UNIT –II
RHEOLOGY

POINTS TO BE COVERED IN THIS TOPIC

- INTRODUCTION
- NEWTONIAN SYSTEM
- NON -NEWTONIAN SYSTEM
- THIXOTROPY AND ITS FOTMULATION
- DETERMINATION OF VISCOSITY




INTRODUCTION

- Rheology is a **greek** word **rheo** means **'to flow'** and **logos** mean **'science'**.
- Rheology is the science of the **flow of a material**.
- It applies to **liquids, solids and semi solids**.
- It also applies to the substance which have complex micro structures such as **suspension, muds, sludges** etc.
- The term rheology was invented by **bingham and crawford.**
- The term also describe **deformation of solids.**
- Viscosity is an expression of the resistance of a fluid to flow, the higher the viscosity, the greater is the resistance.

➢ **Importance of rheology in pharmacy**

- Manufacturers of **medicinal and cosmetic creams, pastes, and lotions** must be capable of producing products with acceptable consistency and **smoothness and reproducing** these qualities each time a new batch is prepared.

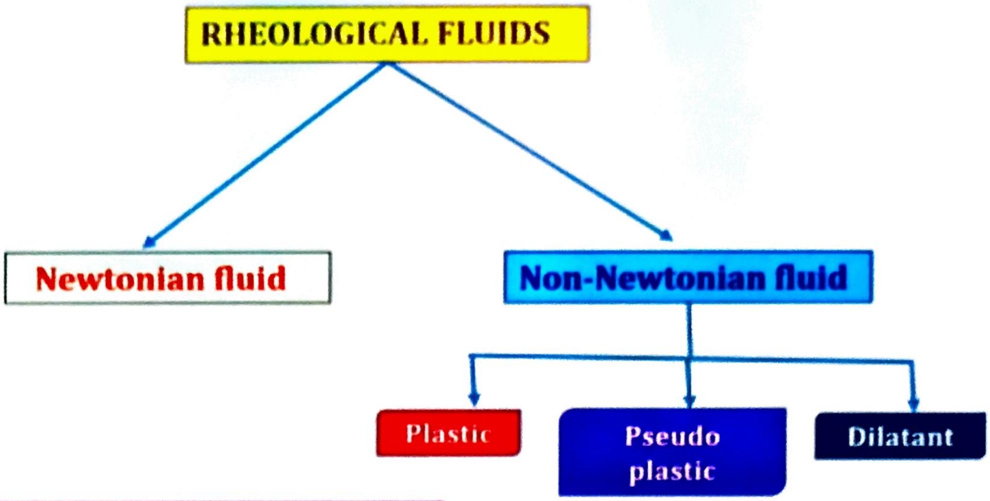
➢ **Rheology is involved in**

- Mixing and flow of materials
- Packaging into containers and removal prior to use. Whether this is achieved by pouring from a bottle, extrusion from a tube, or passage through a syringe needle.

❖ **CLASSIFICATION OF RHEOLOGICAL FLUIDS DIVIDED INTO TWO CATEGORIES:**

i. **Newtonian**
ii. **Non-Newtonian systems**

- The fluid which **obeys newton's law of viscosity** is termed as **Newtonian fluid**
- Those liquid which **do not obey newton's law of viscosity** is termed as **Non-Newtonian fluid.**



NEWTONIAN SYSTEM

- A Newtonian fluid is defined as **one with constant viscosity, with zero shear rate at zero shear stress**, This law states that **"The shear stress in flowing fluid is directly proportional to the rate of shear."**

Shear rate ∝ Shear stress

➢ Examples of Newtonian Fluids

- **Water , Alcohol , Mineral oil, Gasoline**

❖ **NEWTON'S LAW OF FLOW**

- Newton's Law of **Flow states** that the **shear stress between adjacent fluid** layers is **proportional** to the **velocity gradient** between two layers or shear rate

Mathematically

$$\tau \propto dv/dr$$

$$\tau = \eta . dv/dr$$

Where

η is constant, which is coefficient of viscosity or viscosity or dynamic viscosity

τ is shear stress

dv/dr is rate of shear.

✓ **Rate of shear** is defined as **change in velocity (dv)** between two planes of liquid which is separated by **distance (dr).**

- **Shear strain** = dv/dr
- **Shear stress (τ)** is the ratio of shear force to cross sectional area (F'/A) required to bring the flow.
- Viscosity or dynamic viscosity (η) is defined as resistance provided to a layer of liquid when it moves over another layer of liquid.

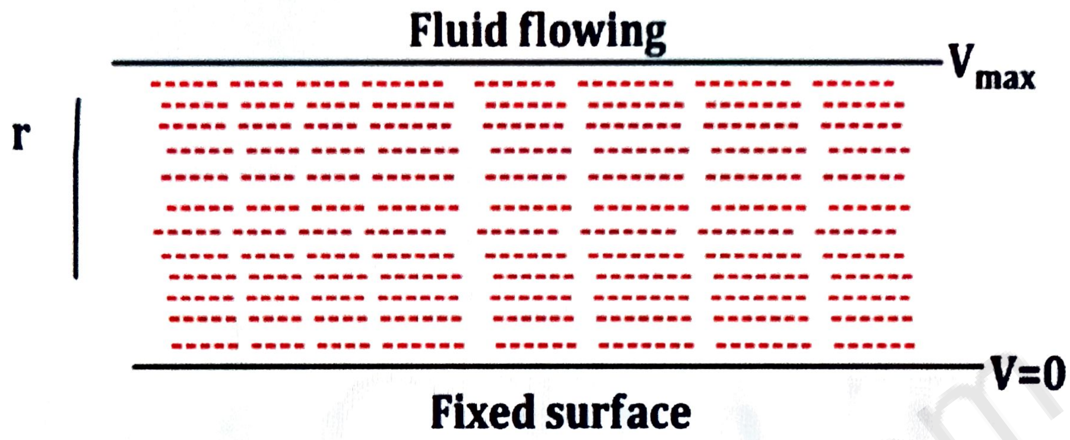


Fig :- Flow of fluids through fixed surface

- **Fixed surface** over which the **fluid is flowing.**
- The distance between **two layer is denoted by r.**
- The layer of liquid which is in contact with fixed surface, they have **zero velocity.**

- Dynamic viscosity is **shear stress** divided by **shear rate.**

$$\frac{F'}{A} = \eta \frac{dv}{dr}$$

Where

- η is the coefficient of viscosity or simply viscosity or absolute viscosity or dynamic viscosity.

$$\eta = \frac{F}{G}$$

❖ KINEMATIC VISCOSITY

- It is defined as the **ratio of dynamic viscosity (η) to the density (p)** of the fluid.

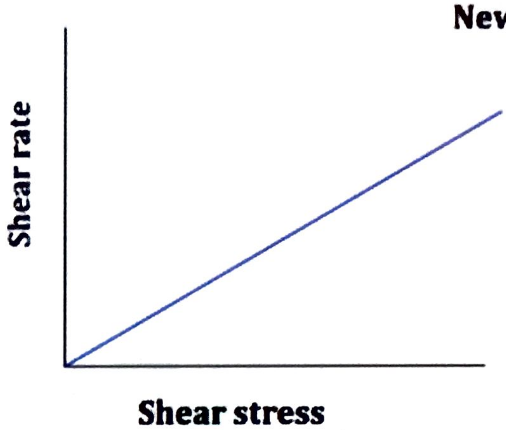
$$\textbf{Kinetics of viscosity (v)} = \frac{\eta}{p}$$

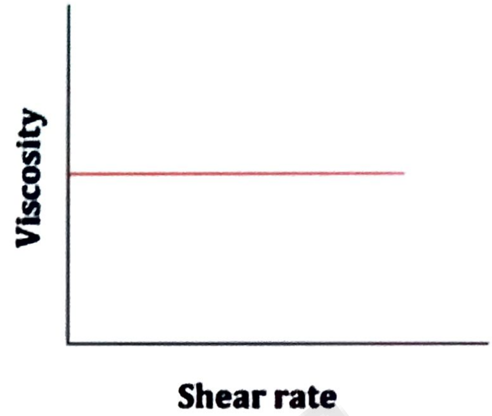
- The SI unit of **kinematic viscosity is m^2/s** and **CGS** unit is **stokes or centistokes.**
- It is a measure of the **resistive flow of the fluids** under influence **gravity.**

❖ EFFECT OF TEMPERATURE ON VISCOSITY

- Viscosity of a **gas increases** with the **increase of temperature.**
- Viscosity of liquid decreases as the temperature is raised & the **fluidity of a liquid, increases with temperature.**

Newtonian





NON -NEWTONIAN SYSTEM

- The majority of fluid pharmaceutical products **do not follow Newton's law of flow.**
- These systems are referred to as **non-Newtonian.**
- Non-Newtonian behavior is generally exhibited by **liquid and solid heterogeneous dispersions.**

Example :- **Colloidal solutions, emulsions, liquid suspensions, and ointments.**

❖ Non-Newtonian Flow

i. **Plastic**
ii. **Pseudo plastic**
iii. **Dilatant**

I. PLASTIC

- The materials that exhibit plastic flow, such materials are known as **Bingham bodies.**
- Plastic flow curves **do not pass through the origin** hut rather intersect the **shearing stress axis** (or will if the straight part of the curve is extrapolated to the axis) at a particular point referred to as the **yield value.**

- A Bingham body does not begin to flow until a **shearing stress** corresponding to the **yield value is exceeded.**
- At stresses below the yield value, the substance acts as an elastic material.
- The slope of the rheogram is termed the **mobility, analogous to fluidity in Newtonian systems,** and its reciprocal is known as the **plastic viscosity, U.**
- The equation describing plastic flow is

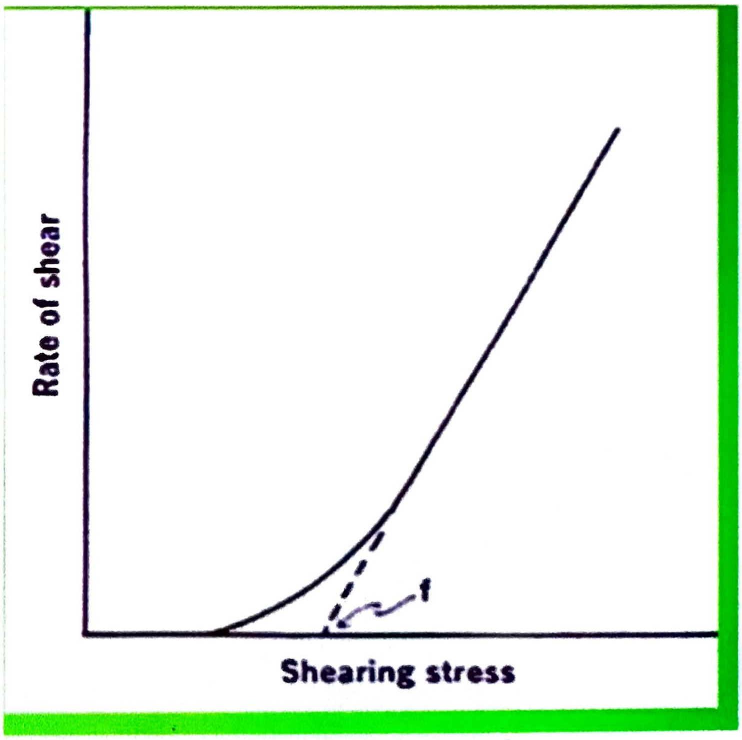
$$U = \frac{F - f}{G}$$

where

- f = yield value, or intercept on the shear stress axis in **dynes/cm^2.**
- Plastic flow is associated with the **presence of flocculated particles in concentrated suspensions**. As a result, a continuous structure is set up throughout the system.
- A yield value exists because of the contacts between adjacent particles (brought about by **van der Waals forces),** which must be broken down before flow can occur.
- Consequently, the yield value is an **indication of force of flocculation**:

✓ The more flocculated the suspension, the higher will be the yield value. Frictional forces between moving particles can also contribute to yield value.

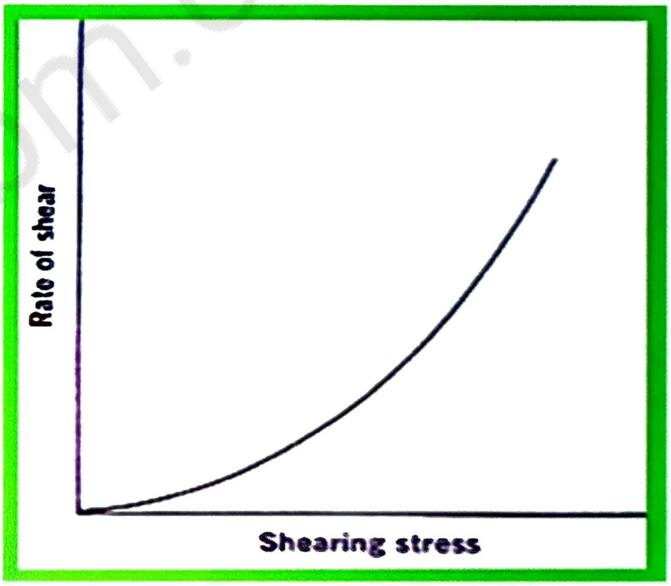
✓ Once the yield value has been exceeded, any further **increase in shearing stress (F - f)** brings about a **directly proportional increase in G, rate of shear.**



✓ In effect, a plastic system resembles a Newtonian system at shear stresses above the yield value.

II. PSEUDO PLASTIC FLOW

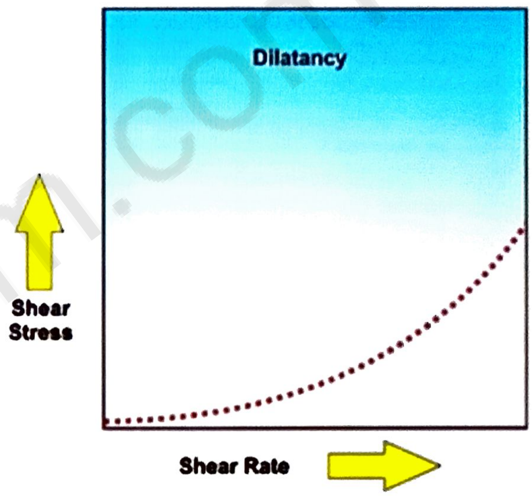
- Pseudo plastic flow is typically exhibited by polymers in solution in contrast to plastic systems, which are composed of flocculated particles in suspension.
- The consistency curve for a pseudo-plastic material begins at the origin (or at least approaches it at **low rates of shear**). Therefore, there is no yield value.
- As the **shear stress increase** progressively, shear rate also increases, viscosity of pseudo plastic material decreases, and curve is not linear
- Viscosity of pseudo plastic system cannot be expressed by single value.
- The viscosity of a pseudo-plastic substance decreases with increasing rate of shear and this system is known as shear thinning system.
- Many pharmaceutical products, including liquid dispersions of natural and synthetic gums (Tragacanth, sodium alginate, methylcellulose. and sodium carboxymethyl cellulose) exhibit pseudo plastic flow.



- As shearing stress is increased, normally disarranged molecules begin to align their long axis in the direction of flow.
- This orientation reduces internal resistance of the material and allows a greater rate of shear at each successive shearing stress.
- Solvent associated with the molecules may be released, resulting in an effective lowering of both the concentration and the site of the dispersed molecules.
- This, too, will decrease apparent viscosity.

iii. DILATANT FLOW

- It is also called shear thickening system.
- The system exhibit enhance resistant to flow with increasing rate of shear
- Actually increasing in volume when sheared hence termed as dilatant system
- The flow is inverse to pseudo plastic flow.
  Ex: Starch powder in water, Concentrated deflocculated suspension.
- Here, the molecules are not completely wetted by the solvent as the stress applied the bulk of system expand or dilate.
- If shear stress is removed, the dilatant system returns to its original state of fluidity.
- Substances possessing dilatant flow properties are invariably suspensions containing a high concentration (about 50% or greater) of small, deflocculated particles.

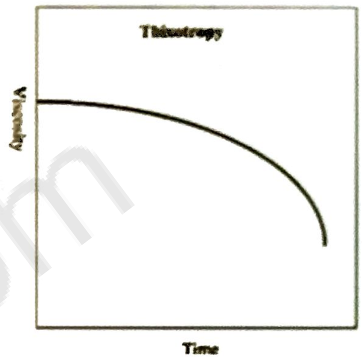


THIXOTROPY

- Thixotropy is defined as the progressive decrease in viscosity with time for a constant applied shear stress followed by a gradual recovery when the stress is removed.
- Thixotropy is a **time-dependent shear thinning property**.
- Thixotropy can be defined as an isothermal and slow recovery of material consistency, lost through shearing.
- If the rate of shear is reduced once the desired maximum is reached, the down-curve would be superimposable on the up-curve.
- This is true for Newtonian systems.
- In case of non-Newtonian systems, the down-curve can be displaced relative to the up-curve. With shear-thinning systems (pseudo plastic), the down-curve is frequently displaced to the left of the

up-curve, showing that the material has a **lower consistency** at any one **rate of shear on the down-curve** than it had on the up-curve.

- This indicates a **breakdown of structure (and hence shear thinning)** that does not reform immediately when **stress is removed or reduced.**
- This phenomenon is known as **Thixotropy.**
- If the system is **viscous or consists of large, heavy particles**. the **Brownian motion is too slow** to re-establish the broken links. More or less, extensive period of rest is required to rebuild the original structure and reach the initial viscosity.
- These events are termed as **gel-sol- transformations.**
- The rheogram of a thixotropic material depends



✓ The **rate** at which **shear is increased or decreased**.

✓ **Constant shear rate and variable shear rate.**

At rest (On storage)	Multi-point contacts (high consistency or high viscosity)	Gel state
	↓ Rapid process	
On shear (equilibrium)	Contacts break down (low consistency or low viscosity)	Sol state
	↓ Not instantaneous	
Set aside (removal of stress	Particle contacts are established due to Brownian motion (high consistency or or high viscosity)	Gel state

Fig :- Particle-particle interactions in a thixo tropic material. Gel-sol-gel transformations.

❖ THIXOTROPY IN FORMULATION

- Thixotropy is a desirable property in **liquid pharmaceutical systems** that ideally should have a **high consistency** in the **container, yet pour or spread easily.**
- **Procaine benzyl penicillin** also known as **procaine penicillin**, is a combination of benzyl penicillin with the **local anaesthetic agent procaine.**
- With regards to suspension stability ,there is a relationship between the degree of thixotropy and thus the **rate of sedimentation** ,the greater the **thixotrophy** , the **lower the rate of settling**.
- Concentration parentral suspension containing from **40 – 70 % w/v** of **procaine penicillin G** in water were found to have a high inherent **thixotrophy** and were **shear thinning.**

❖ MEASUREMENTS OF THIXOTROPHY

- The most apparent characteristic of a **thixotropic system**

↓

Area of hysteresis

i. BULGES

- A careful study of different thixotropic materials may provide a number of **complex rheograms.**
- Concentrated aqueous **magma (gel) of bentonite (10 to 15% by weight)** produces hysteresis loop with a characteristic bulge in the up-curve .

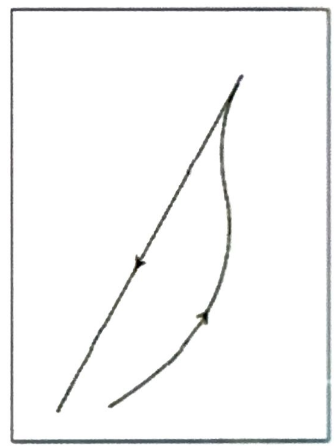


Fig:- Rheogram of a thixotropic material showing a bulge in the hypothesis loop

- The crystalline plates of bentonite form **'a house of cards like structure'** that causes the **swelling of magmas.**

Ex :- Aqueous bentonite gel (10-15 % by weight)

ii. SPURES

- A sharp point of **structural breakdown at low shear rate** in **up curve called spur value.**

- **Ex :- Procaine penicillin gel**
  Carboxymethyl cellulose solution.
- This value represents a spur value sharp point of **structural breakdown at low shear.**

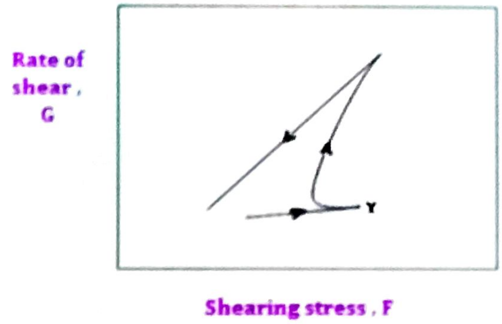


Fig:- Rheogram of a thixotropic material showing a spur value in Y in the hypothesis loop

❖ APPLICATIONS OF THIXOTROPY

- Thixotropy is desirable property in liquid pharmaceutical systems. It has following applications in pharmacy.

✓ A high consistency in the container yet **pour are spread easily.**

✓ A well formulated suspension will **not settle out readily in the container.**

✓ It will become fluid **on shaking** and will remain **so long enough** for a **dose to be dispensed.**

✓ It will **regain consistency** to maintain particles in a **suspended state.**

✓ It is also desirable with **emulsions lotions, creams , ointments and parental suspension to be used for Intramuscular Depot Therapy.**

❖ NEGATIVE THIXOTROPY OR ANTI THIXOTROPY

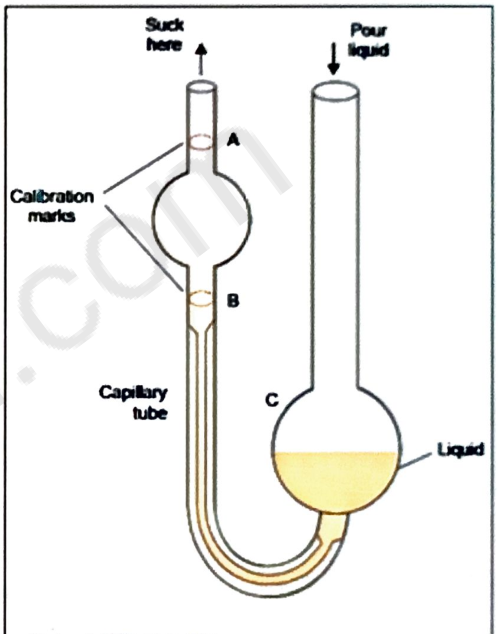
- Rheopexy is phenomena in which a **sol forms a gel more readily** when **shaken or sheared** than when **allow to form the gel** while the material is **kept at rest**. e.g. **Magnesia magma, Clay suspension**
- Represents an **increase rather than a decrease in consistency** on the **down curve.** This increase in **thickness or resistance to flow with increased time of shear.**
- It was detected at **shear rates of greater than 30 1/sec Below 30 1**/see the **magma showed normal thixotropy.**
- It was observed that when magnesia magma was alternately sheared at increasing and then **decreasing rates of shear, the magma continuously thickened** (an increase in shearing stress per unit shear rate) but at a decreasing rate, and it finally reached an equilibrium state in which further cycles of **increasing-decreasing shear rates no longer increased the consistency of the material.**

DETERMINATION OF VISCOSITY

- Newtonian systems the **rate of shear is directly proportional to the shearing stress.**
- Therefore, **single point viscometer** the equipment that works **at a single rate of shear, is sufficient.**
- For evaluation of **Non-Newtonian fluids multipoint viscometers** are required, because the **apparent viscosity** is to be determined at a several of **rates of shear** to get entire **consistency curve.**
- Viscometers are used to determine viscosity.

➢ Viscometers are classified as

1. **Capillary viscometer**
2. **Falling Sphere viscometer**
3. **Rotational viscometers**



Ostwald Viscometer.

1. CAPILLARY VISCOMETER

➢ Example of different capillary viscometers are

i. **Ostwald viscometer (single/one point)**
ii. **Ubbelohde viscometer**

i. OSTWALD VISCOMETER (U-TUBE)

- This is used to determine both **kinematic and dynamic viscosities.**
- The viscosity of a **Newtonian liquid may** be determined by **measuring the time required for the liquid to pass between** two marks as it **flows by gravity** through a **vertical capillary tube**, known as an **Ostwald viscometer.**
- The time of flow of the liquid under test is compared with the time required for a liquid of known viscosity (usually water) to pass between the two marks.

❖ **METHOD**

- Ostwald viscometer is fixed to a stand in vertical position.
- Fluid (under test) is sucked through bulb up to the level above the upper mark A.

- Then fluid is allowed to **flow down** until it reaches to **mark A.** Now start the **stop clock.**
- When fluid reaches the **mark B, stop the clock.**
- The time required for the **fluid to flow from** one mark to another is **measured.**
- The **time of flow of liquid under test** is compared with time required for a liquid of known **viscosity (water).**

❖ **DERIVATION**

- If η_1 **and** η_2 are the viscosities of the unknown and the standard liquids, ρ_1 **and** ρ_2 are the densities of the liquids, and t_1**and** t_2 are the respective flow times in seconds, the **absolute viscosity of the unknown liquid**, η_1 is determined by substituting the experimental values in the equation
- The value η_1 **and** $\eta_2 = \eta_{rel}$ **is known as the** relative viscosity of the liquid under test.

$$\frac{\eta_1}{\eta_2} = \frac{\rho_1 t_1}{\rho_2 t_2}$$

- The liquid flowing through a capillary tube is based on Poiseuille's law.

$$\eta = \frac{\pi r^4 t \Delta P}{8lV}$$

- Where
- ✓ **r** is the radius of the inside of the capillary.
- ✓ **t** is the time of flow.
- ✓ **ΔP** is the pressure head in dyne/cm^2 under which the liquid flows.
- ✓ **I** is the length of the capillary,.
- ✓ **V** is the volume of liquid flowing.
- The **radius, length, and volume** of a given **capillary viscometer** are invariants. So above equation $\eta = K.T\Delta P$
- The pressure head **ΔP** depends on density the ρ of the liquid being measured, the acceleration of gravity (constant value), and the difference in heights of liquid levels in the two arms of the viscometer.

$\eta_1 = K't_1P_1$ ———————————— (i)

$\eta_2 = K't_2p_2$ ———————————— (ii)

- Divide both equations, we get $\frac{\eta_1}{\eta_2} = \frac{\rho_1 t_1}{\rho_2 t_2}$

ADVANTAGES	DISADVANTAGES
Measure precise viscosities for many diverse fluids	No single tube is suitable for all viscosities
Small & Portable	Basic models can only be used for translucent fluids
Inexpensive	Difficult to clean the capillary tubes
Easy to use	
Can use a wide verity of capillary tubes on the same viscometer	

❖ **Applications**

✓ Used for formulation and evaluation of dispersion system such as **colloids, suspensions, emulsions.**

✓ Study of flow of liquids through **capillary tube throw light upon the circulation of blood**

(ii) UBBELOHDE VISCOMETER

- It is also called **suspended-level viscometer.**
- It is used for **higher viscosity cellulosic polymer solutions.**
- This consists of a reservoir on one side and a **measuring bulb with capillary on the other.**
- A liquid is introduced into the **reservoir** and then **sucked** through the **capillary** and the **measuring bulb.**

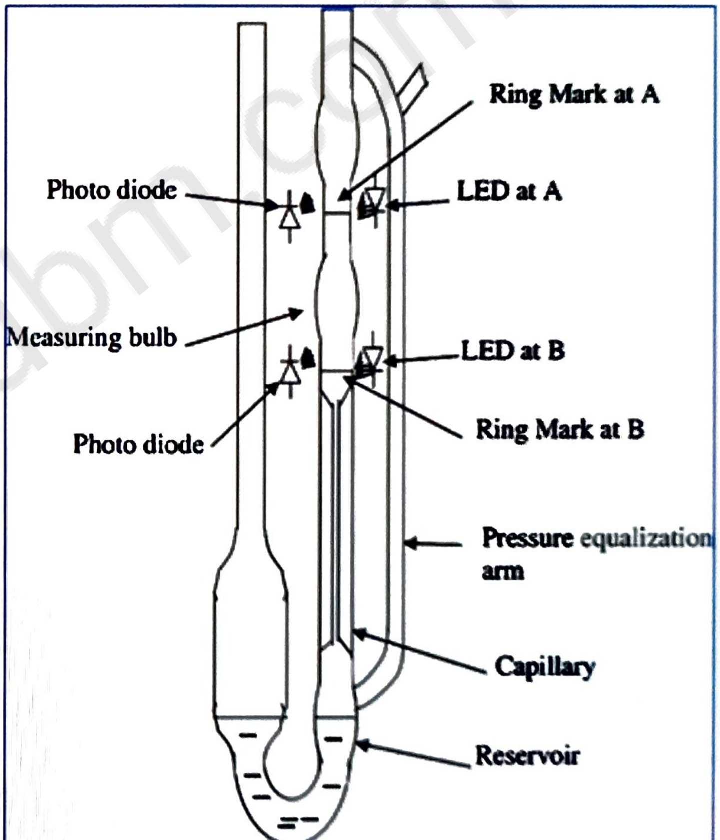


Fig :- UBBELOHDE VISCOMETER

- The liquid is allowed to travel through the **measuring bulb** and the time required for the liquid to cross **two calibrated marks** is a **measure of the viscosity.**
- The **Ubbelohde device** has a third arm extending from the end of the **capillary and opening to the atmosphere.**
- In this way, the **pressure head** depends only on a **fixed height** and **no longer on the total volume of liquid.**

2. FALLING SPHERE VISCOMETER (Single/one point)

- It is called as **Hoeppler falling sphere viscometer**.
- This viscometer is based on the principle of **Stokes' Law.**

❖ METHOD

- Viscometer consists of a **cylindrical glass tube** filled by the **liquid** under **investigation.**
- The tube is enclosed by **constant temperature jacket** in which water is circulated around the **tube.**
- A **glass or steel ball** is allowed to fall down.
- The **falling time is recorded.**
- The viscosity of a **Newtonian liquid** is then calculated from

$$\eta = t(S_b - S_f)B$$

Where

- **t** is the time interval in seconds for the ball to fall between the two points
  S_b and S_f are the specific gravities of the ball and fluid, respectively, at the temperature being used.
- **B** is a constant for a particular ball.

❖ APPLICATIONS

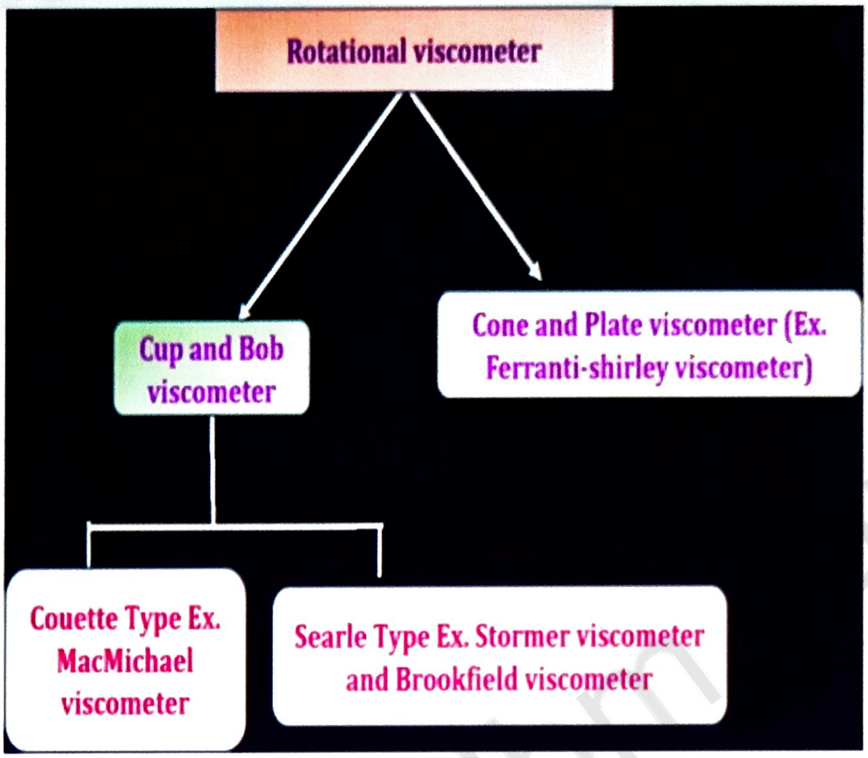
i. Viscometer is **more accurate.**

ii. **Low time-consuming.**

ADVANTAGES	DISADVANTAGES
High shear devices.	Can be maintenance intensive
This is incredibly important when dealing with non-Newtonian fluids which includes most of the fluids used in printing and coating today.	Replacement parts can be costly

3. ROTATIONAL VISCOMETERS

- Rotational viscometers can be used for the accurate **measurement of viscosity** for both **Newtonian and non-Newtonian fluids.**
- The instrument is divided into **two** major categories



i. In the **Couette type** of viscometer, the cup is rotated. The **viscous drag** on the **bob** due to the sample produce **torque** which is proportional to the **viscosity** of the sample.

ii. The **Searle type of viscometer** uses a stationary **cup and a rotating bob**. The torque resulting from the **viscous drag** is measured by a **spring or sensor** used to **drive the bob.**

ADVANTAGES	DISADVANTAGES
Can measure viscosities of opaque, settling, or **non-Newtonian fluids.**	Can be **relatively expensive.**
Useful for characterizing shear- thinning and time-dependent behavior.	**Often large and not portable.**
Speed of the rotating part easily adjusted.	
Often linked to computers for **semi- automated measurement.**	

i. CUP AND BOB VISCOMETER

❖ **Working Principle**

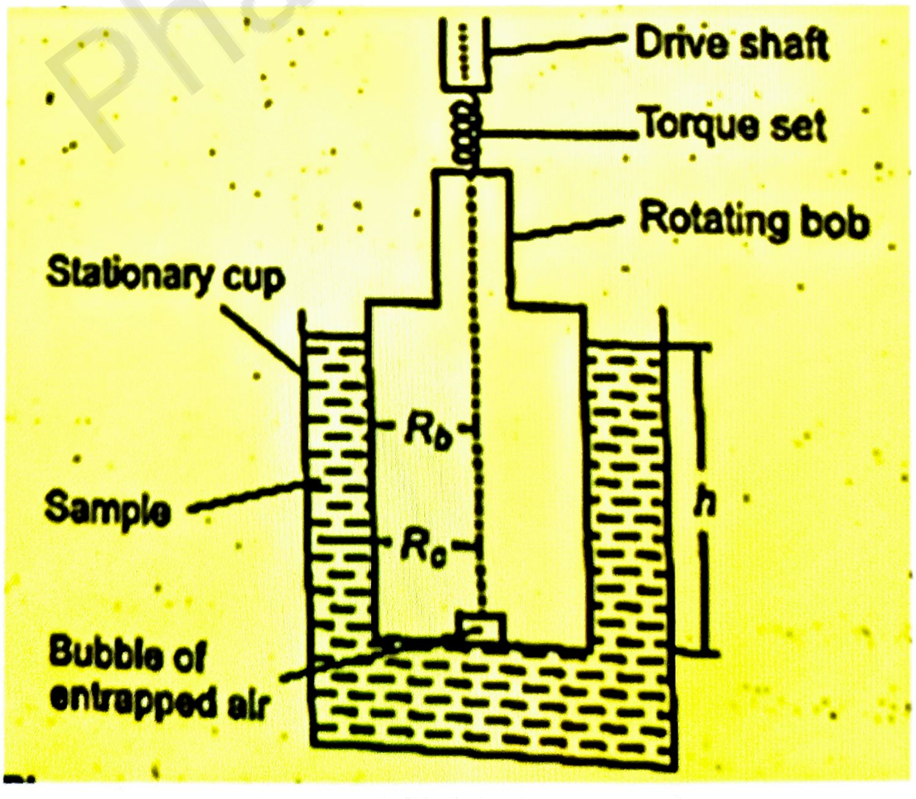
- It is consist of **two coaxial cylinders** of different diameters.
- The outer cylinder forms the **cup into which the inner cylinder or** bob is fixed centrally.
- **Cup and bob viscometer** consist of **central cylindrical bob and stationary cup.**
- The sample is sheared in the space between the **outer wall of a bob and the inner wall of a cup.**
- A known **weight (w)** of sample is used. Determine the time taken by bob.
- To rotate for specific number of times and **convert it into rpm** (revolutions per minute).
- The **rpm (v)** value is considered as shear rate while **weight (w)** as shear stress.
- By using these values, **viscosity of material (η)** can be calculated by

$$\eta = K\,(w/v)$$

where

✓ K is instrument constant.

- The **torque set up** in the bob is measured in terms of angular **deflection Q** of a pointer that exhibit on the scale.



ii. CONE AND PLATE VISCOMETER

- It consist of **flat stationary plate** and a wide angle rotating cone is placed centrally above it.
- The sample is placed at centre of **stationary plate** and then it is raised into the position under the cone.
- Sample is sheared in **narrow gap between stationary plate and rotating cone.**

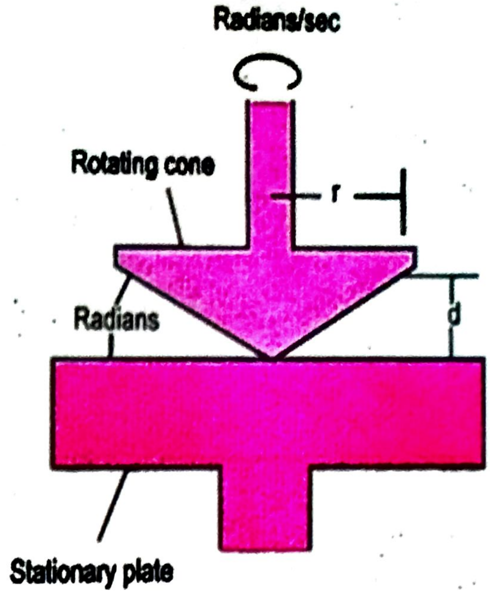


Fig:-Cone And plate viscometer

- The **rate of shear in rpm is increased or decreased.**
- The **torque produced on the cone is measured.**
- The viscosity in case of **cone-plate viscometer** is measured by

$$\eta = K(T/v)$$

Where

- ✓ **T** is **torque reading**
- ✓ **V** is **rpm** (speed of the cone in revolutions per minute)
- ✓ **K** is **instrumental constant**

Plastic viscosity is calculated by

$$U = K\frac{T - T_f}{v}$$

Yield value is calculated by

$$f = K_f \times T_f$$

Where

T_f = torgue at the shearing stress

K_f =Instrumental constant

❖ ADVANTAGES

i. The rate of shear is constant throughout the entire sample being sheared. As a result, any change in plug flow is avoided.

ii. Time saved in cleaning & filling.

iii. Temperature stabilization of the sample during a run

iv. The cone and plate viscometer requires a sample volume of 0.1 to 0.2 ml. This instrument could be used for the rheological evaluation of some pharmaceutical semisolids.

UNIT –II
DEFORMATION OF SOLIDS

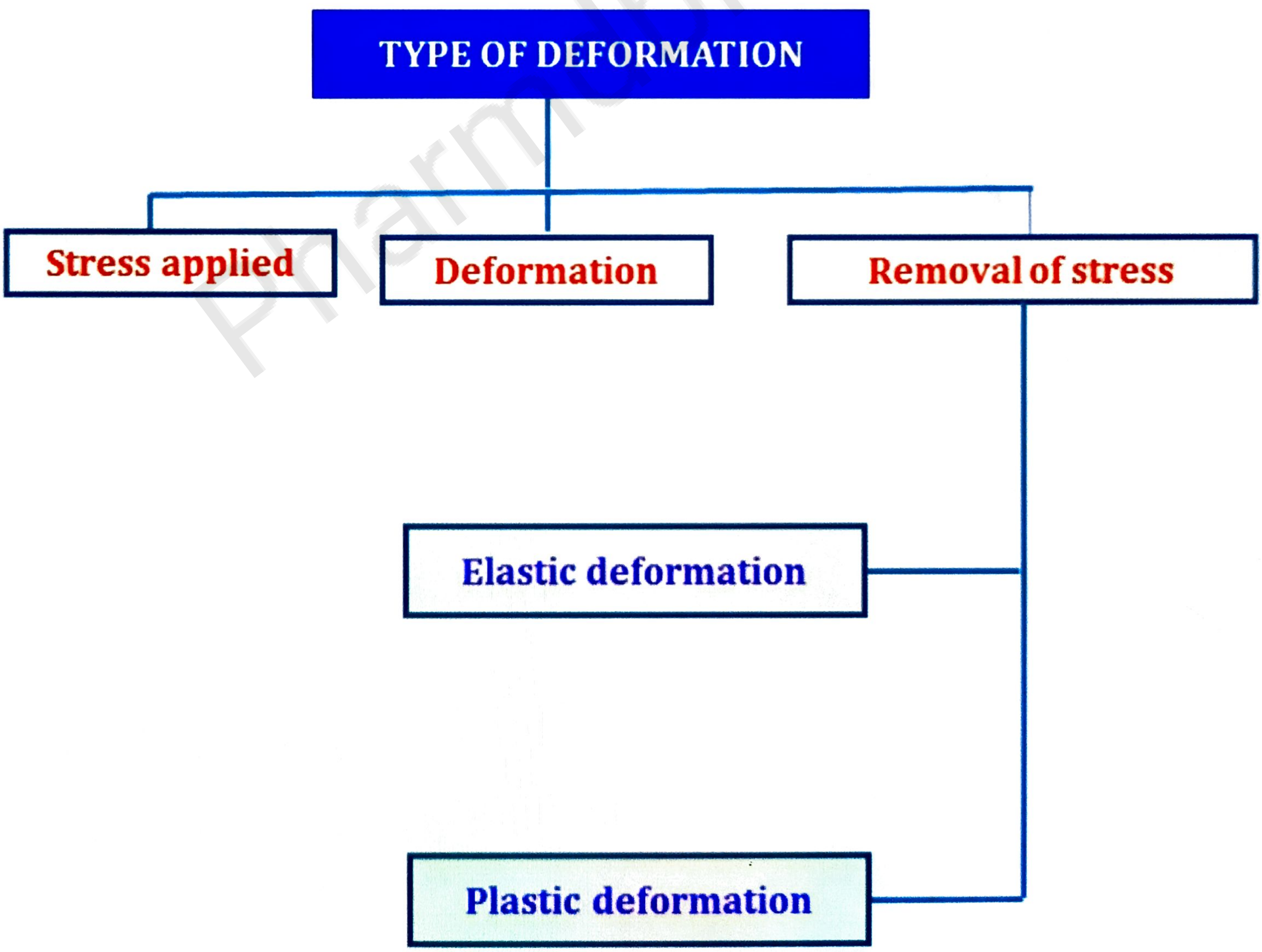
POINTS TO BE COVERED IN THIS TOPIC

- INTRODUCTION
- PLASTIC DEFORMATION & ELASTIC DEFORMATION
- HECKEL EQUATION
- STRESS
- STRAIN
- ELASTIC MODULUS

INTRODUCTION

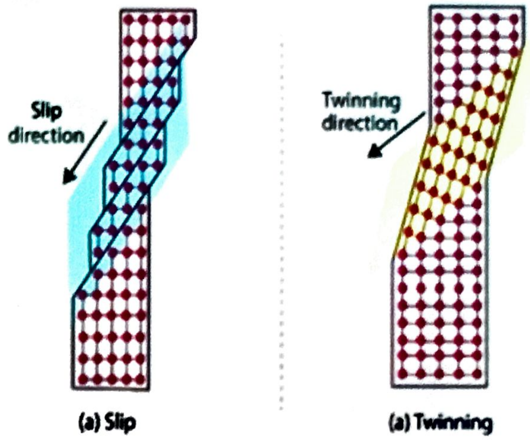
DEFORMATION OF SOLID

- It is defined as change in the **size and shape** of an **object.**
- When applied a **external force.**
- It is term of the concept of **Strain and stress.**
- As deformation occurs **internal inter molecular forces arise** that **oppose the applied force.**
- If the **applied force is not too great** these internal forces are sufficient to completely resists the applied force and allow the object to **assume a new equilibrium state and to return** to its original state when the load is removed.
- A **larger applied force** may lead to a **permanent deformation** of the object or even to its structure failure.
- Depending upon the type of **material, size and geometry** of the **object** and the **forces applied** various **deformation** may result.



PLASTIC DEFORMATION & ELASTIC DEFORMATION

❖ Plastic deformation



- It is **irreversible.**
- Object in **plastic deformation** range will first have undergone **elastic deformation** which is **reversible** so the object will partly return to its **original shape.**
- Plastic deformations in a solid materials **do not obey Hooke's law. Progressive, permanent deformation** under constant load is called **creep.**
- When force is applied to a material, it experiences **elastic deformation followed by plastic deformation.**
- The transition from elastic state **to plastic state** is characterized by the **yield strength of the material.**
- Plastic deformation mechanism is different for **crystalline** and **amorphous materials.**
- For **crystalline materials**, deformation is accomplished through a **process called slip that involves motion of dislocations.**
- In **amorphous materials**, plastic deformation takes place by viscous flow mechanism in which atoms or ions slide past one another under applied stress without any directionality.
- The **ability of metals** to undergo **plastic deformation is called ductility.**
- **Soft thermoplastic** materials have rather large plastic deformation range as do ductile metals such as **copper, silver and gold.**
- An example of a material with a large plastic deformation range is a wet chewing gum which can be stretched dozens of its times its original length.
- Hard thermosetting **plastics, rubber and ceramics** have **minimal plastic deformation ranges.**

> **Under the tensile stress plastic deformation is characterized as**

1. Strain hardening region

✓ Material becomes stronger through the **movement of atomic dislocations**

2. Necking region

✓ Reduction in **cross sectional area of specimen.**

✓ It begins after the ultimate **strength is reached.**

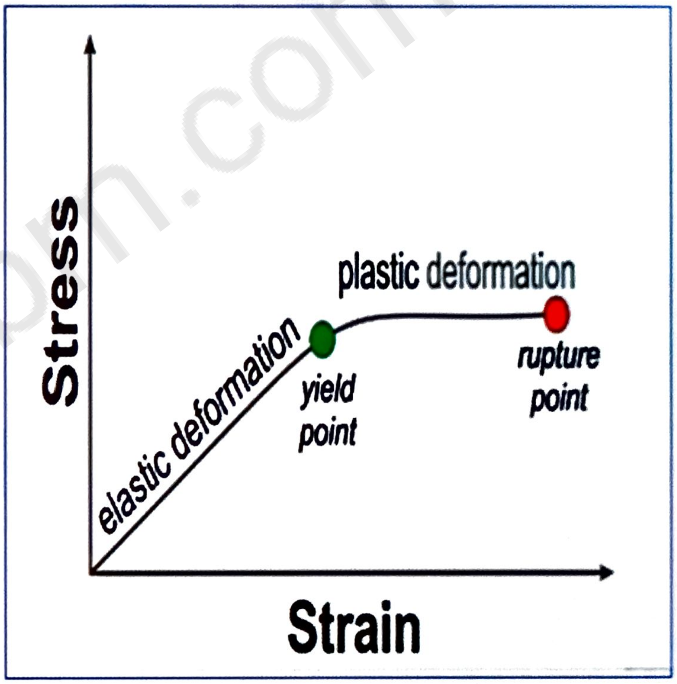
✓ Material can **no longer withstand the maximum stress** and **strain** in the **specimen rapidly increases.**

3. Fracture

✓ Indicates the end **of the plastic deformation.**

❖ Elastic deformation

- When a **load is applied and removed, no permanent deformation** has occurred.
- It is a **reversible process**.
- The material return to its **original shape when force** is removed.
- Such type of behaviour is seen in **metals, ceramics, rubbers and polymers.**



- Elastic deformation in a **solid can take place** due to **change in pressure,** or by an **application of force or load.**
- **Elasticity** depends on depends on both the **chemical bonding** and the **structure of solid.**
- The deformation is said to be an ideal deformation which takes place instantaneously upon application of force or load and disappears **completely on removal of the force or load.**
- Such deformations in a **solid materials obey Hooke's law.**
- Ideal deformation occurs with comparatively **smaller deformation forces.**

❖ Difference between Elastic and Plastic deformation

ELASTIC DEFORMATION	PLASTIC DEFORMATION
The material **return** to its original shape when force is removed	The material **does not return** to its original shape when force is removed.
It is **Reversible**	It is **Irreversible**
In this, **no permanent deformation** occurred	In this **permanent deformation** occurred
In **Elastic deformation** the chemical bonds of substance undergo **stretching and bending**	In **plastic deformation** some of the chemical bonds of substance undergo **breakage**
It is **time dependent**	It is time **in-dependent**
It occurs in **metals within elastic limits**	It occurs **beyond plastic limits**

HECKEL EQUATION

- The Heckel analysis is a most useful method for **estimating the volume** reduction under the compression **pressure in pharmacy.**
- Heckel plots can be affected by **the time of compression**, the **degree of lubrication and size of the die.**
- Heckel equation is that the **densification of the bulk powder** on applying force obeys **first-order kinetics**. The Heckel equation is expressed as

$$\frac{1}{1 - D} = K P + A$$

Where

✓ **D** is the **relative density** of the tablet which is the ratio of tablet density to true density of powder

✓ **P** is **pressure**

✓ **K** is the **slope of straight line portion of the Heckel plot.**

✓ **A** is a **intercept**

- **Kuentz and Leuenberger modified Heckel equation** which explain the transition between the states of a powder to the state of a tablet.

$$\sigma = \frac{1}{C}\left[\rho_c - \rho(1-\rho_c)\ln\left\{\frac{1-\rho}{1-\rho_c}\right\}\right]$$

Where

σ is the **pressure**

ρ is the **relative density**

ρ_c is the **critical density**

C is a **constant.**

- The **constant C** in the **modified Heckel equation** is similar to the **constant K in the Heckel equation.**
- The constant C with high values indicates plastic behaviour while low values indicates brittle powder behavior.
- Hersey & Rees and York & Pilpel differentiate powders into three **types A, B and C.**

✓ **Type A materials**

- Type A materials are comparatively soft and readily undergo plastic deformation.
- The materials that **exhibit type A** behavior is **sodium chloride.**
- A linear relationship is observed with the plot remaining parallel as the applied pressure increase. This indicates the deformation apparently only by **plastic deformation.**

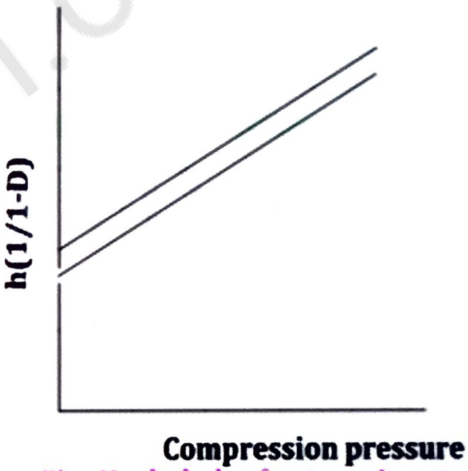


Fig:-Heckel plot for type A materials

✓ **Type B materials**

- The graph shows that there is an **initial curved region** followed by a **straight line.**
- This indicates that at the early stages of the **compression process, particles are fragmenting.**
- **Type B Heckel plots** usually seen in harder materials having higher yield pressures.

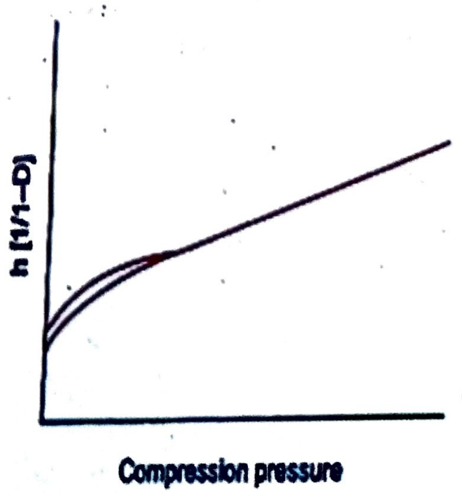


Fig:-Heckel plot for type B Materials

- Lactose is a typical example of such **materials.**

✓ **Type C materials**

- The graph showing an **initial steep linear region** which become superimposed and flattens out as the **applied pressure is increased.**

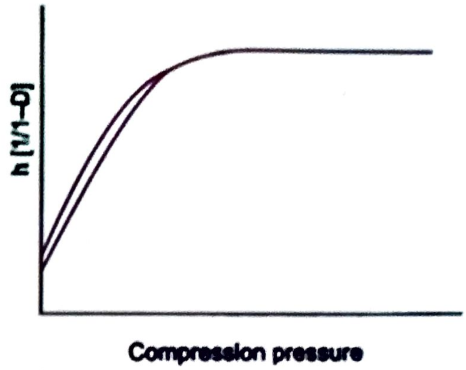


Fig:-Heckel plot for type C Materials

❖ **Significance of Heckel plot**

- The significance of **Heckel plot** is used to characterize single materials and as well as can also be used for **powder mixtures.**
- Type A Heckel plots usually **exhibit a higher final slope** than **type B.**
- This indicates that the **Type A materials** have a **lower yield pressure.**
- The two regions of **Heckel plots in type B** material represent the initial repacking stage and subsequent **deformation process.**
- The **crushing strength of tablets** is also correlated with the values of **k of the Heckel plot.**
- **Larger k values** indicate **harder tablets.**
- The knowledge of this can be used to select **binder during designing of tablet.**

STRESS

- Stress (σ) is the force per unit area that **applies to an object to deform it.**
- Stress (σ) = **Force/Area**
- Its unit is **Nm^{-2} or Pascal**

❖ **TYPE OF STRES**

- There are three type of stress

1. **Direct stress**
2. **Indirect stress**
3. **Combined stress**

1. Direct stress

- These stresses produced under **direct loading condition** i.e. force will be in **line with the axis of member.**
- Based on the type of force acting on the body, it may be **tensile or compressive or shear stresses.**

a. Tensile stress

- It is defined as **tensile force acting per unit area of the body.**
- It is that type of force which produce extension or **elongate the dimension of the body.**
- These **force will be in line with the axis of member.**
- The tensile stress is the **ratio of change in length to the original length.**

b. Compressive stress

- It is defined as **compressive force acting per unit area** of the body.
- In this the **forces applied is opposite to each other.**

c. Shear stress

- It is defined as shear force acting per unit area of the body.

2. Indirect stress

- These stress **occur due to torque produced in the body.**

3. Combined stress

- These stress are the **combination of direct and indirect stress.**

STRAIN

- Strain (ε) is the **measure of the amount of deformation.**
- If the bar has **original length (L)** and when the load is applied on a bar the length of bar will change which is indicated as **(ΔL/L)**
- **Strain (ε) = ΔL/L**
- It has no unit.

❖ **TYPE OF STRAIN**

1. **Tensile strain:** It is defined as **ratio of increase in length to original length of bar**
2. **Compressive strain:** It is defined as **ratio of decrease in length to** original length of bar

3. Shear strain : The strain produced by shear force is called shear strain.

ELASTIC MODULUS

- It is the ratio of **stress to strain.**
- It is expressed as **Elastic modulus = stress/strain.**
- The constant of proportionality depends on the material being deformed and the **nature of the deformation.**
- This constant is called the **Elastic modulus.**
- The **elastic modulus determines** the **amount of force** required **per unit deformation.**
- A material with **large elastic modulus** is difficult to deform, while one with **small elastic modulus** is easier to deform.
- The elastic modulus under the law of **Hooke's law.**
- This law state that, **In an elastic member stress is directly proportional to the strain within elastic limit.**

$$\sigma \propto \varepsilon$$

$$\sigma = E.\varepsilon$$

$$\text{OR } E = \sigma/\varepsilon$$

- Where,

E is constant known as **modulus of elasticity** or **young modulus**

σ is **stress**

ε is **strain**

- Initially, a **stress-strain curve is a straight line.**
- As the stress increases, the **curve is no longer straight.**
- When the stress exceeds the elastic limit, the object is permanently distorted and **does not return** to its **original shape** after the **stress is removed.**

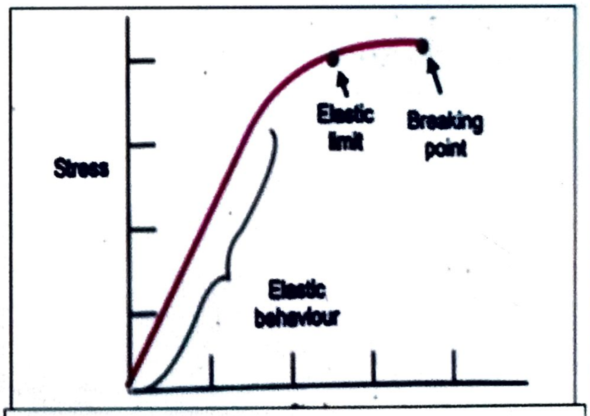


Fig:-Stress strain relationship for elastic solid

- Hence, the shape of the object is **permanently changed.**
- As the **stress is increased** even further, the material ultimately breaks.