is exposed to high temperature service.
- A good lubricant should have flash-point at least above the temperature at which it is to be used. This safeguards against risks of fire, during the use of the lubricant.

Cloud and Pour-points:

- When an oil is cooled slowly, the temperature at which it becomes cloudy or hazy in appearance is called its “cloud-point”
- while the temperature at which the oil ceases to flow or pour, is called its “pour-point”.
- Cloud and pour-points indicate the suitability of lubricants in cold conditions.
- Lubricant used in a machine working at low temperatures should possess low pour-point; otherwise solidification of lubricant will cause jamming of the machine.
- It has been found that presence of waxes in the lubricating oil raise the pour-point.