FDE449 Physical Properties of Foods

Rheological Properties of Foods

Content
1) Reology
2) Viscosity
3) Types of flow

Reoloji

«Rheo» means «flow», «logia» means «science» in Greek.

- Rheology has been defined as the deformation of objects under the influence of applied forces.
- Rheology is the science that studies the deformation of materials including flow.
- Rheology describes the properties of flow in liquids and deformation in solids.

Rheology

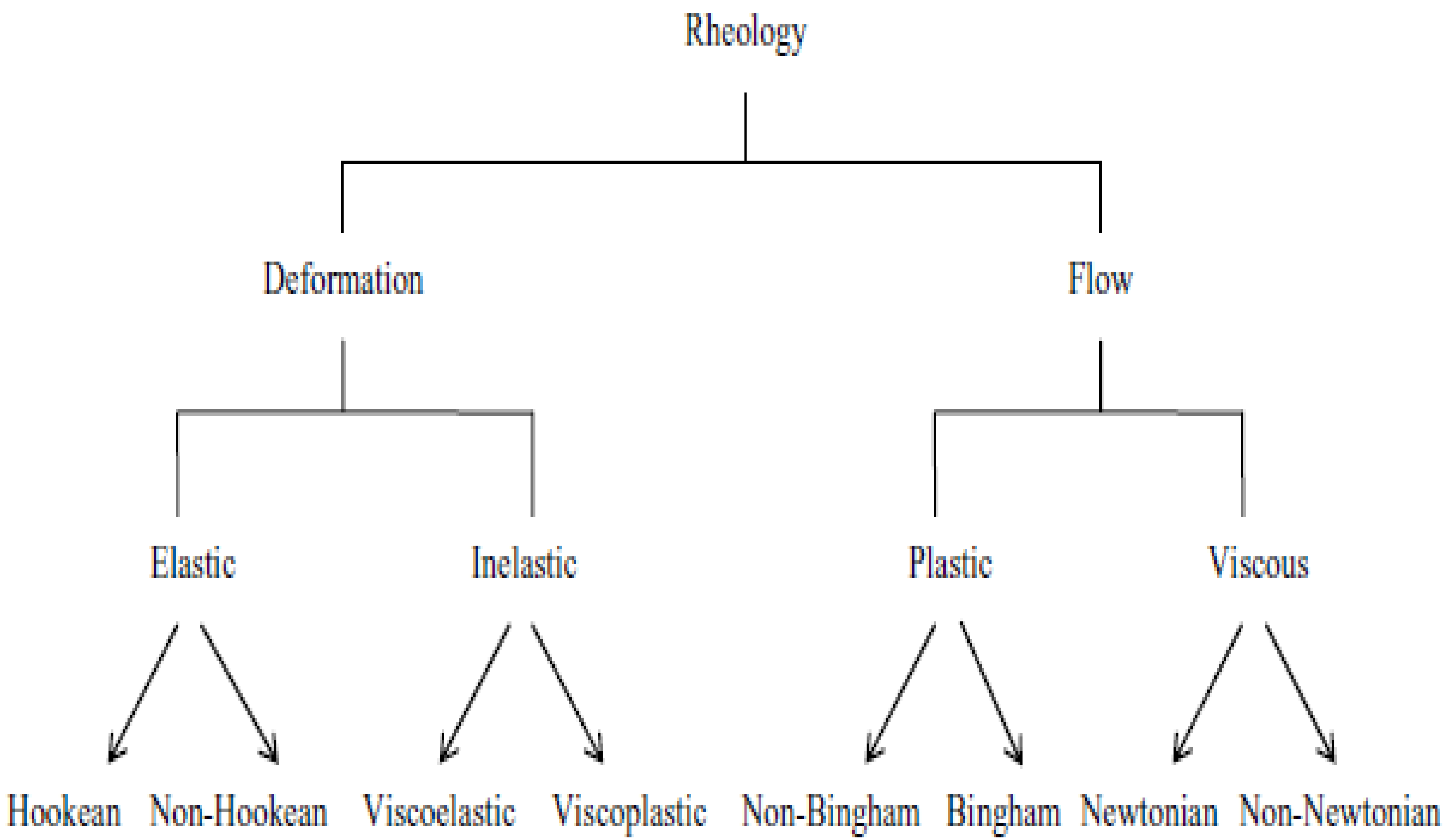
Foods are subjected to forces during processing, particularly

- size reduction operations and
- expression (pressing) processes;
- in addition, packaging material such as cans and flexible pouches will undergo stress,
- particularly during heating, as the contents expand.
- From the mechanical point of view, equipment should be designed to withstand high pressures.
- Also of extreme importance is the mechanical properties of food and their relationship to texture.

Rheologic data;

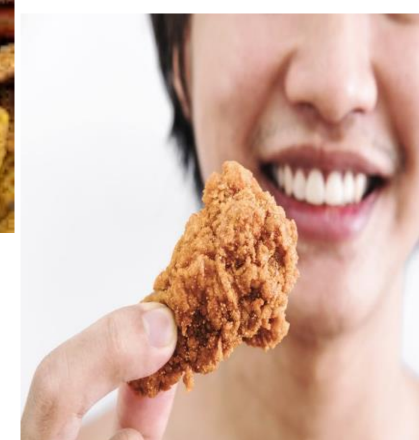
- Rheological data are required in product quality evaluation,
- in engineering calculations, and
- process design.

Classification of rheology



- For liquid or semi-liquid foods, viscosity or consistency
- For solid foods, texture
- If a substance flows with the effect of weight, it is liquid, if it does not flow, it is solid.



Viscosity

- In many food-processing operations it is essential to know the viscosity of the fluid being processed, so that the most suitable equipment can be selected.

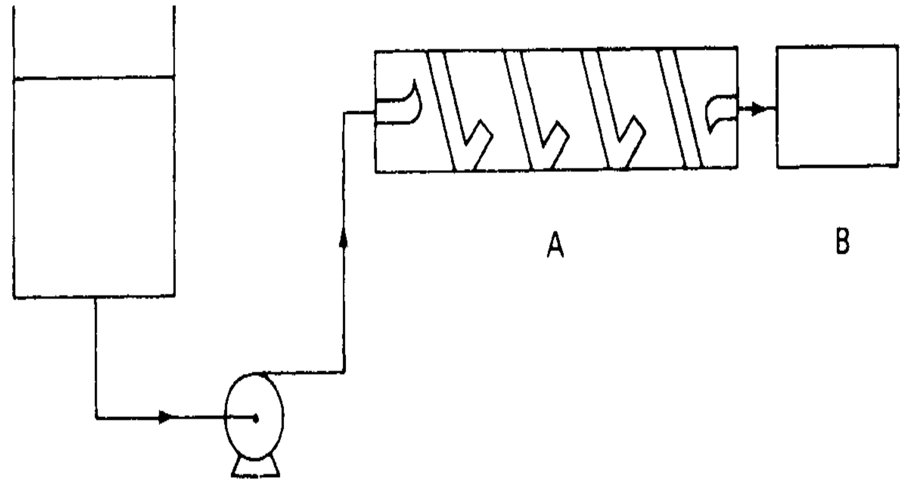
During some operations, the viscosity may change considerably. Such as:

- heating,
- cooling,
- Homogenization and
- and concentration as well as during many industrial fermentations by moulds;

these viscosity changes need to be considered when designing these processes.

Measurement of viscosity is often very important for quality control, particularly on products that we expect to be of a particular consistency in relation to appearance or mouth feel, e.g. cream, yoghurt, tomato paste and custards.

- Consider a processing application where milk or fruit juice is being pumped from tank, by pump, through a pasteurizer A, to a bottling plant B or packaging unit.
  - The function of the pump is to supply energy to overcome both the internal resistance within the fluid and the frictional resistance between the fluid and the pipe walls.
  - The factors affecting the energy input will be the pressure (or head) required, the volumetric flow rate and the magnitude of the fluid viscosity and their frictional forces.
  - As the fluid viscosity increases, the frictional forces will increase and more energy would be required.



Flow through a heat exchanger A and packaging unit B.

Viscosity

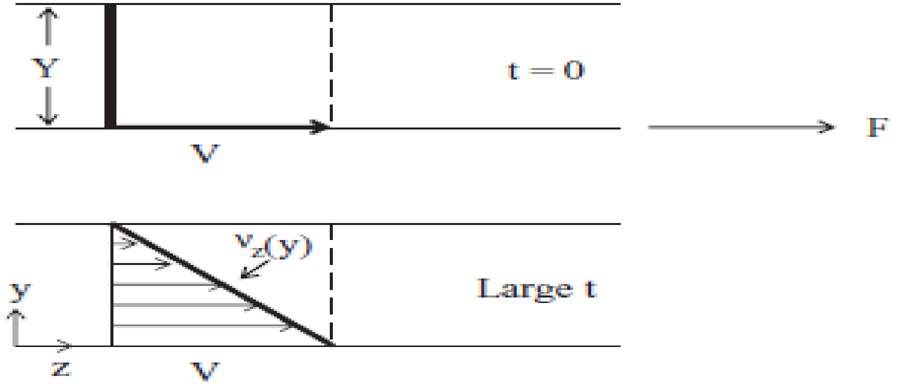
- The viscosity of a fluid is a measure of its resistance to deformation at a given rate. For liquids, it corresponds to the informal concept of "thickness":
- for example, syrup has a higher viscosity than water.

Three types of viscosity is defined:

- Dynamic viscosity(μ)
- Kinematic viscosity (v)
- Relative and specific viscosity

Newton's Law of Viscosity

- Consider a fluid between two large parallel plates of area A, separated by a very small distance Y .
- The system is initially at rest but at time t = 0, the lower plate is set in motion in the z-direction at a constant velocity V by applying a force F in the z-direction while the upper plate is kept stationary.
- At t = 0, the velocity is zero everywhere except at the lower plate, which has a velocity V. Then, the velocity distribution starts to develop as a function of time.
- Finally, steady state is achieved and a linear velocity distribution is obtained. The velocity of the fluid is experimentally found to vary linearly from zero at the upper plate to velocity V at the lower plate, corresponding to no-slip conditions at each plate.



- Experimental results show that the force required to maintain the motion of the lower plate per unit area is proportional to the velocity gradient, and the proportionality constant, μ, is the viscosity of the fluid:

$$\frac{F}{A}=\mu\frac{V}{y}$$

- The microscopic form of this equation is known as Newton's law of viscosity:
- $\tau_{yz} = -\mu\frac{dv_z}{dy} = -\mu\gamma_{yz}$

where

- τ_{yz} = shear stress (N/m^2),
- μ = viscosity (Pa·s),
- γ_{yz} = shear rate (1/s).
- Shear stress and shear rate have two subscripts: z represents the direction of force and y represents the direction of normal to the surface on which the force is acting. A negative sign is introduced into the equation because the velocity gradient is negative, that is, velocity decreases in the direction of transfer of momentum.

Example: Two parallel plates are 0.1 m apart. The bottom plate is stationary while the upper one is moving with a velocity V. The fluid between the plates is water, which has a viscosity of 1 cp.

(a) Calculate the momentum flux necessary to maintain the top plate in motion at a velocity of 0.30 m/s.

(b) If water is replaced with a fluid of viscosity 100 cp, and momentum flux remains constant, find the new velocity of the top plate.

Illustration of example

Units of viscosity in the various systems

System of units	Shear stress	Shear rate	Dynamic viscosity
SI	$N\ m^{-2}$	s^{-1}	$N\ s\ m^{-2}$ (or poiseuille (Pl))
cgs	$dyn\ cm^{-2}$	s^{-1}	$dyn\ s\ cm^{-2}$ (or poise (P))
Imperial	$lbf\ ft^{-2}$	s^{-1}	$lbf\ s\ ft^{-2}$

Conversion: $1.488\ N\ s\ m^{-2} = 1\ lbf\ s\ ft^{-2}$.

- The unit of dynamic viscosity (μ): Pa s = N s/ m^2 (Poiseuille-PI)

In SI system:

- $$\mu = Pa\ s = \frac{(N)}{m^2} s = \frac{(kg\ m)}{s^2\ m^2} s = \frac{kg}{m\ s}$$

In cgs system:

- $\mu = \frac{dyn\ s}{cm^2}$ = poise (P), 1 Poise = 0.1 N s/m^2 = 0.1 Pa s

Centipoise, which is one percent of poise, is often used.

1 centi poise (cp) = 10^{-2} P = 10^{-3} Pa s

Table 4.2 — Viscosity values at 20 °C.

Fluid	Viscosity ($N\,s\,m^{-2}$)	Fluid	Viscosity ($N\,s\,m^{-2}$)
Carbon dioxide	1.48×10^{-5}	20% sucrose (g per 100 g of solution)	2×10^{-3}
Water	1.002×10^{-3}	40% sucrose (g per 100 g of solution)	6.2×10^{-3}
Carbon tetrachloride	0.969×10^{-3}	60% sucrose (g per 100 g of solution)	58.9×10^{-3}
Olive oil	84×10^{-3}	Honey (average values after mixing) (25 °C)	6000×10^{-3}
Castor oil	986×10^{-3}	Milk	2×10^{-3}
Glycerol	1490×10^{-3}	Ethanol	1.20×10^{-3}
		n-hexane	0.326×10^{-3}

The dynamic viscosities of some simple fluids at 20°C

Viscosity values of some materials

- Water has a viscosity of 1 cp at 20.2 ^{o}C.
- Most gases and simple fluids exhibit Newtonian behaviour at the shear rates normally encountered.
- Gases have the lowest viscosity values.
- Simple fluids such as water, dilute solutions and organic solvents are considered to be low-viscosity fluids.
- It should be noted that, as the solids concentration increases, the viscosity increases, so that during certain unit operations, such as evaporation and reverse osmosis, the viscosity increases, the changes being more marked at higher solids contents.
- In the concentration of proteins by ultrafiltration, it is the viscosity that limits the extent of the concentration.

Viscosity values of some materials

- Proteins have a much more marked effect on viscosity than do salts or minerals in equal concentrations.
- Milk has a variable viscosity, depending upon its chemical composition, while homogenization increases its viscosity.
- Oils are much more viscous than water.
- Most food-grade oils are Newtonian in behaviour.

Temperature effect on viscosity

- Viscosity varies with temperature.
- The difference in the effect of temperature on viscosity of liquids and gases is related to the difference in their molecular structure.
- Viscosity of most of the liquids decreases with increasing temperature.
- On average there is about a 2% change in viscosity for each degree Celsius change in temperature.
- Temperatures should be controlled to within ± 0.1^{o}C during viscosity determinations.

Kinematic viscosity

It is the ratio of dynamic viscosity of the fluid to the density of the fluid.

Kinematic viscosity, ν = dynamic viscosity/ density

$$\nu = \frac{\mu}{\rho}$$

Unit in SI system: m^2/ s

in cgs system: cm^2/s, Stoke

Dimension of kinematic viscosity are L^2/T and the most common unit is the STOKE (St)

1 stoke (St) = 10^{-4} m^2/s

L:lenght, *T*: temperature

Relative and specific viscosities

- Viscosity in emulsions and suspensions is usually measured in comparative terms. For example, the viscosity of the emulsion or suspension is compared with the viscosity of the pure solution.

- Relative viscosity= $\dfrac{\text{viscosity of emulsion/suspension}}{\text{viscosity of pure solvent}}$

Specific viscosity

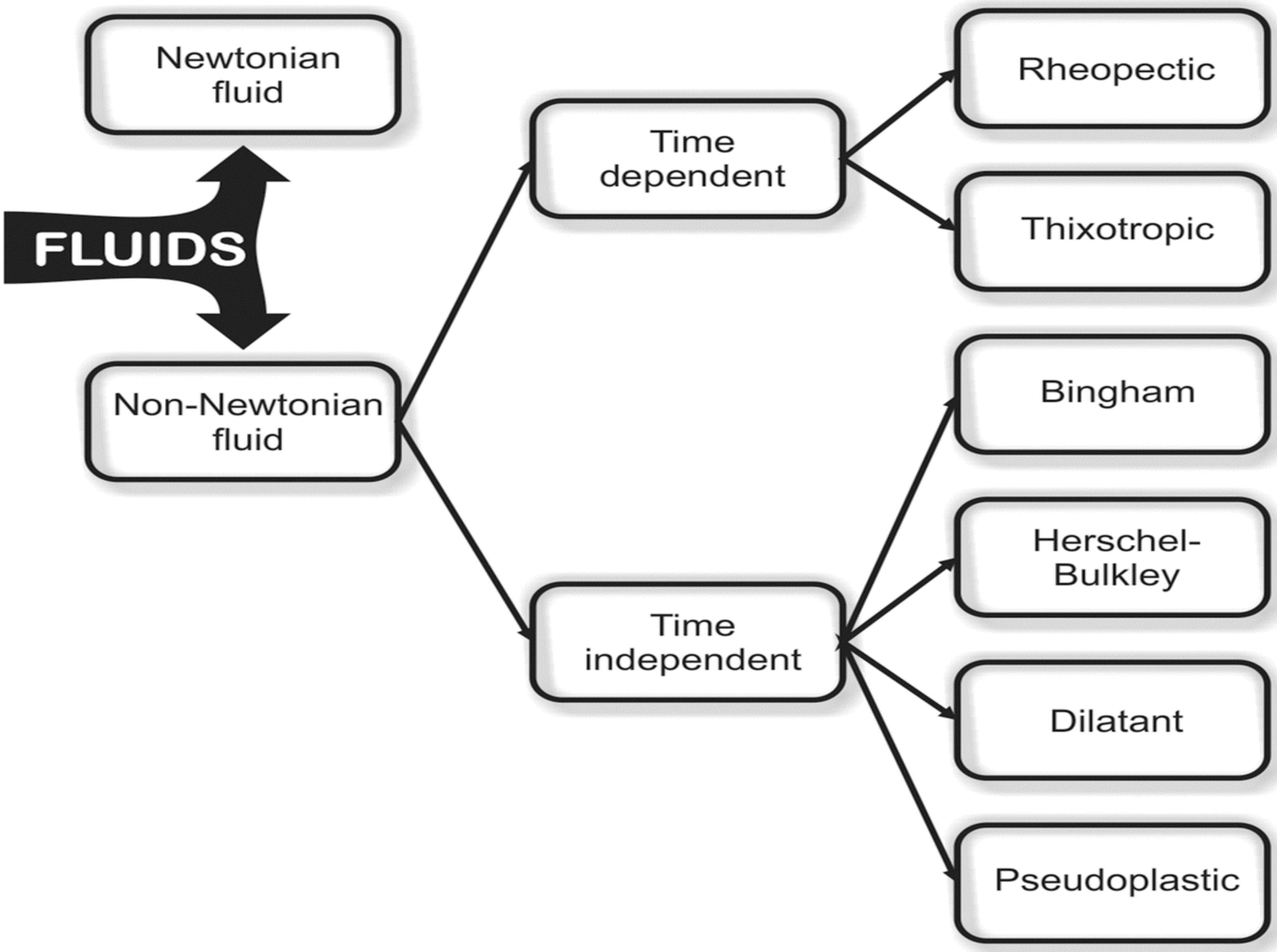
It is defined as the increment due to the addition of the solute, i.e.

Specific viscosity, η_{sp}

$$\eta_{sp} = \eta_{relative} - 1$$

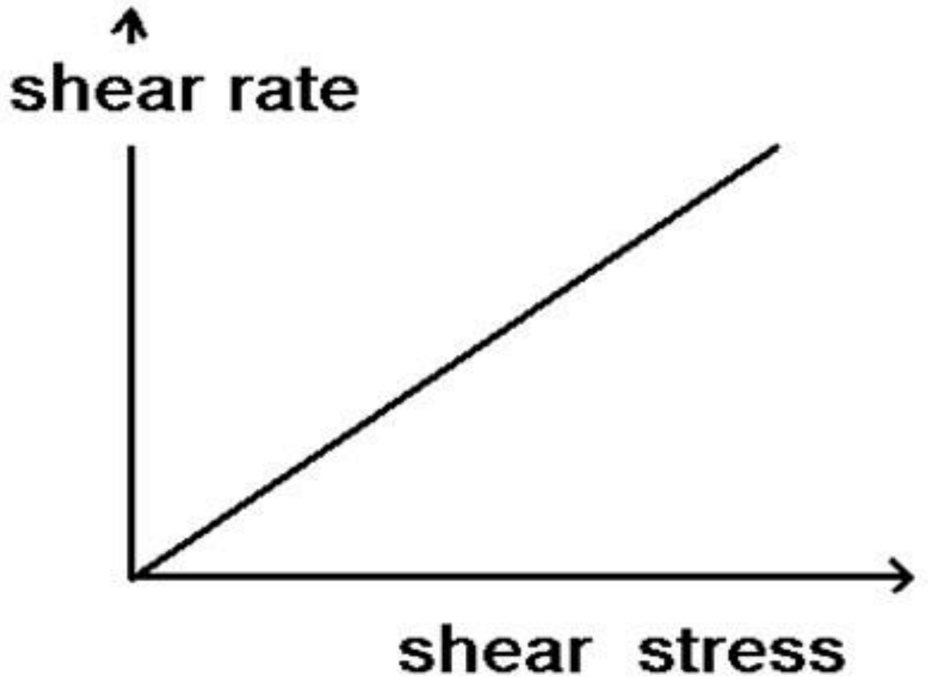
Relative viscosity is useful in understanding the behavior of some biopolymers (such as galactomannan, carboxymethyl cellulose).

Liquids by flow characteristics:

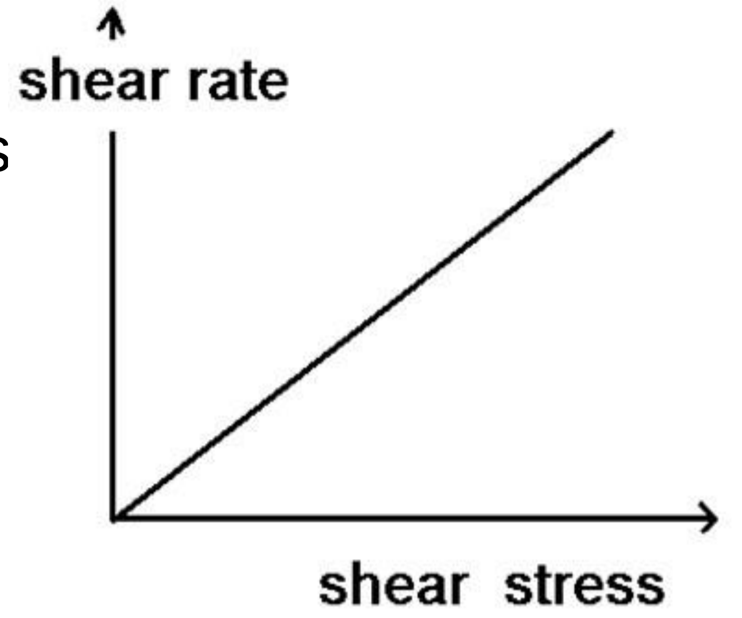


Newtonian behaviour :

- Ideal liquids.
- Obey Newton's law.
- Isotropic (they show the same property in all directions).
- There is a linear relationship between the shear stress and the shear rate.

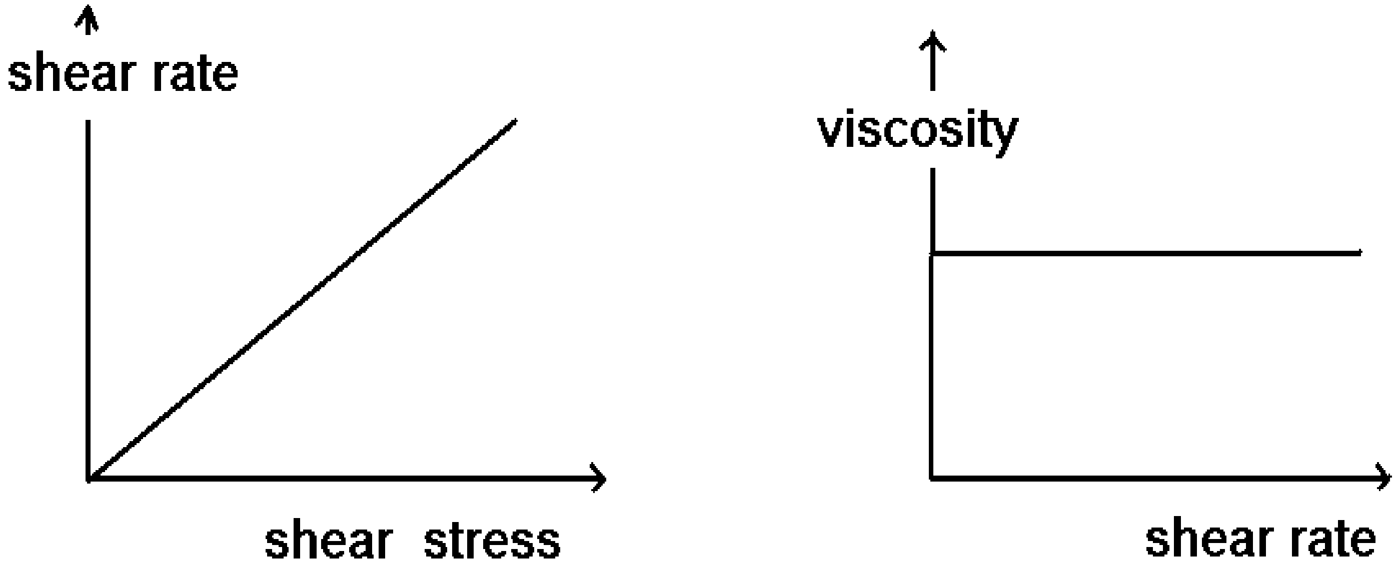


- If the shear stress applied to the fluid is directly proportional to the rate of deformation, in other words, if its viscosity does not change, this fluid is called Newtonian.
- The slope is constant and independent of the deformation rate.
- In these systems, shear stress increases in proportion to the rate of change of shear deformation (shear rate).
- In other words, there is a linear relationship between the (dv/dy) ratio and the applied shear stress.



Newtonian fluids

- Gas
- Oil
- Water
- Liquids containing more than 90% water (tea, coffee, beer, carbonated drinks, juices and milk).



Rheograms of newtonian fluids

- Data for fluids are often presented in the form ofshear stress-shear rate diagrams, plotted in either a linear or a log-log form. Such plots are called rheograms. It is prepared by plotting the shear stress against the shear rate.
- The figure shows the rheogram of a Newtonian system. In these systems, the flow curve is a straight line through the origin.

Non-Newtonian fluids

- there is not a linear relationship between the shear stress and the shear rate.
- do not obey Newton's law.

Examples of non-Newtonian fluids:

- concentrated solutions of macromolecules (starches, proteins and gums)
- Colloidal materials such as emulsions, suspensions, pastes.

The viscosity and shearing action are dependent upon a number of factors such as the following:

(a) The nature of the continuous and dispersed phase.

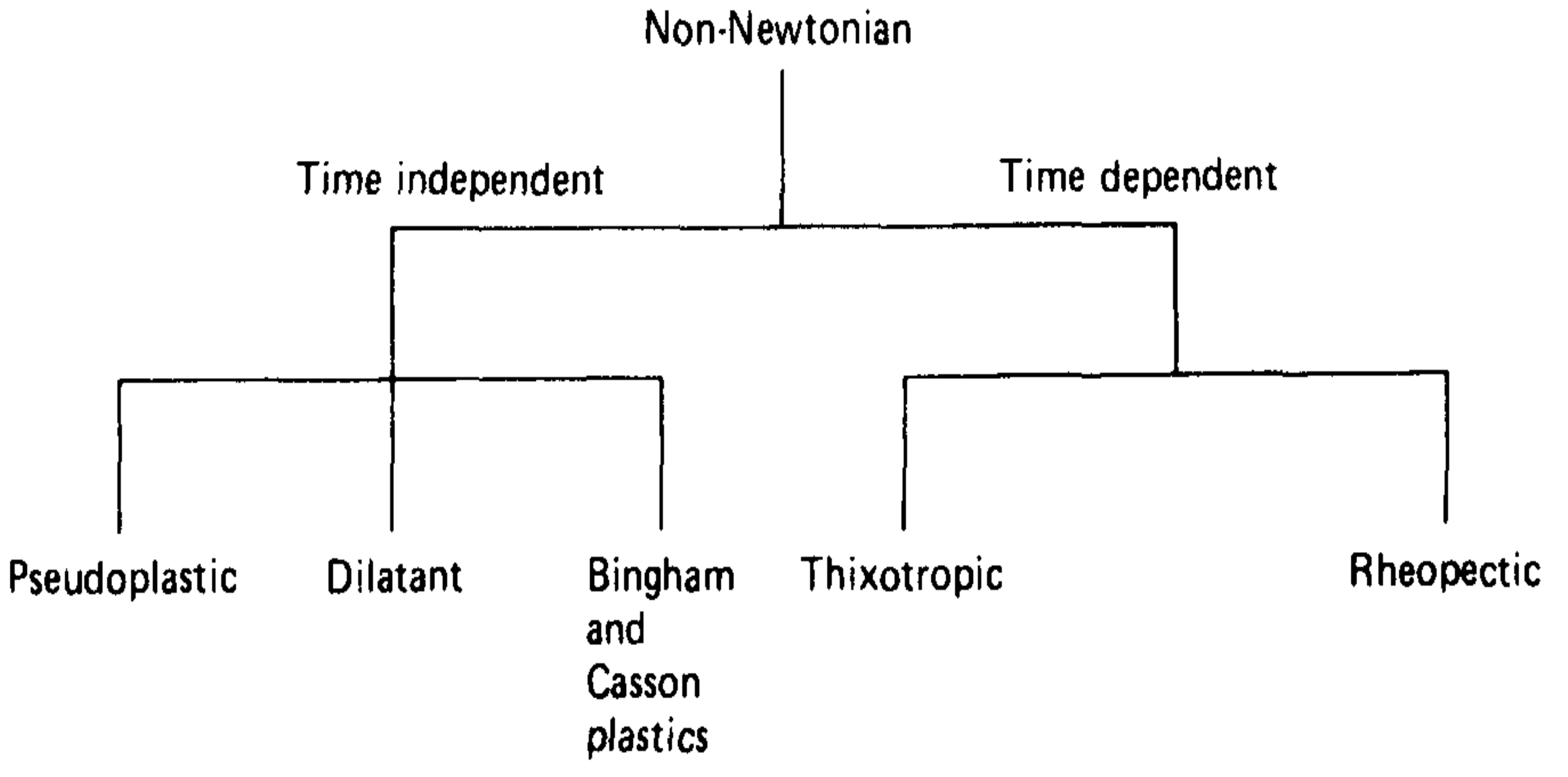
(b) Particle-particle interaction and particle-solvent interaction.

(c) The concentration of particles, their shape, size and chemical composition.

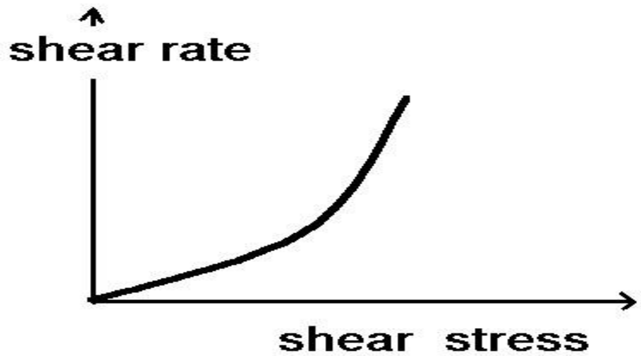
Many natural and formulated foods are colloidal in nature, e.g. milk, cream, mayonnaise and tomato paste. Non-Newtonian fluids are more difficult to deal with and to classify experimentally, as the viscosity will depend upon the experimental conditions selected.

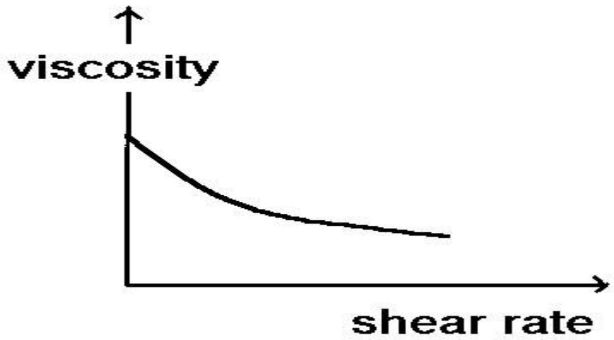
The viscosity recorded under those conditions is termed the apparent viscosity μ_a and is equal to the shear stress divided by the shear rate (similar to a Newtonian fluid).

Non-Newtonian fluids can be further subdivided into two major division:

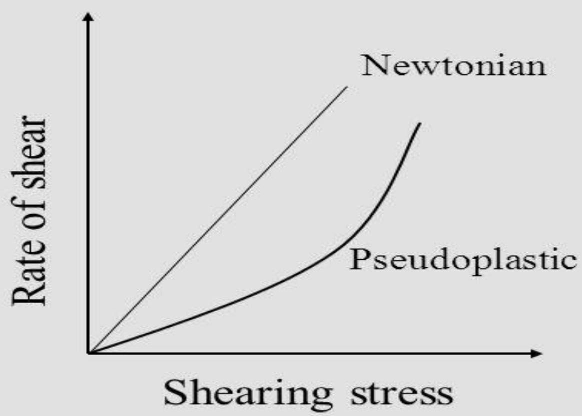


1) Pseudoplastik behaviour





Pseudoplastic Flow



Pseudoplastic materials always flow like a liquid but viscosity decreases as shear rate increases, e.g. mayonnaise.

Decrease in viscosity with shear rate may be due to: orientation and disentaglement increasing with shear rate; or solvating layers being sheared away resulting in decreased particle size.

Pseudoplastic behaviour

- In these types of fluids, as shear rate increases friction between layers decreases. Shearing causes entangled, long-chain molecules to straighten out and become aligned with the flow, reducing viscosity.
- A typical example for shear thinning fluids is paint.
- When paint is on the surface but brushing is not applied, its viscosity increases and prevents it from flowing under the action of gravity.
- When paint is applied to a surface by brushing which shears the paint, its viscosity decreases.
- Another example for a pseudoplastic fluid is the ink in a ballpoint pen.

Pseudoplastic fluids

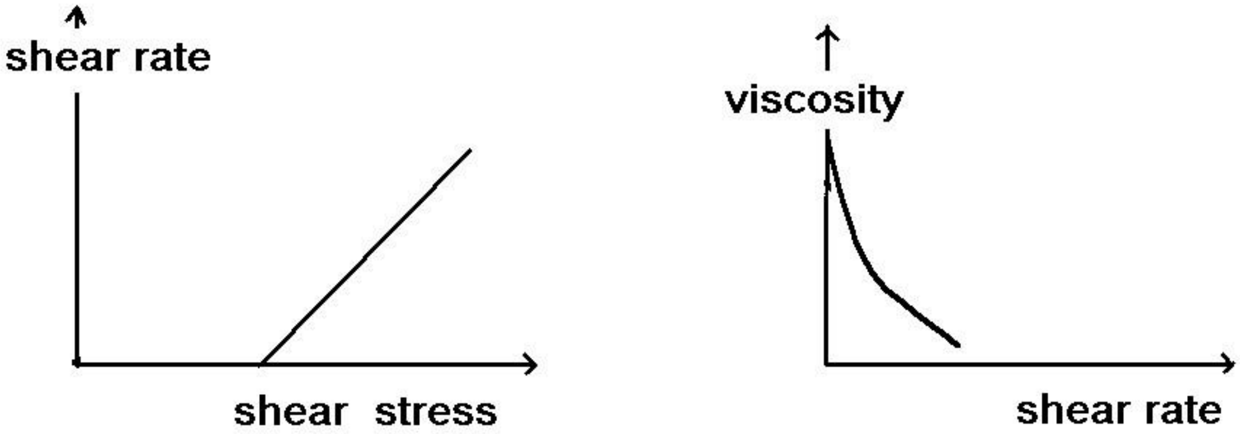
Fruit and vegetable products such as:

- applesauce,
- banana puree, and
- concentrated fruit juices are good examples of pseudoplastic fluids in food systems

Rheological behavior of foods may change depending on concentration.

The rheological behavior of concentrated grape juice with a Brix value of 82.1 showed shear thinning behavior. However, diluted samples with a Brix value of 52.1 to 72.9 can be Newtonian.

2) Plastic (Bingham) behaviour



Plastik akış reogramı

- At low shear stresses, they behave like solids and there will be no deformation until a critical (yield) shear stress is reached.
- Beyond that shera stress, the fluid will flow.
- The minimum force required to flow the liquid is called the yield value.
- The plastic flow curve does not pass through the origin.

Example : Mayonnaise

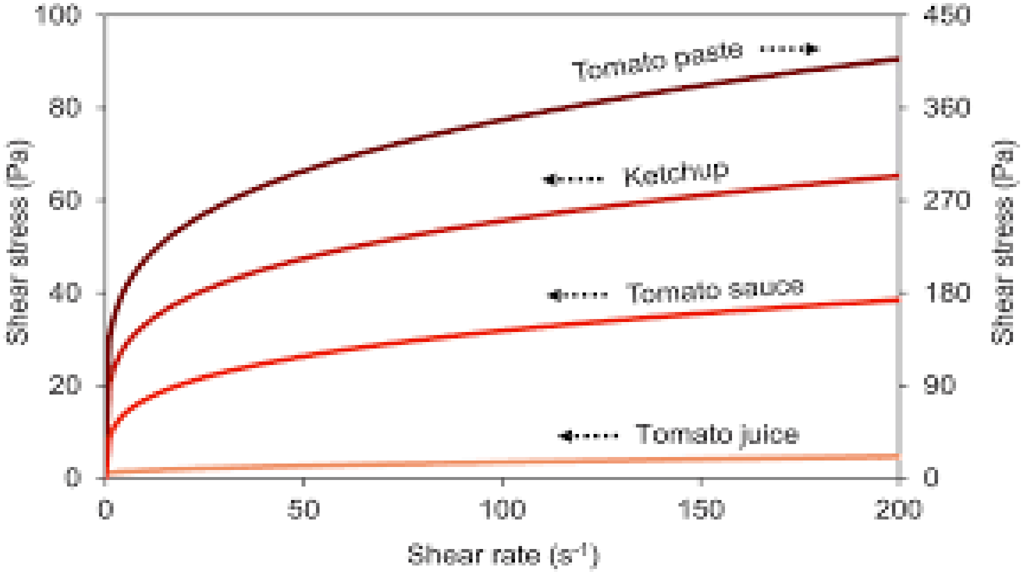
Toothpaste

- These types of liquids do not flow immediately and flow occurs when the shear stress reaches a certain threshold value (yield value).
- The rheogram is initially curved, then straight. The liquid begins to flow after the point where the line cuts the x-axis.
- It behaves like an elastic material at stresses below the threshold value. After the threshold value, the increase in shear stress increases in proportion to the shear rate.
- After the threshold value, it behaves like the flow of Newtonian systems.
- When the threshold value is reached, the bonds between the particles arising from the Van der Waals force are broken. Once the threshold value is exceeded, the fluid starts to flow and the plastic fluid may exhibit Newtonian, pseudoplastic, or dilatant flow behavior.

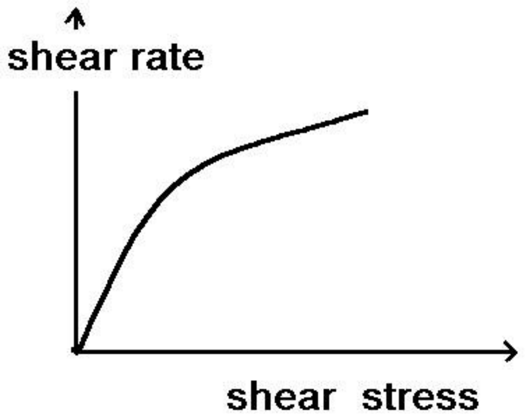
- Mayonnaise
- Ketchap

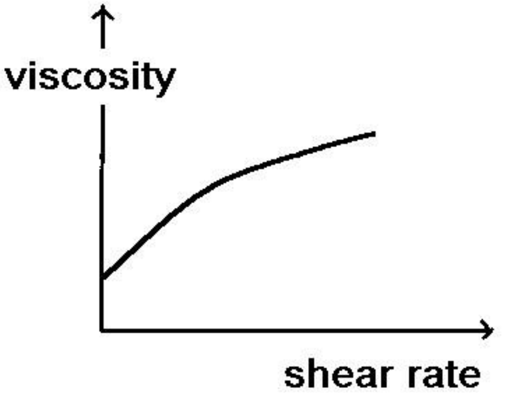
There is no flow unless pressure is applied.

- Ketchup will not flow without shaking the bottle, but once it has flowed, it is not necessary to continue shaking.

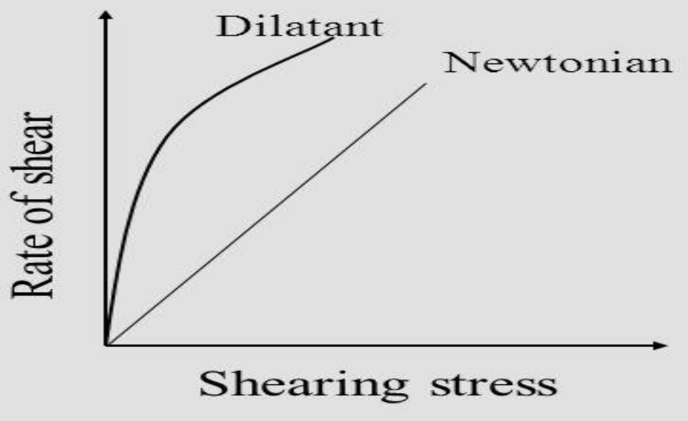


3) Dilatant (shear tickening) fluids





Dilatant Flow



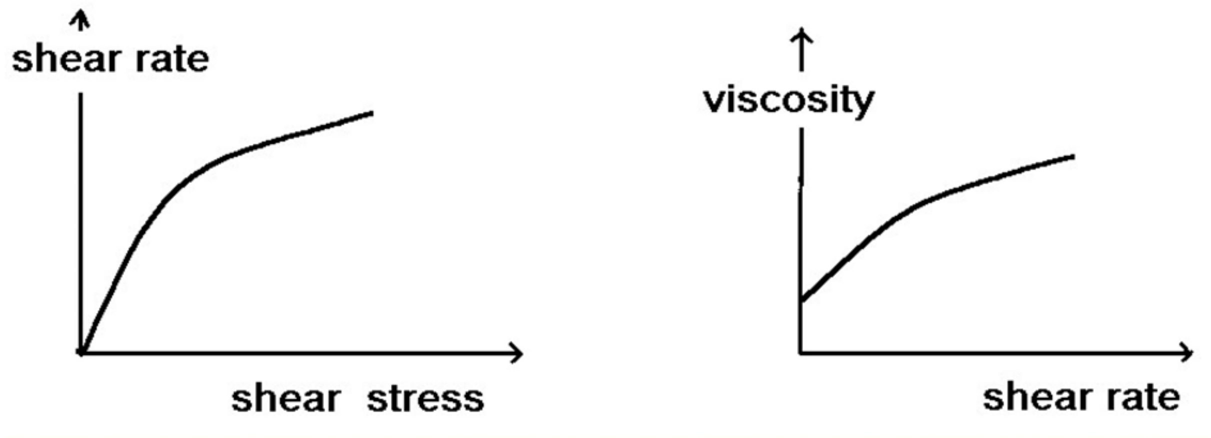
Dilatant fluids are characterised by increasing viscosity with increasing shear rate.

Dilatant behaviour is not nearly as common as pseudoplastic behaviour.

Dilatant behaviour is sometimes observed in suspensions at high solids content.

Dilatant Flow

- Certain suspensions with a high percentage of dispersed solids exhibit an in resistance to flow with increasing rates of shear.
- Such systems actually increase in volume when sheared are called dilatant.
- Dilatant materials «shear tickening systems.»
- When the stress is removed, a dilatant system returns to its original state of fluidity.



Examples of dilatant foods

- Liquid chocolate
- 40% corn starch solution

In this type of fluids, as the deformation rate increases, internal friction and apparent viscosity increase.

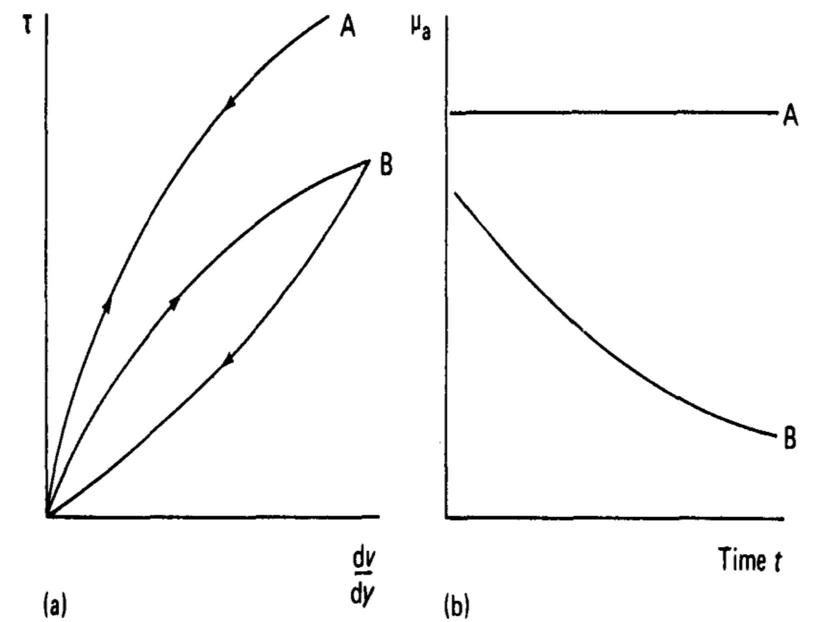
- Corn starch
- Unmodified starches (waxy corn, rice, barley, potato, wheat starches) show thickening behavior.
- The amylopectin component was responsible for shear thickening properties.
- If the increase in viscosity is accompanied by volume expansion, shear thickening fluids are called «dilatant fluids». **All the dilatant fluids are shear thickening.

Time-dependent fluids

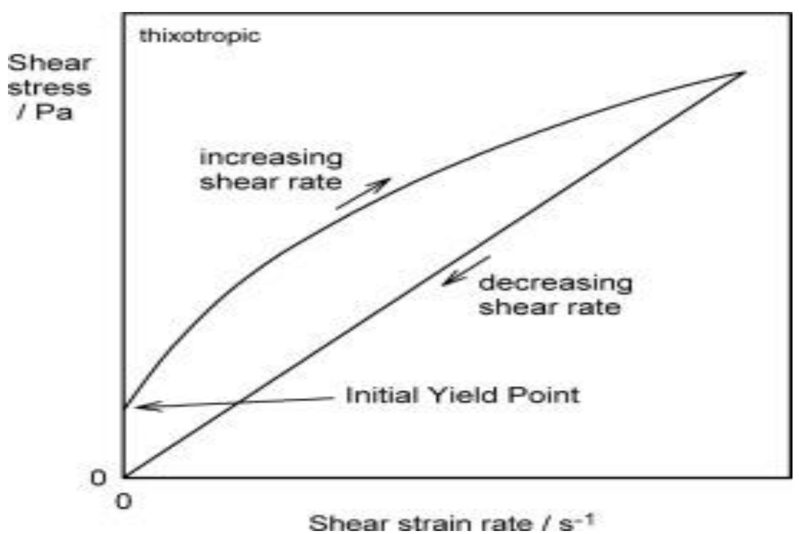
- Thixotropic
- Rheopectic

Thixotropy

- It is the decrease in viscosity as a function of time upon shearing, then recovery of original viscosity as a function of time without shearing.



Comparison of rheograms for a time-independent fluid (lines A) and a time-dependent fluid (lines B): (a) shear stress against shear rate; (b) apparent viscosity against time at a constant shear rate.

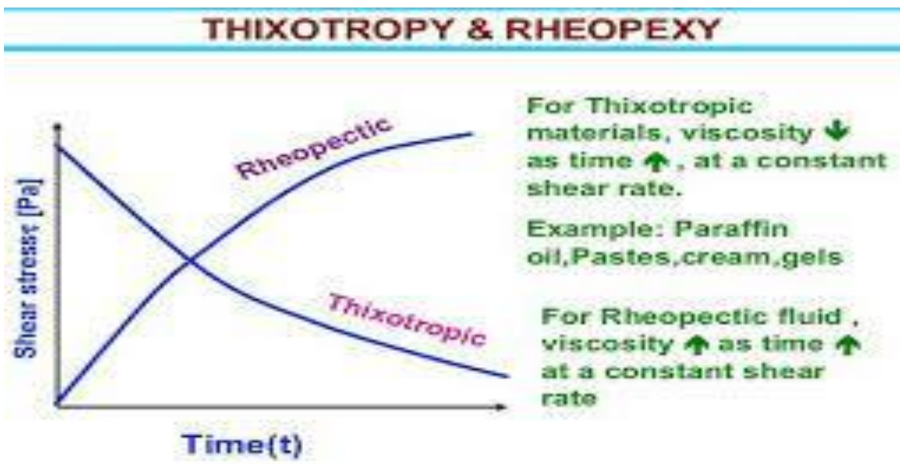


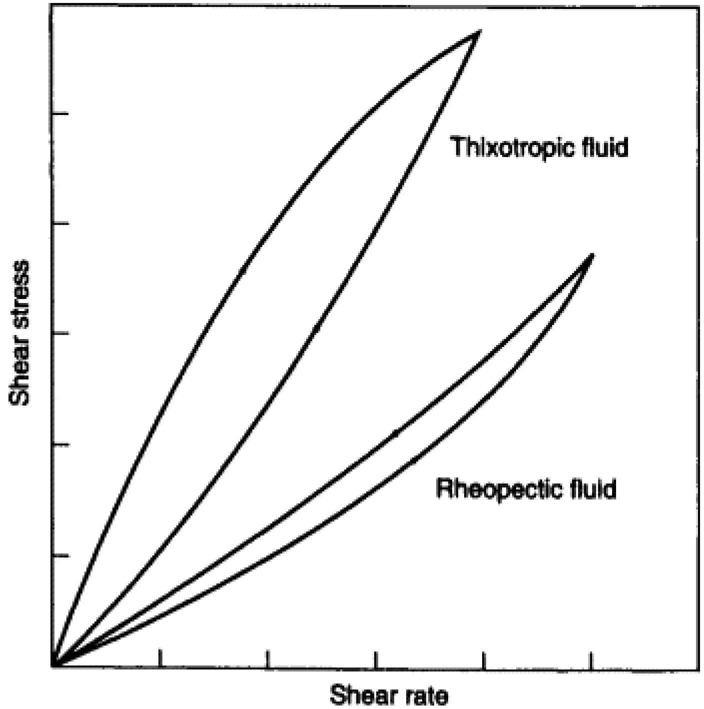
Some example of Thixotropic fluids:

- cytoplasm of cells,
- some varieties of honey,
- some types of clay,
- gelatin, xanthan gum, etc.

Rheopectic behaviour

- Contrary to thixotropic behavior, viscosity increases with time at a constant deformation rate.
- It is a much rarer condition than thixotropic behavior.





Rheopectic behaviour

- Also, they show an increased viscosity upon agitation. That means, when the fluid is shaken, it becomes thick, or it may even solidify.
- Moreover, higher the shear stress, more viscous that fluid becomes. It is because the microstructure of these rheopectic fluids is constructed under continuous shearing. Therefore, it is named as shear-induced crystallization.

- Some common examples of rheopectic fluids include some gypsum pastes, printer ink, lubricants, etc.

Viscoelasticity

Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Viscous materials, like honey, resist shear flow and strain linearly with time when a stress is applied. Elastic materials strain when stretched and quickly return to their original state once the stress is removed. Viscoelastic materials have elements of both of these properties and, as such, exhibit time-dependent strain. Whereas elasticity is usually the result of bond stretching along crystallographic planes in an ordered solid, viscosity is the result of the diffusion of atoms or molecules inside an amorphous material.

Viscoelastic vs Viscoplastic

	Viscoelastic	Viscoplastic
DEFINITION	Viscoelastic materials are polymer substances that show both viscous and elastic properties during the deformation of the material	Viscoplastic materials are polymer substances that show both viscous and plastic properties during the deformation of the material
PROPERTIES	Viscosity and elasticity	Viscosity and plasticity
RECOVERABILITY	Recoverable deformation	Unrecoverable deformation

Viscosities of some materials at room temperature

Material	Viscosity (Pa s)
Air	10^{-5}
Water	10^{-3}
Olive oil	10^{-1}
Glyserol	1
Honey	10
Maple syrup	10^{2}
Glass	10^{40}