RHEOLOGY

The term rheology, comes from the Greek rheo ("to flow") and logos ("science"). Rheology is used to describe the flow of liquids and the deformation of solids.

Viscosity is an expression of the resistance of a fluid to flow; the higher the viscosity, the greater is the resistance.

The simple liquids can be described in terms of absolute viscosity (single value).

The heterogeneous dispersions rheologic properties are more complex, however, and cannot be expressed by a single value.
Manufacturers of medicinal and cosmetic creams, pastes, and lotions must be capable of producing products with acceptable consistency and smoothness.

Valuable information can be obtained by use of analytic methods of rheology, for formulating better pharmaceutical products.
The rheology of product can affect patient acceptability, physical stability, and even biologic availability.
Rheologic properties of a pharmaceutical system can influence the selection of processing equipment.

Classes of materials according to types of flow:

1. Newtonian systems or
2. Non-Newtonian systems.

NEWTONIAN SYSTEMS

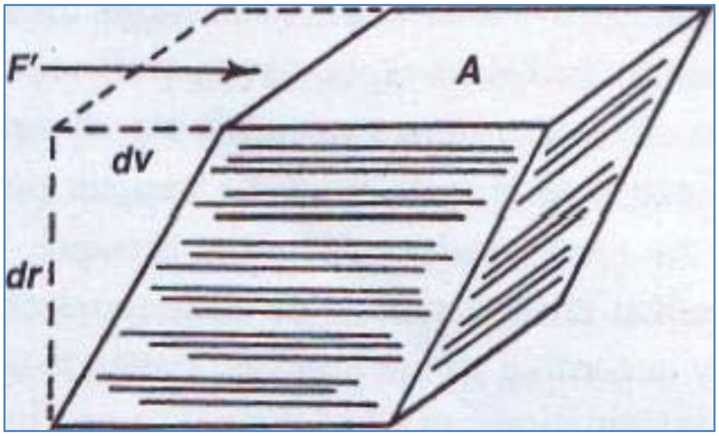
Newton's Law of Flow

<u>Rate of shear</u> or the velocity gradient: $(\frac{dv}{dr})$=G

Is the difference of velocity, dv, between two planes of liquid separated by an infinitesimal distance dr.

<u>Shearing stress</u> :$(\frac{F'}{A})$=F

Is the force per unit area required to bring about flow.



<u>Newton</u> was recognized that the higher the viscosity of a liquid, the greater is the force per unit area (shearing stress) required to produce a certain rate of shear. Hence, rate of shear should be directly proportional to shearing stress, or

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

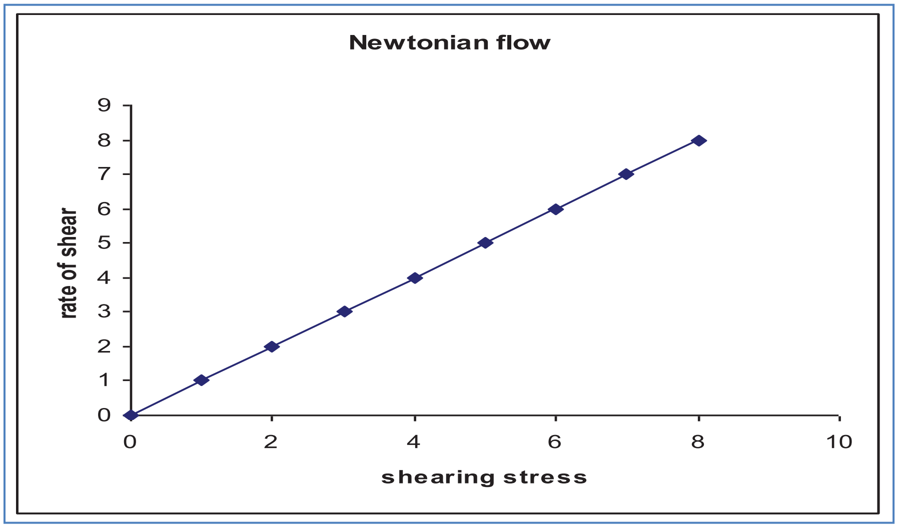
Where, η is the coefficient of viscosity, usually referred to simply as viscosity.

Above equation is frequently written as

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

where, F = F'/A and G = dv/dr.

A representative flow curve, or rheogram, obtained by plotting F versus G for a Newtonian system is shown in this figure.



The unit of viscosity is the poise, defined as the shearing force required to produce a velocity of 1 cm/sec between two parallel planes of liquid each 1 cm^2 in area and separated by a distance of 1 cm. The units for poise are dyne sec cm^{-2} (i.e., dyne sec/cm^2) or g cm^{-1} sec^{-1} (i.e., g/cm sec).

A more convenient unit for most work is the centipoise (cp), 1 cp being equal to 0.01 poise.

Fluidity, φ, a term sometimes used, is defined as the reciprocal of viscosity:

$$\varphi = \frac{1}{\eta}$$

Kinematic Viscosity

Kinematic viscosity is the absolute viscosity divided by the density of the liquid at a specific temperature:

$$\text{Kinematic viscosity} = -$$

The units of kinematic viscosity are the stoke (s) and the centistoke (cs).

Absolute viscosities of some Newtonian liquids at 20 C° commonly used in pharmacy are given in this table

Liquid	Viscosity (cp)
Castor oil	1000
Olive oil	100
Water	1.0019

Note. Water is ordinarily used as a standard for viscosity of liquids. Its viscosity at 25°C is 0.8904 cp.

Temperature Dependence and the Theory of Viscosity

The viscosity of liquid decreases as temperature is raised, and the fluidity of a liquid (the reciprocal of viscosity) increases with temperature. The dependence of the viscosity of a liquid on temperature is expressed approximately for many substances by an equation analogous to the Arrhenius equation of chemical kinetics:

$$= Ae^{E\nu RT}$$

where A is a constant depending on the molecular weight and molar volume of the liquid and E_V, is an "activation energy" required to initiate flow between molecules.

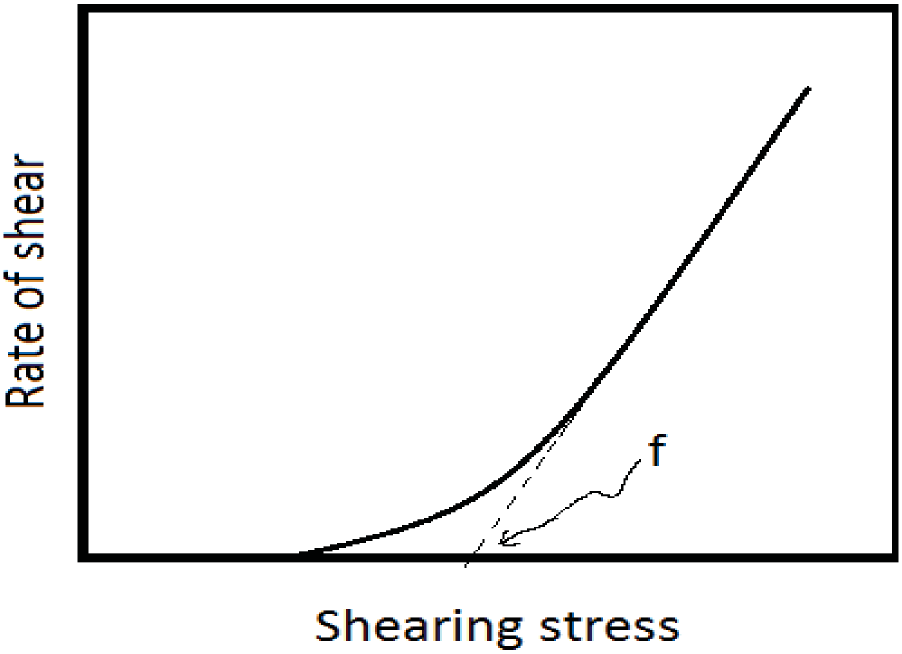
NON-NEWTONIAN SYSTEMS

The majority of fluid pharmaceutical products are not simple liquids and 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 such as colloidal solutions, emulsions, liquid suspensions, and ointments. When non-Newtonian materials are analyzed in a rotational viscometer and results are plotted, various consistency curves, representing three classes of flow, are recognized:

Plastic, pseudoplastic, and dilatant.

Plastic Flow

In Figure below, the curve represents a body that exhibits plastic flow; such materials are known as Bingham bodies.



Plastic flow curves do not pass through the origin, but 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.

Yield value is an important property of certain dispersions.

The slope of the rheogram in the Figure 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

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

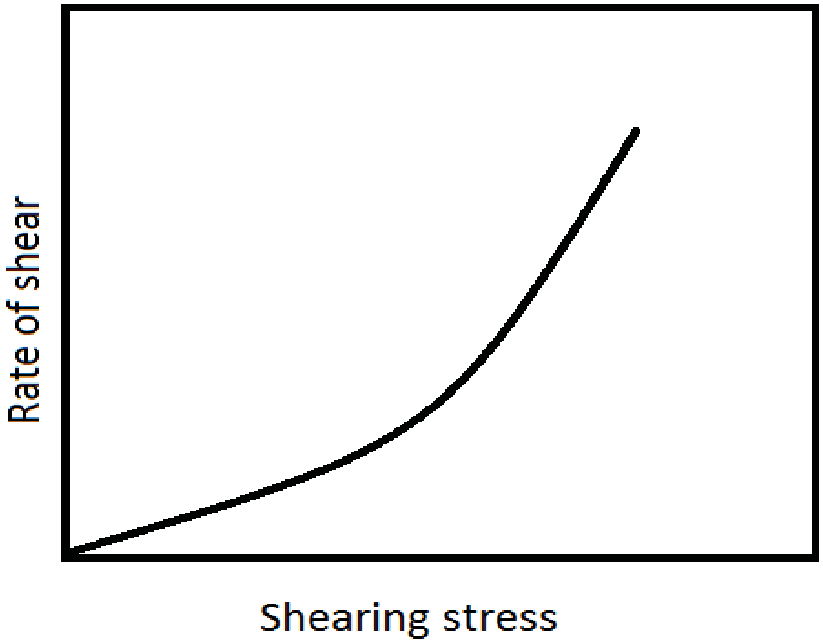
Where, f is the yield value, or intercept, on the shear stress axis in dynes/cm^2.

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.

Pseudoplastic Flow

Many pharmaceutical products, including liquid dispersions of natural and synthetic gums (e.g., sodium alginate, and methylcellulose) exhibit pseudoplastic flow.

Pseudoplastic flow is typically exhibited by polymers in solution, in contrast to plastic systems, which are composed of flocculated particles in suspension. As seen in this Figure, the consistency curve for a pseudoplastic material begins at the origin. Therefore, there is no yield value as there is in a plastic system.



Furthermore, because no part of the curve is linear, the viscosity of a pseudoplastic material cannot be expressed by any single value.

The viscosity of a pseudoplastic substance decreases with increasing rate of shear.

An apparent viscosity can be obtained at any rate of shear from the slope of the tangent to the curve at the specified point.

The most satisfactory representation for a pseudoplastic material, however, is probably a graphic plot of the entire consistency curve.

Objective comparisons between different pseudoplastic systems are more difficult than with either Newtonian or plastic systems. For example, Newtonian systems are completely described by viscosity, η, and plastic systems are adequately described by yield value, f, and plastic viscosity, U.

However, the exponential formula can be used to compare rheology of pseudoplastic materials to be compared.

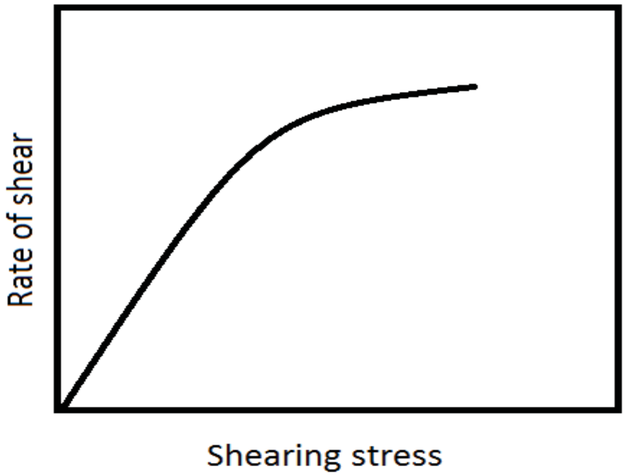
$$F^N = \eta' G$$

The exponent N rises as flow becomes increasingly non-Newtonian.

When N = 1, the equation reduces to equation ($\eta = \frac{F}{G}$) and flow is Newtonian. The term η' is a viscosity coefficient.

Dilatant Flow

Certain suspensions with a high percentage of dispersed solids exhibit an increase in resistance to flow with increasing rates of shear. Such systems actually increase in volume when sheared and are hence termed dilatant; Figure illustrates their flow properties.



This type of flow is the inverse of that possessed by pseudoplastic systems.

Whereas pseudoplastic materials are frequently referred to as "shear-thinning systems," dilatant materials are often termed "shear-thickening systems." When stress is removed, a dilatant system returns to its original state of fluidity. Equation ($F^N = \eta$ 'G) can be used to describe dilatancy in quantitative terms. In this case, N is always less than 1 and decreases as degree of dilatancy increases. As N approaches 1, the system becomes increasingly Newtonian in behavior. Substances possessing dilatant flow properties are invariably suspensions containing a high concentration (about 50 % or greater) of small, deflocculated particles.

THIXOTROPY

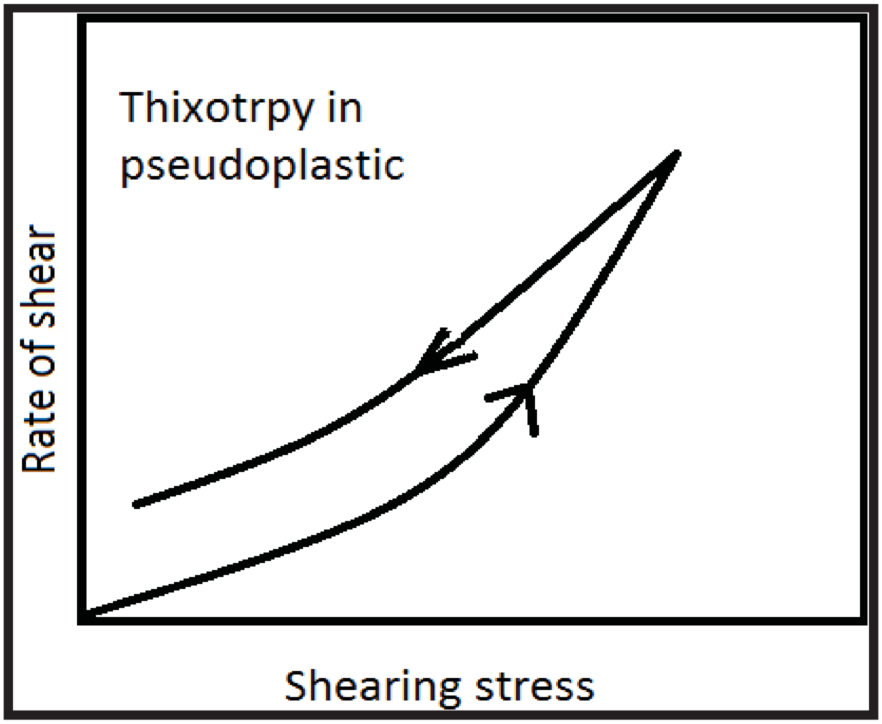
Several types of behavior are observed when rate of shear is progressively increased and plotted against resulting shear stress.

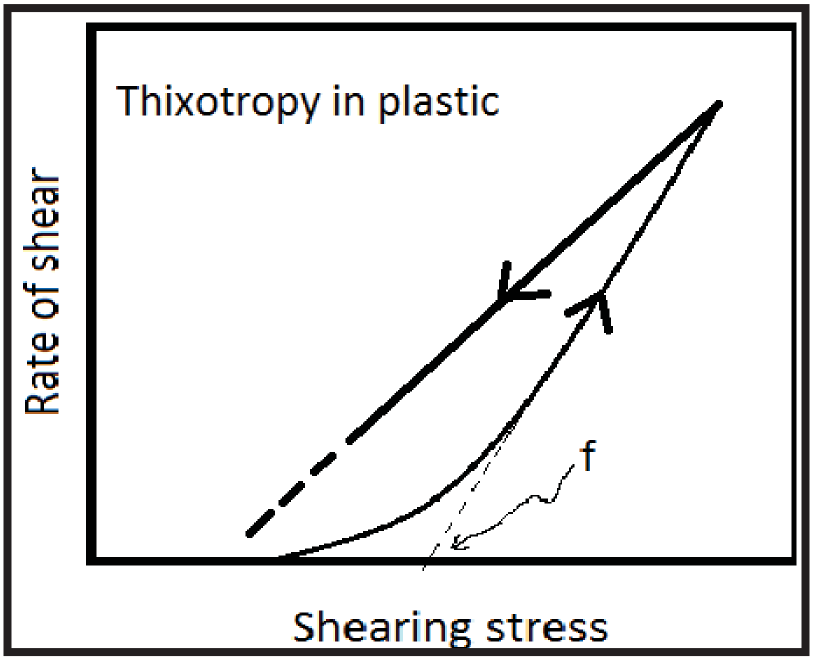
If the rate of shear were reduced when the maximum had been reached, and the resulted downcurve is identical with the upcurve, this system is Newtonian systems.

With shear-thinning systems (i.e., pseudoplastic), the downcurve is frequently displaced to the left of the upcurve (Figure), showing that the material has a lower consistency at the downcurve than at upcurve.

This phenomenon, known as thixotropy, can be defined as "an isothermal and comparatively slow recovery, on standing of a material, of a consistency lost through shearing."

Typical rheograms for plastic and pseudoplastic systems exhibiting this behavior are shown in the following Figure.





Rheograms obtained with thixotropic materials are highly dependent on the rate at which shear is increased or decreased and the length of time a sample is subjected to any one rate of shear.

Hysteresis loop: Is the area between the upcurve and downcurve of rheogram.

So the rheogram for same product is different depending on time of shear, rate of shear, and degree of structure in the sample.

This is an important point to bear in mind when attempting to obtain a quantitative measure of thixotropy.

Measurement of Thixotropy

The area of hysteresis has been proposed as a measure of thixotropic breakdown; it can be obtained readily by means of a planimeter or other suitable technique.

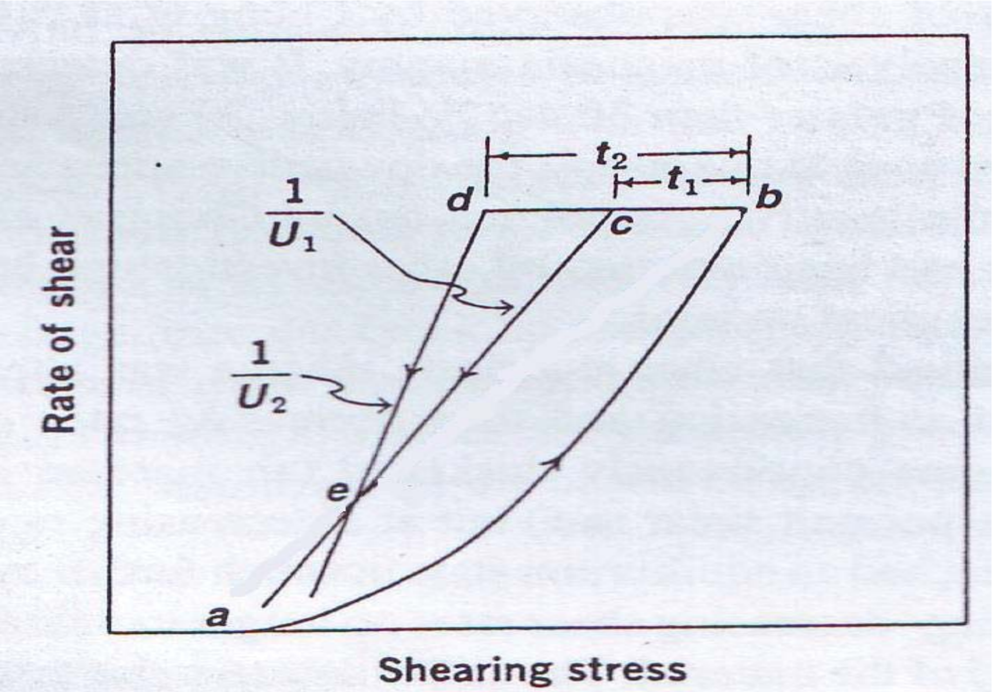
With plastic (Bingham) bodies, two approaches are frequently used to estimate degree of thixotropy. The first is to determine structural breakdown with time of a plastic system possessing thixotropy when subjected to a constant rate of shear for t. (the maximum shear rate is constant, the time of holding before reducing shearing stress is different)

Based on such a rheogram,

a thixotropic coefficient, B, the rate of breakdown with time at constant shear rate, is calculated as follows:

$$B = \frac{U1-U2}{ln\frac{t2}{t1}}$$

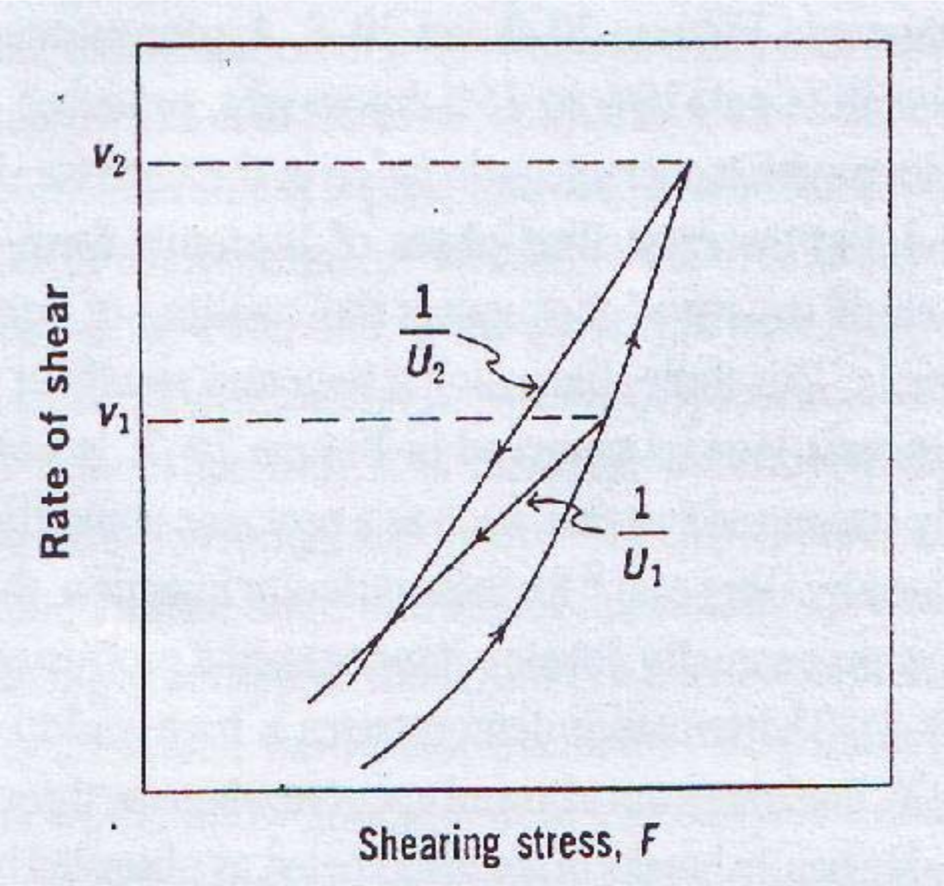
where U1, and U2 are the plastic viscosities of the two downcurves, calculated from equation ($U = \frac{F-f}{G}$), after shearing at a constant rate for t1 and t2 seconds, respectively.



The second approach is to determine the Structural breakdown of a plastic system possessing thixotropy when subjected to increasing shear rates. (The maximum shear rate is different; the time of holding before reducing shearing stress is constant). The principle involved in this approach is two hysteresis loops are obtained having different maximum rates of shear, v1, and v2. In this case, a thixotropic coefficient, M, the loss in shearing stress per unit increase in shear rate, is obtained from

$$M = \frac{U1 - U2}{\ln(\frac{v2}{v1})}$$

where M is in dynes sec/cm^2 and U1, and U2 are the plastic viscosities for two separate downcurves having maximum shearing rates of v1 and v2, respectively.



V_2
V_1
Rate of shear
$\frac{1}{U_2}$
$\frac{1}{U_1}$
Shearing stress, F

Negative Thixotropy

Negative thixotropy or antithixotropy, it is phenomenon represents an increase rather than a decrease in consistency on the downcurve. This increase in thickness with increased time of shear was observed in the rheologic analysis of magnesia magma. It was detected at shear rates of greater than 30 sec^{-1}; below 30 sec^{-1} the magma showed normal thixotropy, the downcurve appearing to the left of the upcurve

Negative thixotropy or antithixotropy should not be confused with dilatancy or rheopexy.

Dilatant systems are deflocculated and ordinarily contain greater than 50% by volume of solid dispersed phase, whereas antithixotropic systems have low solids content (1%-10%) and are flocculated.

Rheopexy is a phenomenon in which solid forms a gel more readily when gently shaken than when allowed to form the gel while the material is kept at rest. In a rheopectic system, the gel is the equilibrium form, whereas in antithixotropy, the equilibrium state is the sol.

DETERMINATION OF RHEOLOGIC PROPERTIES

Choice of Viscometer

Because shear rate in a Newtonian system is directly proportional to shearing stress, instruments that operate at a single shear rate can be used. These "single-point" instruments provide a single point on the rheogram; extrapolation of a line through this point to the origin will result in a complete rheogram.

For Non-Newtonian, a single-point determination is virtually useless in characterizing its flow properties. It is therefore essential that, with non-Newtonian systems, the instrument can operate at a variety of shear rates. Such multipoint instruments are capable of producing a complete rheogram for non-Newtonian systems.

The main instruments used for determination of rheological properties : Capillary, falling-sphere, cup-and-bob, and cone-and-plate viscometers. The first two are single-shear-rate instruments suitable for use only with Newtonian materials, whereas the latter two (multipoint, rotational instruments) can be used with both Newtonian and non-Newtonian systems.

VISCOELASTICITY

Viscoelastic measurements are based on the mechanical properties of materials that exhibit both viscous properties of liquids and elastic properties of solids. Many of the systems studied in pharmacy belong to this class, examples being creams, lotions, ointments, suppositories, suspensions, and the colloidal dispersing, emulsifying, and suspending agents.

Pharmaceutical areas in which rheology is significant

1. Fluids

a. Mixing

b. Particle-size reduction of disperse systems with shear

c. Passage through orifices, including pouring, packaging in bottles, and passage through hypodermic needles

d. Fluid transfer, including pumping and flow through pipes e. Physical stability of disperse systems

2. Quasisolids

a. Spreading and adherence on the skin

b. Removal from jars or extrusion from tubes

c. Capacity of solids to mix with miscible liquids d. Release of the drug from the base

3. Solids

a. Flow of powders from hoppers and into die cavities in tabletting or into capsules during encapsulation

b. Packagability of powdered or granular solids

4. Processing

a. Production capacity of the equipment

b. Processing efficiency