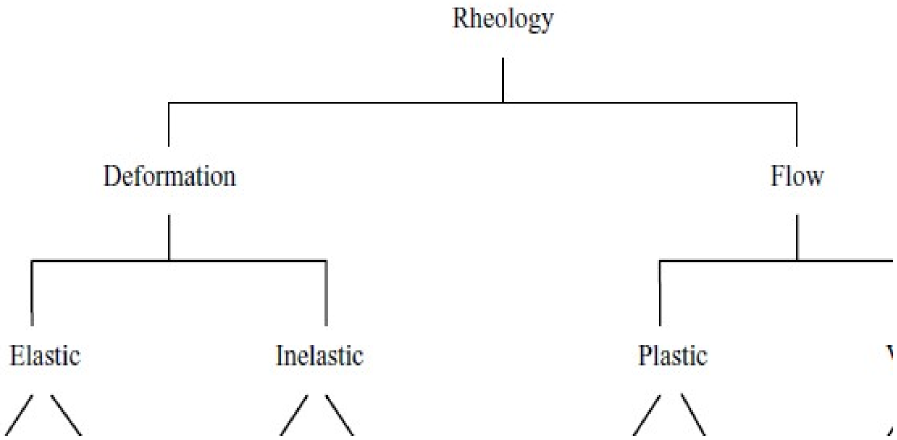
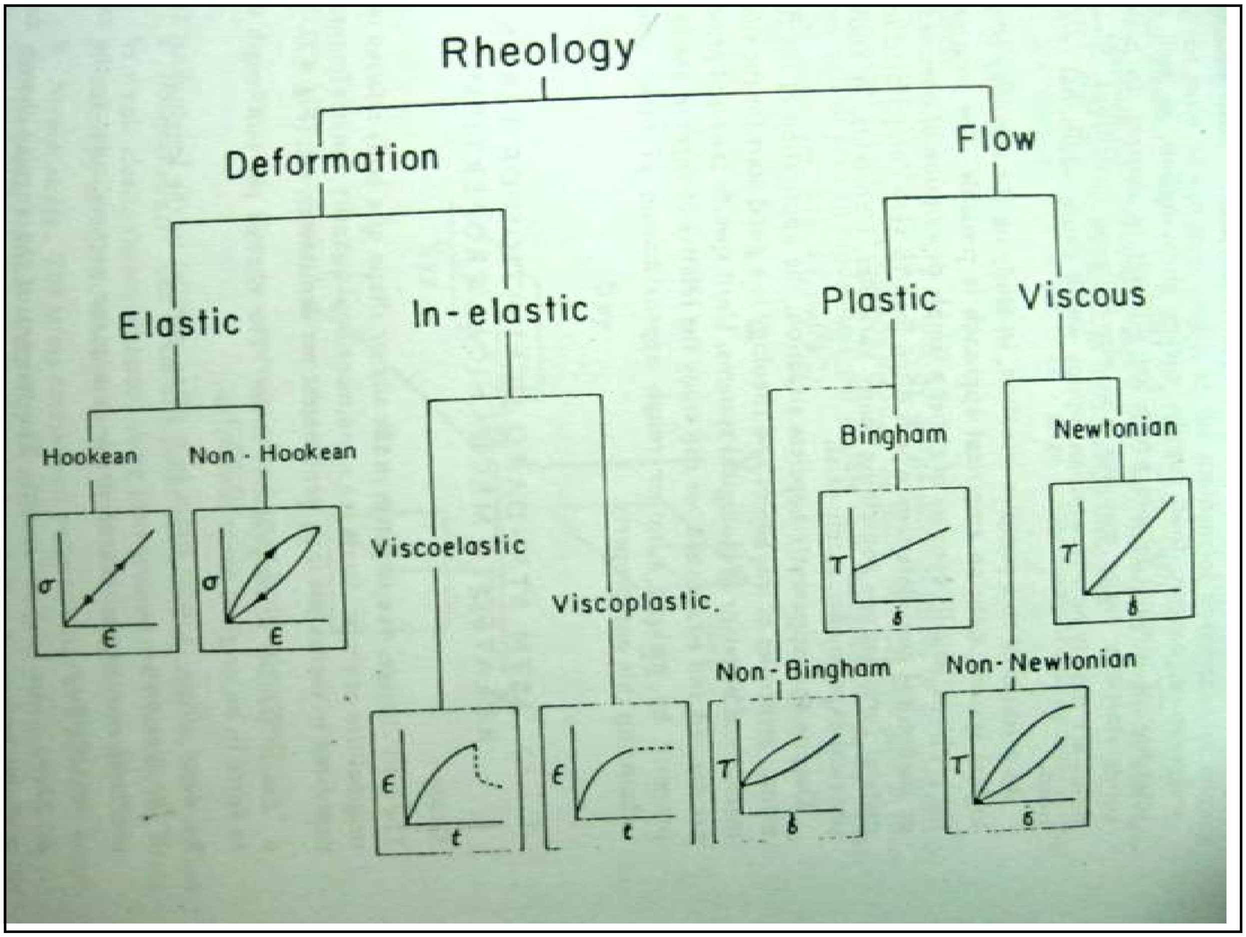
# Rheology and Texture

# Introduction

- The first use of the word "rheology" is credited to Eugene C. Bingham (circa 1928) who also described the motto of the subject as "panta rhei," from the works of Heraclitus, a pre-Socratic Greek philosopher active about 500 B.C. meaning "everything flows".
- Rheology is now well established as the science of the deformation and flow of matter: It is the study of the manner in which materials respond to applied stress or strain.

# Classification of rheology




Rheology
Deformation
Flow
Elastic
In-elastic
Plastic
Viscous
Hookean
Non - Hookean
Viscoelastic
Viscoplastic.
Bingham
Newtonian
Non - Bingham
Non - Newtonian
σ
ε
t
τ
δ̇

- The classical definition of rheology divides into two parts.
- (1) Deformation usually applies to materials that are predominantly **solidlike** in nature.
- (2) Flow usually applies to materials that are predominantly **fluid-like** in nature.
- Distance, symbol *l, is measured* The most important elements in both deformation and flow are the fundamental quantities of distance, time and mass.
- *in meters (m)* Time, symbol *t, is measured in seconds (s)* Mass, symbol *m, is measured in kilograms, (kg)*

# Some basic definitions

- **Stress:** Stress is the force per unit area, symbol $\sigma$ ( *sigma)*. It is expressed in units of pascals (Pa) . The equation describing stress is simply: $\sigma = F/A$
- ***Deformation (strain):*** Strain refers to the change in size or shape of a material when it is subjected to a stress. It is denoted by ε (epsilon) and may be described in several ways:

$$\varepsilon = \frac{l_0 - l}{l_0} = \frac{\Delta l}{l_0} \text{ for compr}$$

$$\varepsilon = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0} \text{ for te}$$

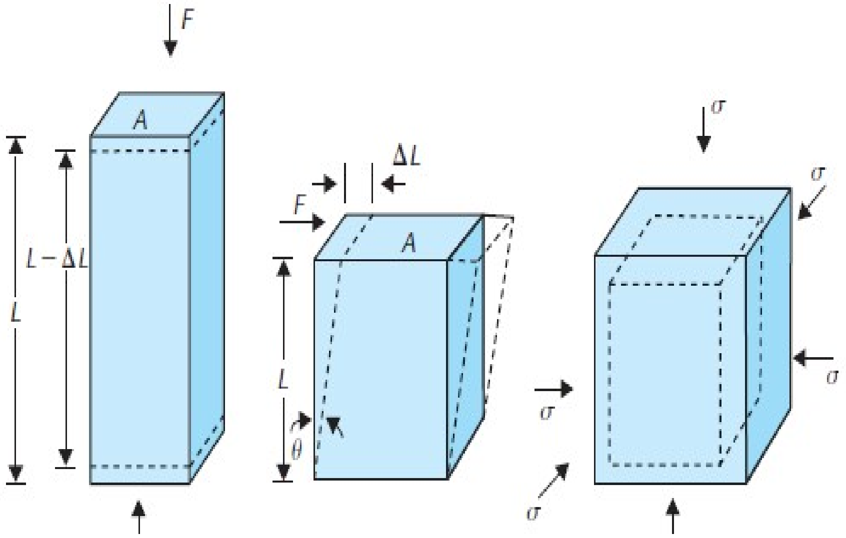
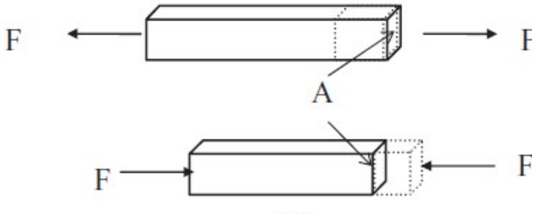
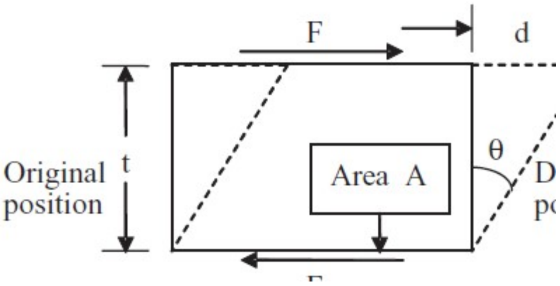


**Figure 3.**
compress
(bulk) co
solid. In s
the shear
from Rao
Engineeri
Figure 5.1
Dekker In



(a)



Shear strain $\gamma = \tan\theta = d$

# Classical Ideal Materials

- 1- Ideal elastic behavior (Hookean body)
- 2- Ideal plastic behavior (St. Venant body)
- 3- Ideal viscouse behavior (newtonian liquid)

# FLOW OF MATERIAL

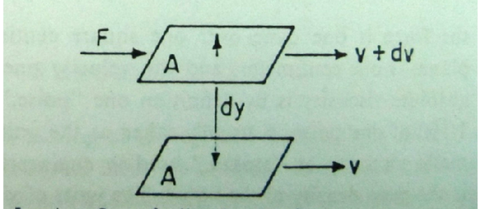
- Viscous Fluids
- Plastic Fluids

# Newton’s Law of Viscosity

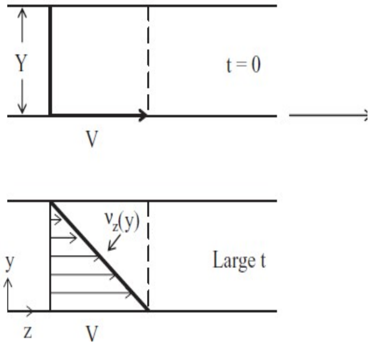
Viscosity is defined as the resistance of a fluid to flow. The unit of dynamic viscosity is (Pa · s) in the SI system and poise (g/cm · s) in the CGS system.

# 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 (Fig. 2.2). 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.*



Laminar flow of a liquid under shear



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:

$$\tau_{yz} = -\mu \frac{d\mathrm{v}_z}{dy} = -\mu \dot{\gamma}$$

where

$\tau_{yz}$ = shear stress (N/r
$\mu$ = viscosity (Pa·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 2.1.** Two parallel plates are 0.1 m apart. The bottom plate is stationar one is moving with a velocity $V$ (Fig E.2.2.1). The fluid between the plates is w viscosity of 1 cp.

(a) Calculate the momentum flux necessary to maintain the top plate in motio 0.30 m/s.

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

**Solution:**

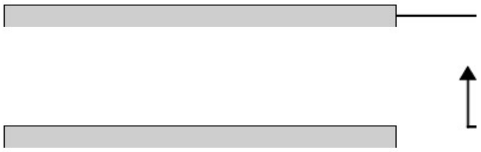
(a) $\mu_w = 1 \text{ cp} = 1 \times 10^{-3} \text{ Pa} \cdot \text{s}$

Newton's law of viscosity is used to determine shear stress:

$$d\mathrm{v}_x$$

(b) $\mu = 100 \text{ cp} = 0.1 \text{ Pa} \cdot \text{s}$

$$0.003 = -0.1 \text{ Pa} \cdot \text{s} \frac{(0 - V)\,\text{m/s}}{\phantom{0.1}} \Rightarrow V = 0.0$$



**Viscosity** is defined as the resistance of a fluid to flow. The unit of dynamic viscosity is (Pa · s) in the SI system and poise (g/cm · s) in the CGS system.

**Momentum diffusivity or kinematic viscosity**, which has the same units as thermal diffusivity ($\alpha = k/\rho\ cp$) *in heat transfer and mass diffusivity (DAB) in mass transfer, is defined to make the* transport properties analogous. Its unit is m2/s in SI and stoke (cm2/s) in CGS. It is the ratio of dynamic viscosity to density of fluid:

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

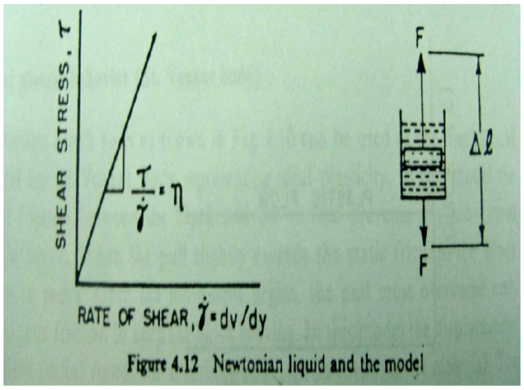
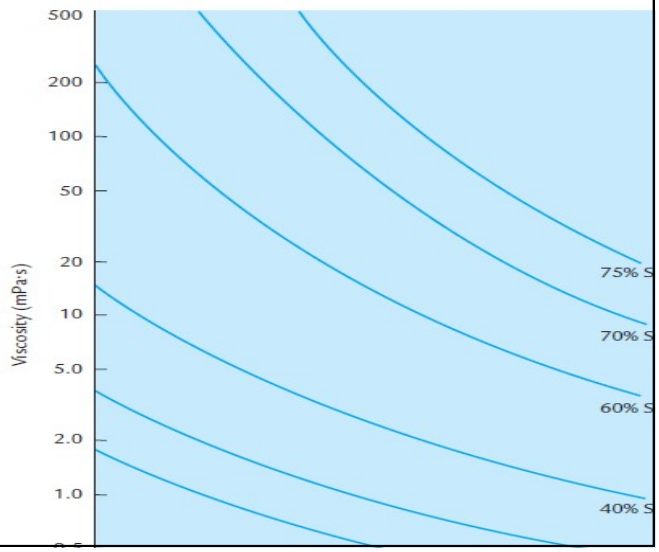


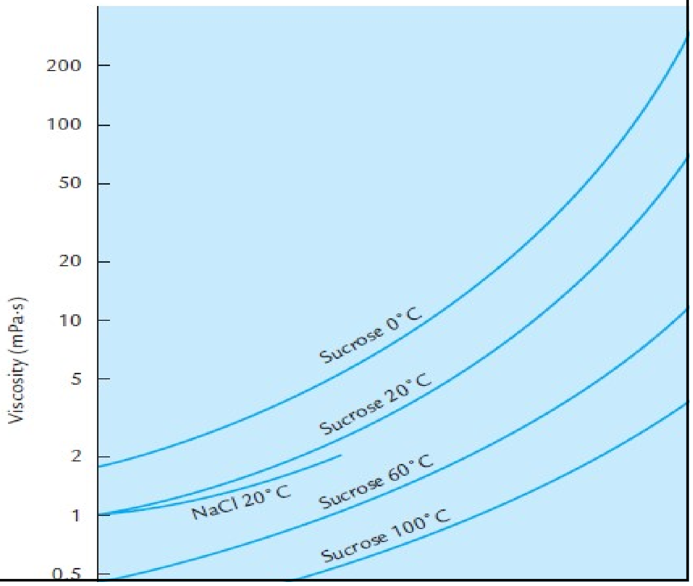
Figure 4.12 Newtonian liquid and the model

# Factors Affecting Viscosity

- **Temperature:** There is usually an inverse relationship between viscosity and temperature.

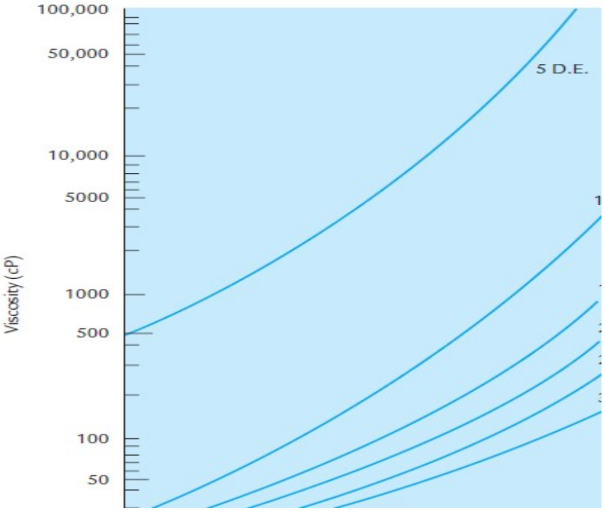


- **Concentration of Solute:** There is usually a direct nonlinear relationship between the concentration of a solute and viscosity at constant temperature.



- **Molecular Weight of Solute**: There is usually a nonlinear relationship between the molecular weight of the solute and the viscosity of the solution at equal concentrations.

**Figure 3.12** Viscosity–concentration–molecular weight relationships for hydrolyzed cornstarch syrups. (From Murray and Luft, 1973; courtesy of Grain Processing Corp. Reprinted from *Food Technol.* **27**, 33. Copyright by Institute of Food Technologists.)



- **Pressure:** The viscosity of most liquids is essentially constant over a pressure range of 0–100 atm. Hence the pressure effect can usually be ignored for foods.

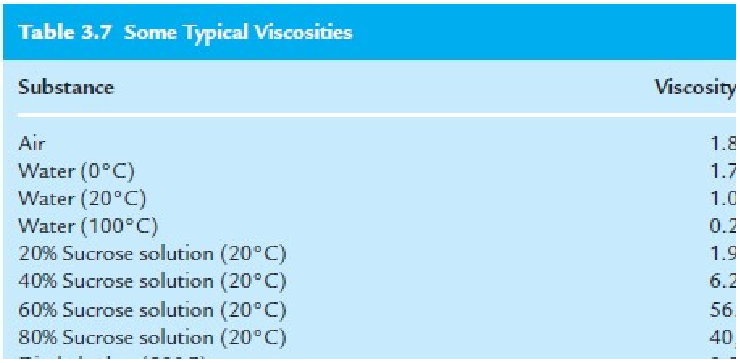


**Table 3.7 Some Typical Viscosities**

| Substance | Viscosity |
|---|---|
| Air | 1.8 |
| Water (0°C) | 1.7 |
| Water (20°C) | 1.0 |
| Water (100°C) | 0.2 |
| 20% Sucrose solution (20°C) | 1.9 |
| 40% Sucrose solution (20°C) | 6.2 |
| 60% Sucrose solution (20°C) | 56. |
| 80% Sucrose solution (20°C) | 40, |

# Viscous Fluids

- Viscous fluids tend to deform continuously under the effect of an applied stress. They can be categorized as Newtonian or non-Newtonian fluids.

## *Newtonian Fluids*

- Fluids that follow Newton’s law of viscosity are called Newtonian fluids. The slope of the shear stress versus shear rate graph, which is viscosity, is constant and independent of shear rate in Newtonian fluids. Gases; oils; water; and most liquids that contain more than 90% water such as tea, coffee, beer, carbonated beverages, fruit juices, and milk show Newtonian behavior.

# Non-Newtonian Fluids

Fluids that do not follow Newton’s law of viscosity are known as non-Newtonian fluids. Shear thinning or shear thickening fluids obey the power law model (Ostwald-de Waele equation):

$$\tau_{yz} = k\left(\frac{dv_z}{dy}\right)^n = k(\dot{\gamma}_{yz})^n$$

For shear thinning (pseudoplastic) flui

For shear thickening fluids $n > 1$

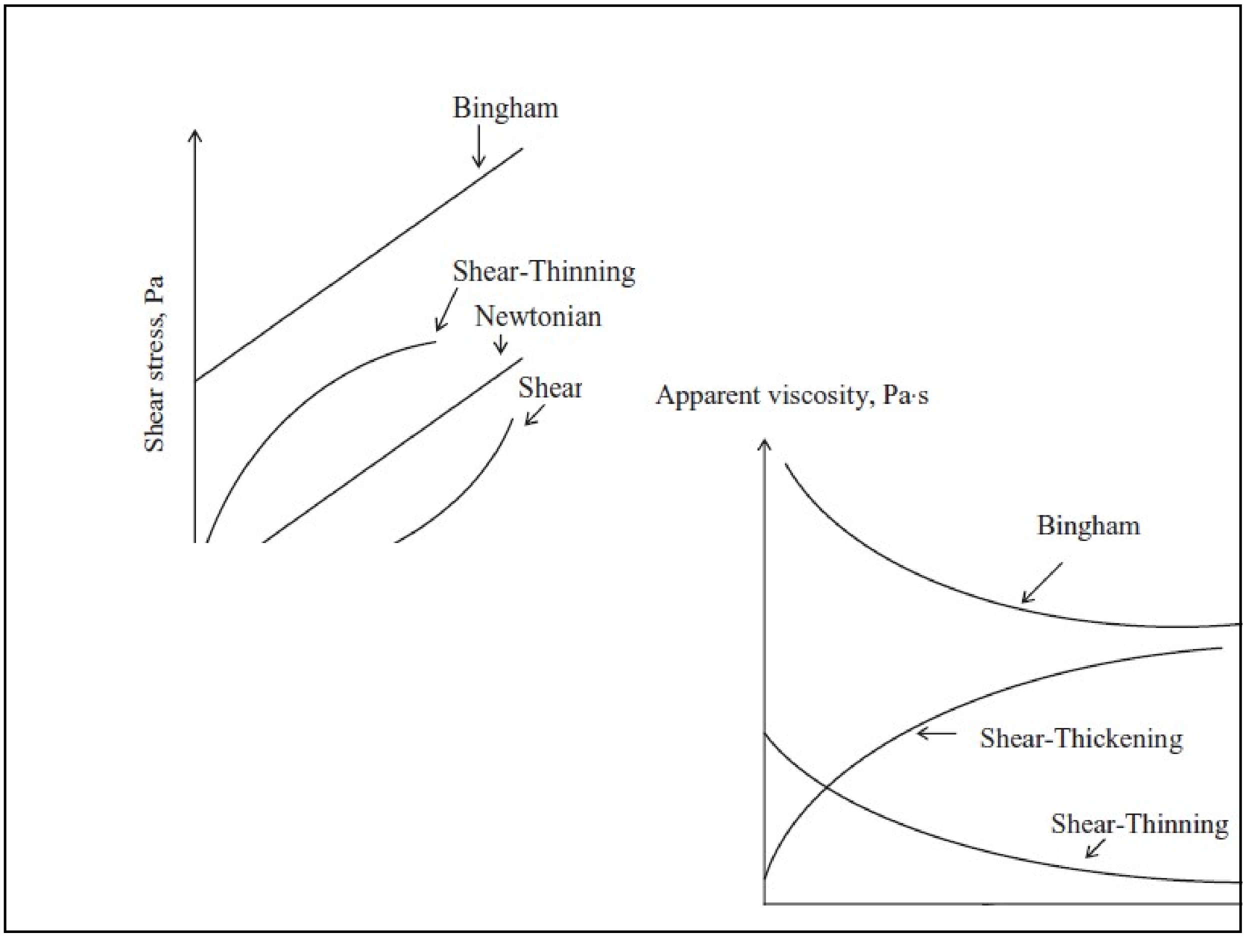
where

$k =$ the consistency coefficient (I

$$\eta(\dot{\gamma}) = \frac{k(\dot{\gamma})^n}{\dot{\gamma}} = k(\dot{\gamma})$$

## *Non-Newtonian Fluids*

- **(a) Shear Thinning (Pseudoplastic) Fluids.** 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.
- **(b) Shear Thickening Fluids.** In these types of fluids, as shear rate increases, the internal friction and apparent viscosity increase.


Bingham
Shear-Thinning
Newtonian
Shear
Shear stress, Pa
Apparent viscosity, Pa·s
Bingham
Shear-Thickening
Shear-Thinning

# Plastic Fluids

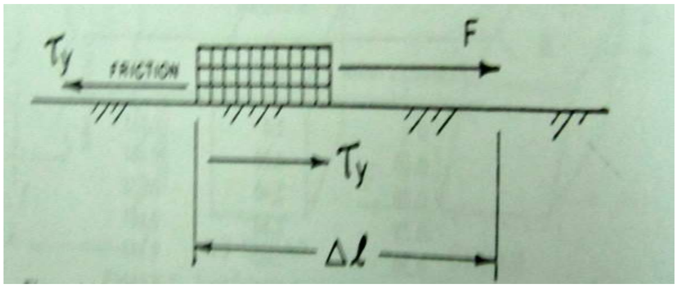
## *1-Bingham Plastic Fluids*

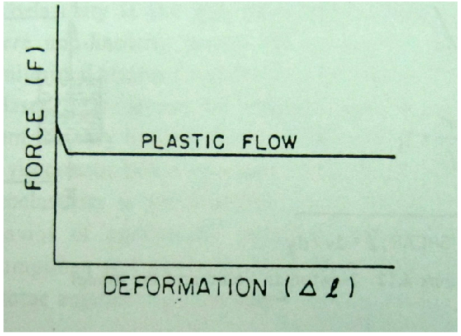
- In these types of fluids, fluid remains rigid when the magnitude of shear stress is smaller than the yield stress ($\tau_0$) *but flows like a Newtonian fluid when the shear stress exceeds* $\boldsymbol{\tau_0}$**.**

$$\tau_{yz} = \tau_0 + k\left(\frac{dv_z}{dv}\right.$$

$$\eta(\dot{\gamma}) = \frac{\tau_0 + k(\dot{\gamma})}{\dot{\nu}} = \frac{\tau_0}{\dot{\nu}}$$

# Ideal plastic behavior (St. Venant body)





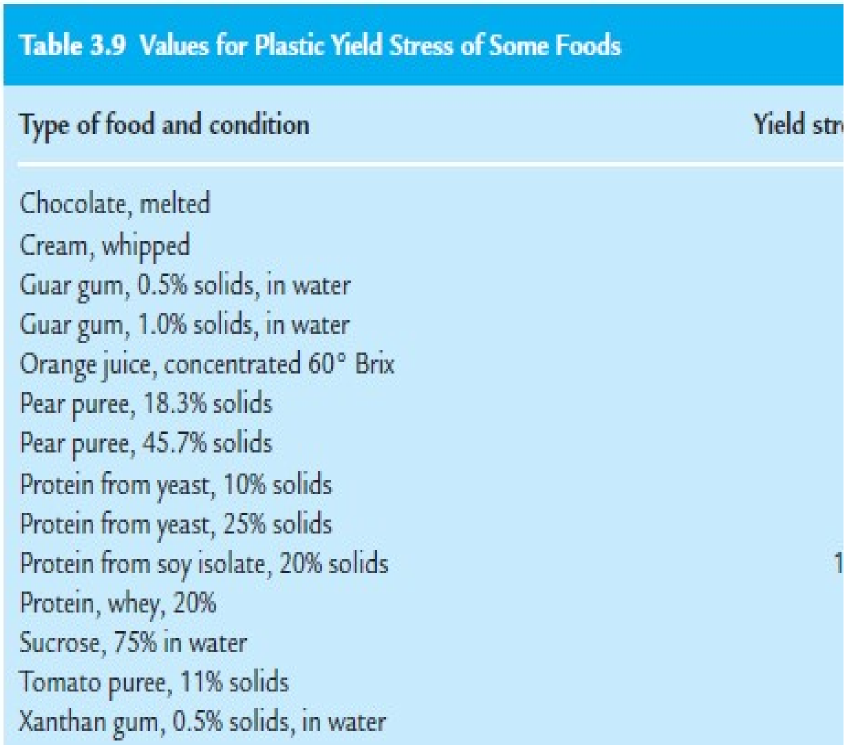


**Table 3.9 Values for Plastic Yield Stress of Some Foods**

| Type of food and condition | Yield str |
|---|---|
| Chocolate, melted | |
| Cream, whipped | |
| Guar gum, 0.5% solids, in water | |
| Guar gum, 1.0% solids, in water | |
| Orange juice, concentrated 60° Brix | |
| Pear puree, 18.3% solids | |
| Pear puree, 45.7% solids | |
| Protein from yeast, 10% solids | |
| Protein from yeast, 25% solids | |
| Protein from soy isolate, 20% solids | 1 |
| Protein, whey, 20% | |
| Sucrose, 75% in water | |
| Tomato puree, 11% solids | |
| Xanthan gum, 0.5% solids, in water | |

## *2- Non-Bingham Plastic Fluids*

In these types of fluids, a minimum shear stress known as yield stress must be exceeded before flow begins, as in the case of Bingham plastic fluids. However, the graph of shear stress versus shear rate is not linear.

Herschel-Bulkley model:

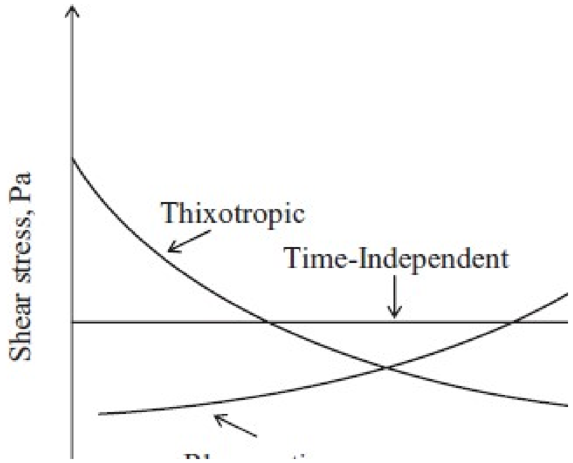
$$\tau_{yz} = \tau_0 + k\left(\dot{\gamma}_{yz}\right)$$

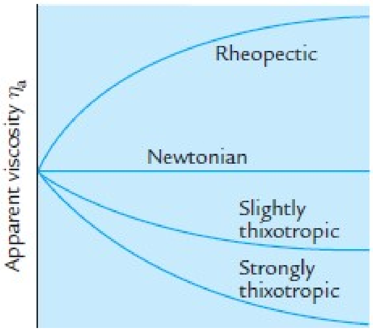
Casson model:

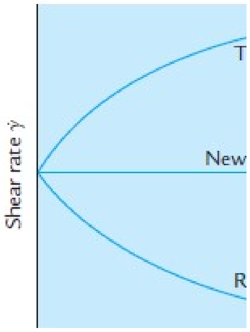
$$(\tau_{yz})^{0.5} = (\tau_0)^{0.5} + k(\dot{\gamma}_y$$

# Time Dependency

- When some fluids are subjected to a constant shear rate, they become thinner (or thicker) with time.
- **thixotropic fluids:** Fluids that exhibit decreasing shear stress and apparent viscosity with respect to time at a fixed shear rate are called thixotropic fluids (shear thinning with time). This phenomenon is probably due to the breakdown in the structure of the material as shearing continues. Gelatin, egg white, and shortening can be given as examples of this type of fluid.
- **rheopectic fluids:** In rheopectic fluids (shear thickening with time), shear stress and apparent viscosity increase with time, that is, the structure builds up as shearing continues. Bentonite–clay suspensions show this type of flow behavior. It is rarely observed in food systems.


Shear stress, Pa
Thixotropic
Time-Independent


Apparent viscosity $\eta_a$
Rheopectic
Newtonian
Slightly thixotropic
Strongly thixotropic


Shear rate $\dot{\gamma}$
T
New
R

# Solution Viscosity

In the case of solutions, emulsions, or suspensions, viscosity is often measured in comparative terms, that is, the viscosity of the solution, emulsion, or suspension is compared with the viscosity of a pure solvent. Solution viscosities are useful in understanding the behavior of some biopolymers including aqueous solutions of locust bean gum, guar gum, and carboxymethyl cellulose.

Viscosities of pure solvents and suspensions can be measured and various values can be calculated from the resulting data. The relative viscosity, *ηrel is expressed as:*

$$\eta_{rel} = \frac{\eta_{\text{suspension}}}{\eta_{\text{solvent}}} = 1 +$$

where

$X_d^v$ = volume fraction occupied by the disperse

The specific viscosity, $\eta_{sp}$ i

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

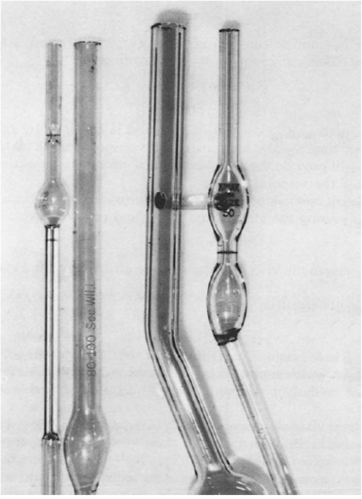
The reduced viscosity, $\eta_{red}$ is:

$$\eta_{red} = \frac{\eta_{sp}}{C}$$

# VISCOSITY MEASUREMENT

## 1-Capillary Flow Viscometers

Capillary flow viscometers are generally in the form of a U-tube. These types of viscometers are very simple, inexpensive, and suitable for low-viscosity fluids. There are different designs of capillary viscometers. A typical design of capillary viscometer is shown in Fig. 6.2.



F
c

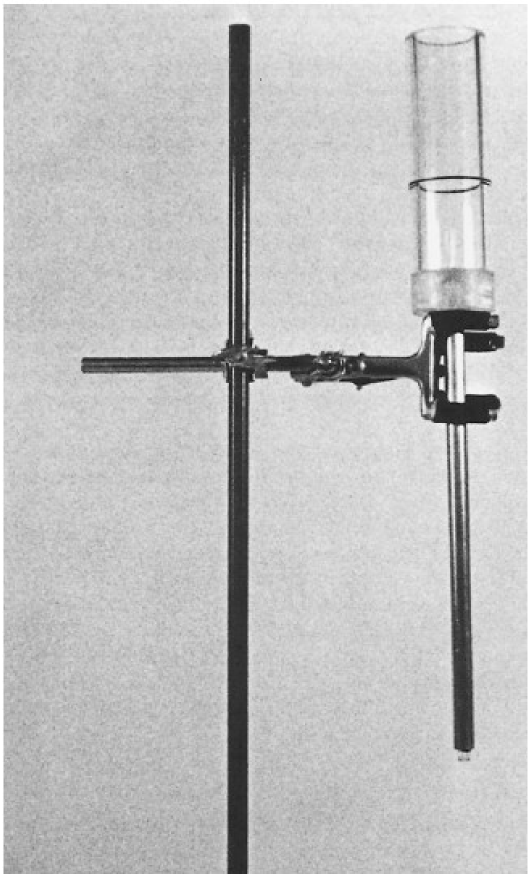


**Figure 6.3** The Lamb–Lewis Capillary Viscometer. (Courtesy of National Food Processors Assoc.)

# 2-Tube viscometer

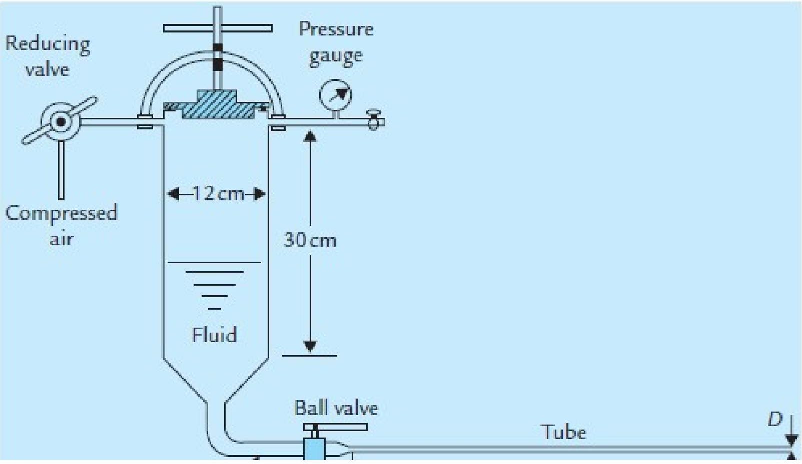
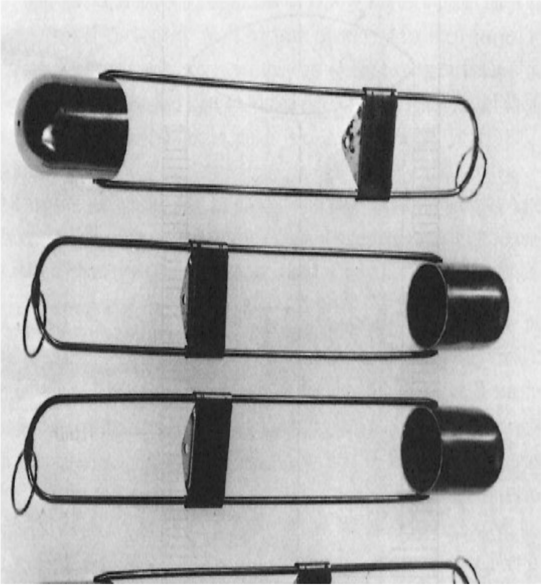


**Figure 6.4**
(From Sara
Reprinted f
**22** (12), pa
Institute of

# 3-Orifice Type Viscometers

In orifice type viscometers, the time for a standard volume of fluid to flow through an orifice is measured. They are used for Newtonian or near-Newtonian fluids when extreme accuracy is not required. In the food industry, the most commonly used one is a dipping type Zahn viscometer that consists of a 44-mL capacity stainless steel cup with a handle and with a calibrated circular hole in the bottom. The cup is filled by dipping it into the fluid and withdrawing it. The time from the start of withdrawing to the first break occurring in the issuing stream is recorded.



Figu
visco
type)

# 4- Falling Ball Viscometers

These types of viscometers involve a vertical tube where a ball is allowed to fall under the influence of gravity. It operates on the principle of measuring the time for a ball to fall through a liquid under the influence of gravity.
When the ball falls through the fluid, it is subjected to gravitational force, drag force, and buoyancy force (Fig. 2.9). Making a force balance:
Net force (*FNet) = Gravitational force (FG)− Buoyancy force (FB)− Drag force (FD)*

$$\frac{\pi D_p^3 \rho_p}{6}\frac{dv}{dt} = \frac{\pi D_p^3 \rho_p g}{6} - \frac{\pi D_p^3 \rho_f g}{6} - \frac{c_D \pi 1}{\;}$$

where

$D_p$ = diameter of the ball (m),
$\rho_p$ = density of the ball (kg/m$^3$),
$\rho_f$ = density of the fluid (kg/m$^3$),
$c_D$ = drag coefficient

$$\mu = \frac{D_p^2(\rho_p - \rho_f}{18 v_t}$$

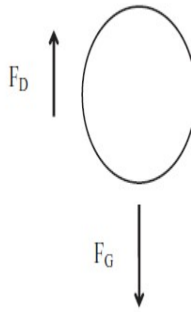
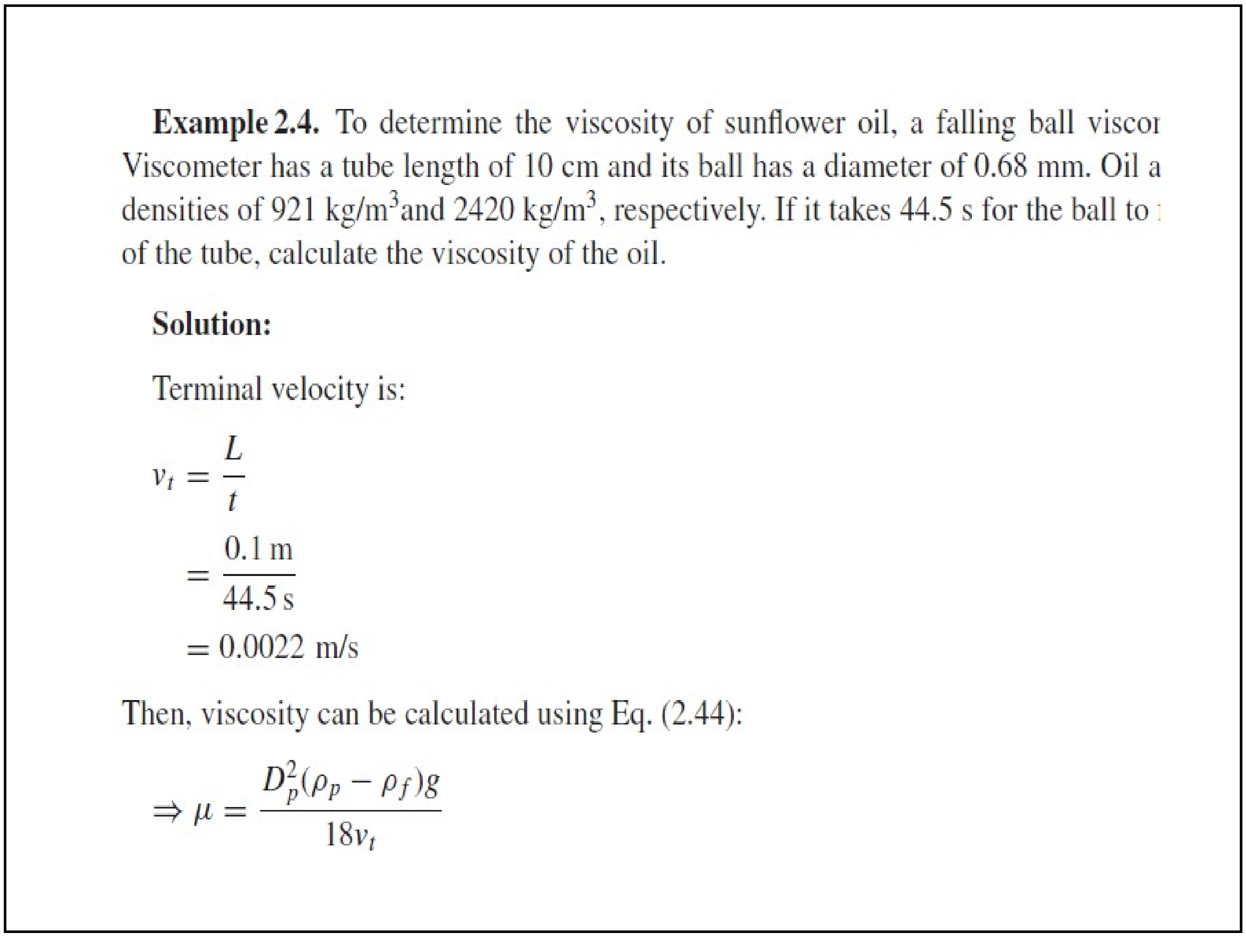


Figure 2.9 Forces acting on a ball in falling ball viscometer



**Example 2.4.** To determine the viscosity of sunflower oil, a falling ball visco
Viscometer has a tube length of 10 cm and its ball has a diameter of 0.68 mm. Oil a
densities of 921 kg/m$^3$and 2420 kg/m$^3$, respectively. If it takes 44.5 s for the ball to
of the tube, calculate the viscosity of the oil.

**Solution:**

Terminal velocity is:

$$v_t = \frac{L}{t}$$

$$= \frac{0.1\ \text{m}}{44.5\ \text{s}}$$

$$= 0.0022\ \text{m/s}$$

Then, viscosity can be calculated using Eq. (2.44):

$$\Rightarrow \mu = \frac{D_p^2(\rho_p - \rho_f)g}{18v_t}$$

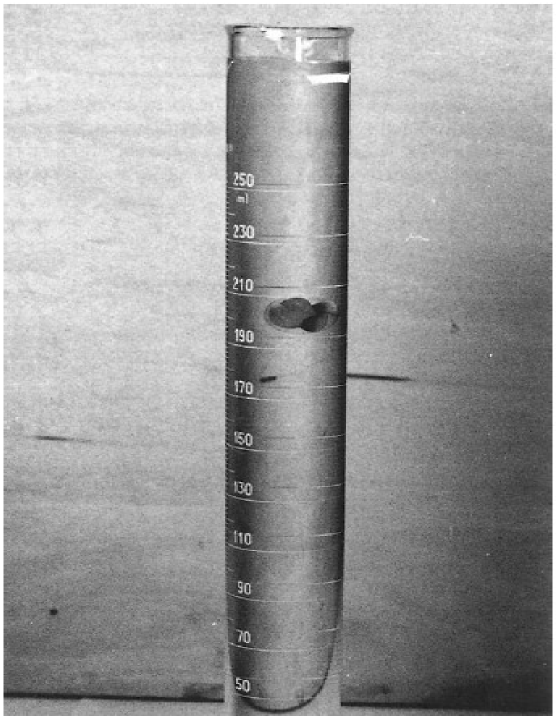


**Figure 6.9**
viscometer i
laboratory (
falling throu

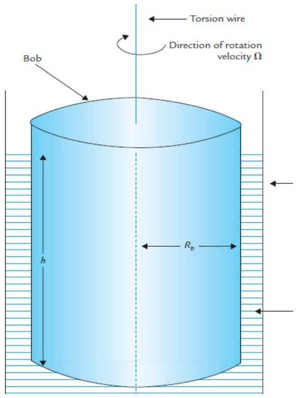
## 5-Rotational Viscometers

- In rotational viscometers, the sample is sheared between the two parts of the measuring device by means of rotation. In agitation, the shear rate is proportional to the rotational speed. It is possible to measure the shear stress as the shear rate is changed. In addition, a sample can be sheared for as long as desired. Therefore, rotational viscometers are the best for characterization of non-Newtonian and time-dependent behavior. There are different forms of these viscometers, as described in the following sections.

### *5-1- Concentric Cylinder (Coaxial Rotational) Viscometers*

This type of viscometer consists of two annular cylinders with a narrow gap between them. The fluid to be measured is placed in the gap.

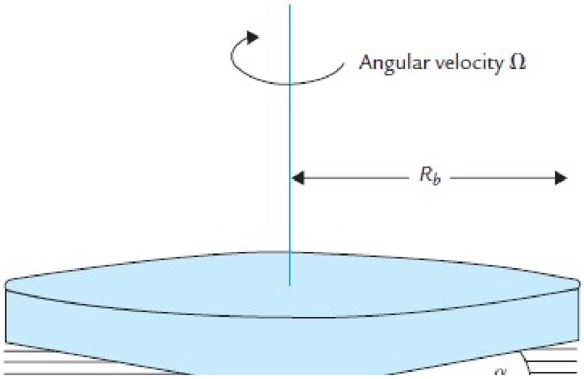
It can be used for both Newtonian and non-Newtonian foods.



## 5-2- Cone and Plate Viscometers

The operating principle for cone and plate viscometers is similar to that for concentric cylinder viscometers. The system consists of a circular plate and a cone with radius R *with its axis perpendicular* to the plate and its vertex in the plane of the surface of the plate.

Usually, the cone is rotated at a known angular velocity (). The fluid is placed in the gap between the cone and plate and transmits torque to the plate.



# 5-3- Other rotational viscometers

## 5-3-1- Single-Spindle Viscometers (Brookfield Viscometer)

A spindle attached to the instrument with a vertical shaft is rotated in the fluid and the torque necessary to overcome the viscous resistance is measured. Different spindles are available in various sizes which may be rotated at different speeds. A suitable spindle and a rotational speed for a particular fluid are selected by trial and error. This device gives the viscosity of Newtonian fluids directly since it is calibrated with Newtonian oils. The steady-state deflection is noted and a conversion chart is provided to estimate the apparent viscosity under the test conditions. It is possible to determine apparent viscosity at different speeds (shear rates), but since it is not possible to state the exact shear rate that the fluid is subjected to, shear stress–shear rate data cannot be presented. The results are normally presented in the form of apparent viscosity against rotational speed. A range of calibration fluids is available for checking the accuracy of the equipment. It is possible to determine whether the fluid is time dependent or not by using this viscometer.


BROOKFIELD
PROGRAMMABLE
DV-II + VISCOMETER

5-3-2- FMC Consistometer

5-3-3- Corn Industries Viscometer

5-3-4- Paddle Viscometer

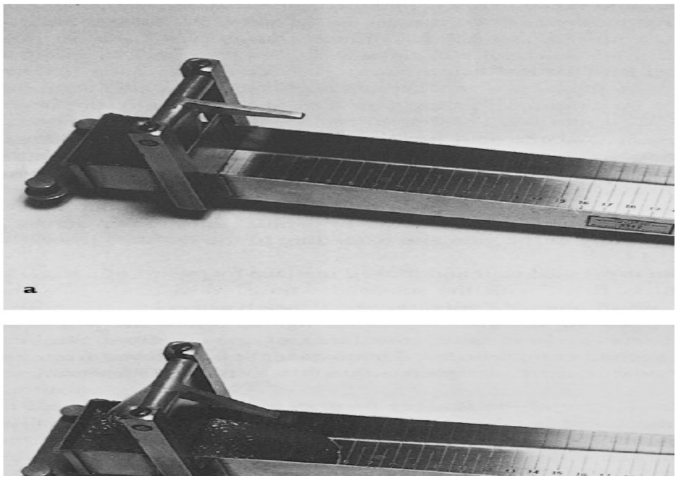
5-3-5- Brabender Viscograph

***6- Vibrational (Oscillation) Viscometer***

***7- Back extrusion viscometer***

***8- Imitative viscometer***

**Figure 5.8** The Bostwick Consistometer: (a) sample is in first compartment with gate closed; (b) gate is open and sample has flowed along the second compartment.



# Rheometer

A **rheometer** is a laboratory device used to measure the way in which a liquid, suspension or slurry flows in response to applied forces. It is used for those fluids which cannot be defined by a single value of viscosity and therefore require more parameters to be set and measured than is the case for a viscometer. It measures the rheology of the fluid.

There are two distinctively different types of *rheometers*. Rheometers that control the applied shear stress or shear strain are called **rotational or shear rheometers**, whereas rheometers that apply extensional stress or extensional strain are **extensional rheometers**. Rotational or shear type rheometers are usually designed as either a native strain-controlled instrument (control and apply a user-defined shear strain which can then measure the resulting shear stress) or a native stress-controlled instrument (control and apply a user-defined shear stress and measure the resulting shear strain).

## *Types of shear rheometer*

**- Pipe or Capillary**

**-Rotational cylinder**

**- Cone and plate**

**- Linear Shear**

## *Types of extensional rheometer*

Commercially available extensional rheometers have been segregated according to their applicability to viscosity ranges. Materials with a viscosity range from approximately 0.01 to 1 Pa.s. (most polymer solutions)are best characterized with capillary breakup rheometers, opposed jet devices, or contraction flow systems. Materials with a viscosity range from approximately 1 to 1000 Pa.s. are used in filament stretching rheometers. Materials with a high viscosity >1000 Pa.s., such as polymer melts, are best characterized by constant-length devices.

Rheometer with cylinder measuring system (left) and cone/plate measuring system (right)

modular Rotational Rheometer with cylinder and cone/plate and plate/plate measuring systems

FiSER filament stretching extensional rheometer

Dynamic Shear Rheometer

# Deformation of Material

- **Elastic**

1- Ideal elastic (Hookean )

2- Non- Hookean

- **In- elastic**

1- viscoelastic

2- Viscoplastic

# Ideal elastic behavior (Hookean body)

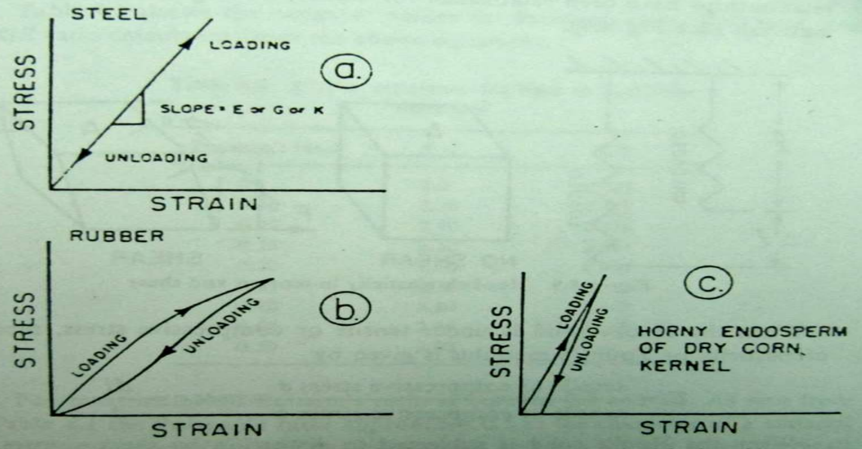


**Figure 4.8** (a) Linear elasticity in steel, (b) non-linear elasticity in rubber, (c) Inelasticity in Corn

- **Young's Modulus:** *Young's modulus of elasticity is the ratio of stress to strain when an elastic* solid material is compressed or extended. It is a measure of stiffness and was developed by Thomas Young, an English physicist (1773–1829) and it is described by the equation:

$$E = \frac{\text{stress}}{\text{strain}} = \frac{F_{,}}{\Delta l}$$

- **Shear Modulus:** *Shear modulus is the ratio of shearing stress to shearing strain and is described*
- by the equation:

$$G = \frac{\text{shearing stress}}{\text{shearing strain}} = \frac{I}{\,}$$

- **Bulk Modulus:** *Bulk modulus is the ratio of the stress to the change in volume:*

$$K = \frac{\text{hydrostatic pressure}}{\text{volumetric strain}} = -$$

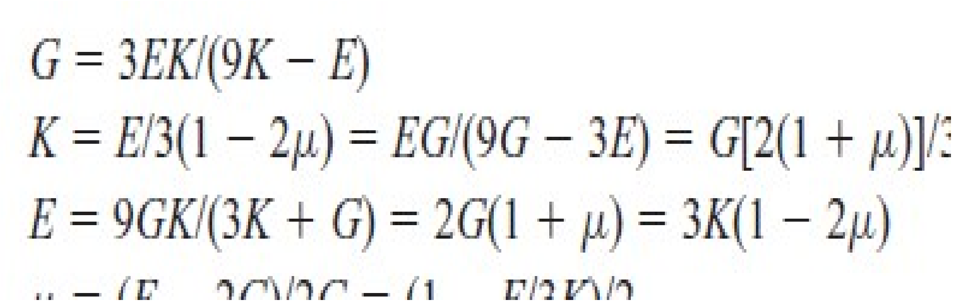
- **Poisson’s Ratio:** *Poisson’s ratio is named after the French physicist Siméon Denis Poisson*

(1781–1840) and is described by the equation:

$$\mu = \frac{\text{lateral strain}}{\text{axial strain}} = \frac{\text{change in width per unit wid}}{\text{change in length per unit len}}$$

## Interrelations Between Moduli:

- Rheological theory shows that for elastic materials these four moduli are interrelated as follows:



$$G = 3EK/(9K - E)$$

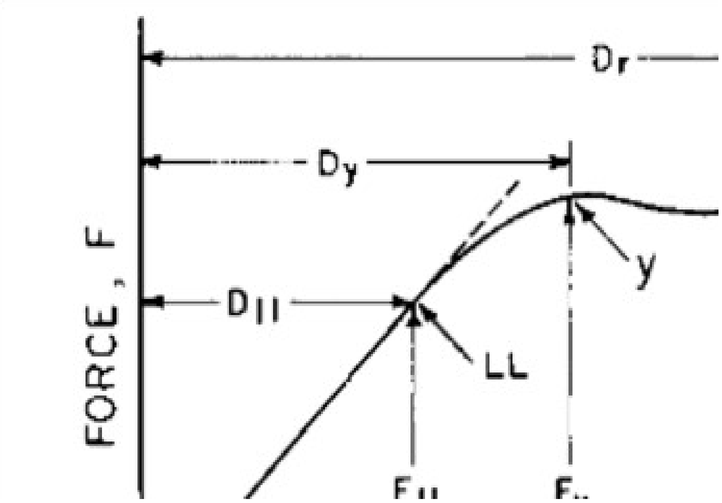
$$K = E/3(1 - 2\mu) = EG/(9G - 3E) = G[2(1 + \mu)]/3$$

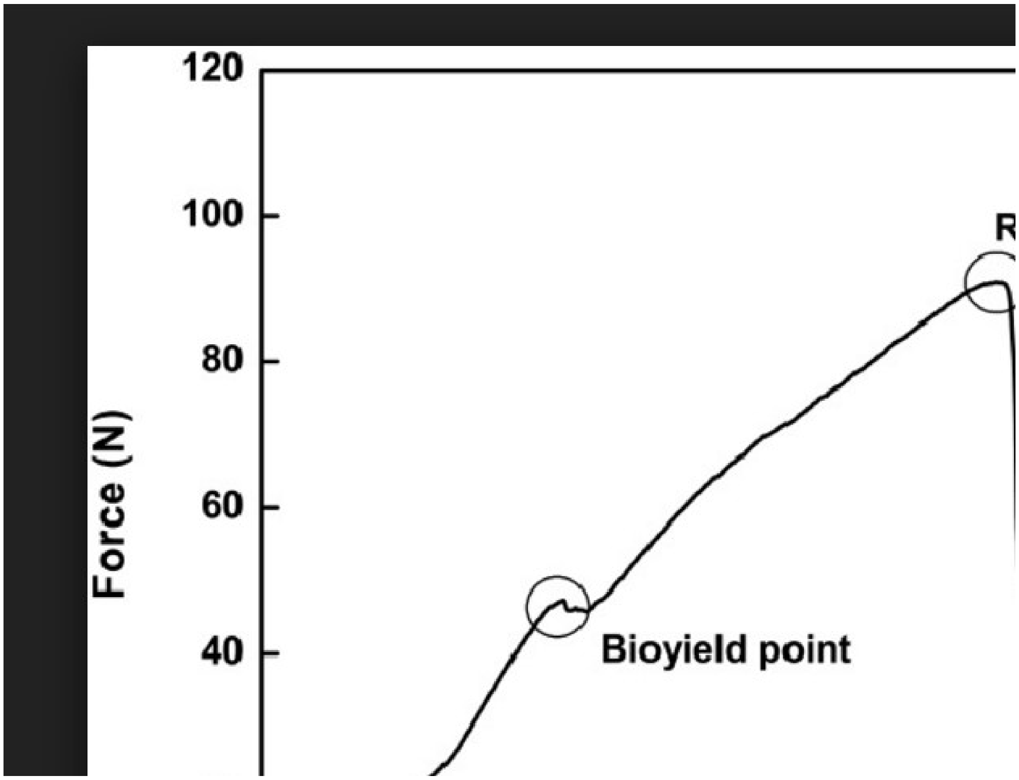
$$E = 9GK/(3K + G) = 2G(1 + \mu) = 3K(1 - 2\mu)$$

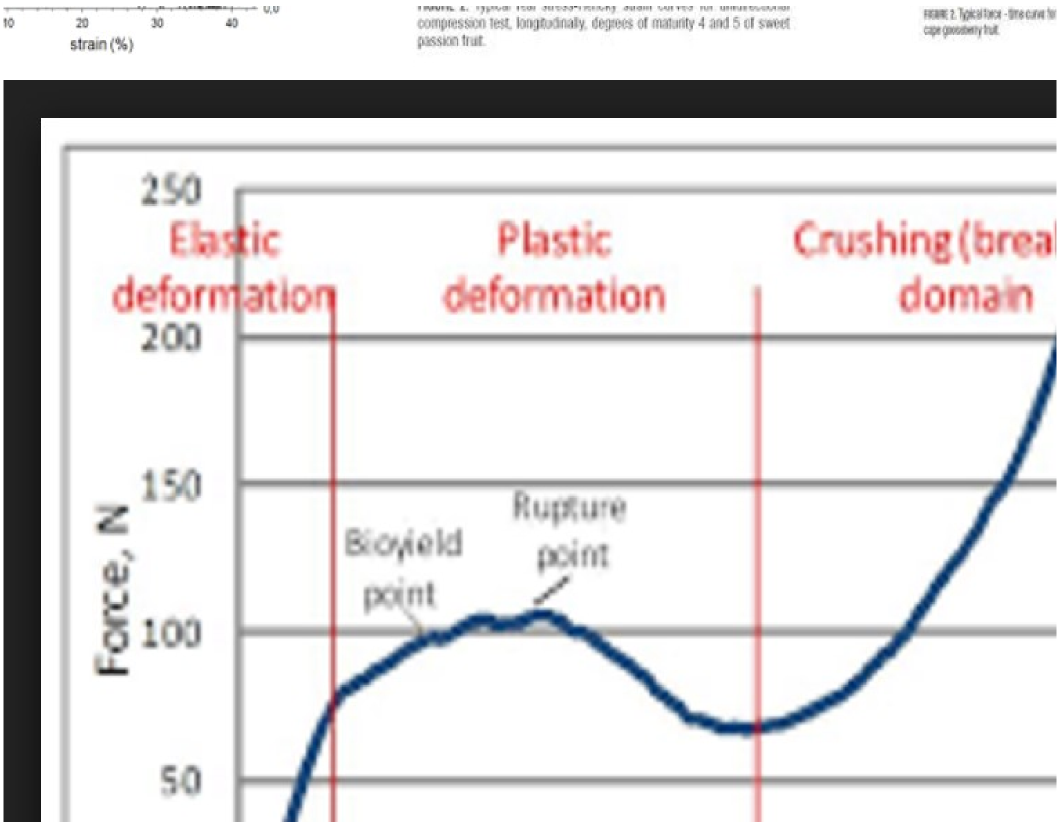
$$\mu = (E - 2G)/2G = (1 - E/3K)/2$$

- **Bioyield point** is defined as the point at which an increase in deformation is observed with a decrease or no change of force. In some agricultural products, the presence of this bioyield point is an indication of initial cell rupture.
- **Rupture point** is a point on the stress–strain or force-deformation curve at which the axially loaded specimen ruptures under a load. Rupture point corresponds to a failure in the macrostructure of the specimen while bioyield point corresponds to a failure in the microstructure of the sample.

[redacted]

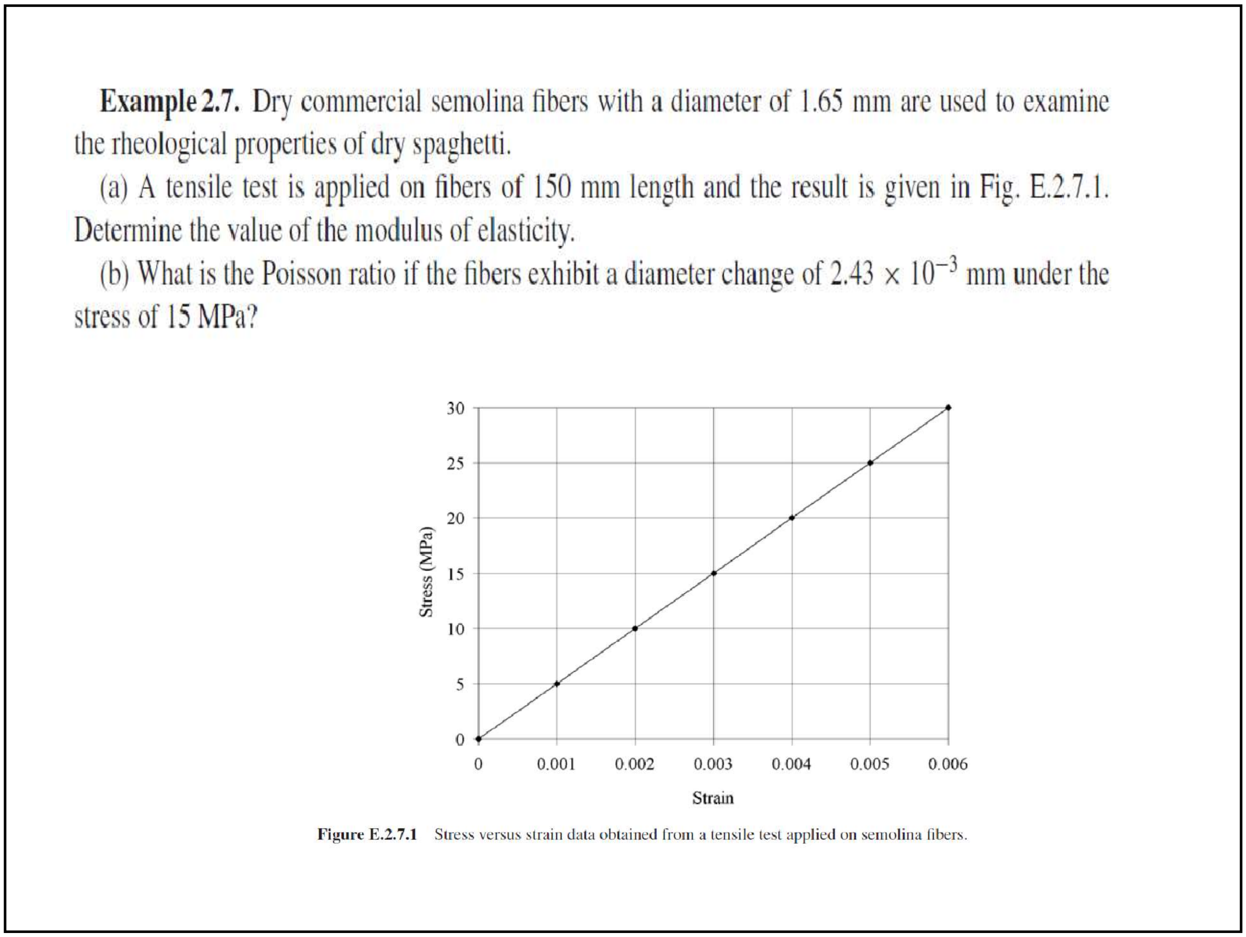



120
100
80
60
40
Force (N)
Bioyield point
R



compression test, longitudinally, degrees of maturity 4 and 5 of sweet passion fruit.

FIGURE 2. Typical force - time curve fo cape gooseberry fruit.

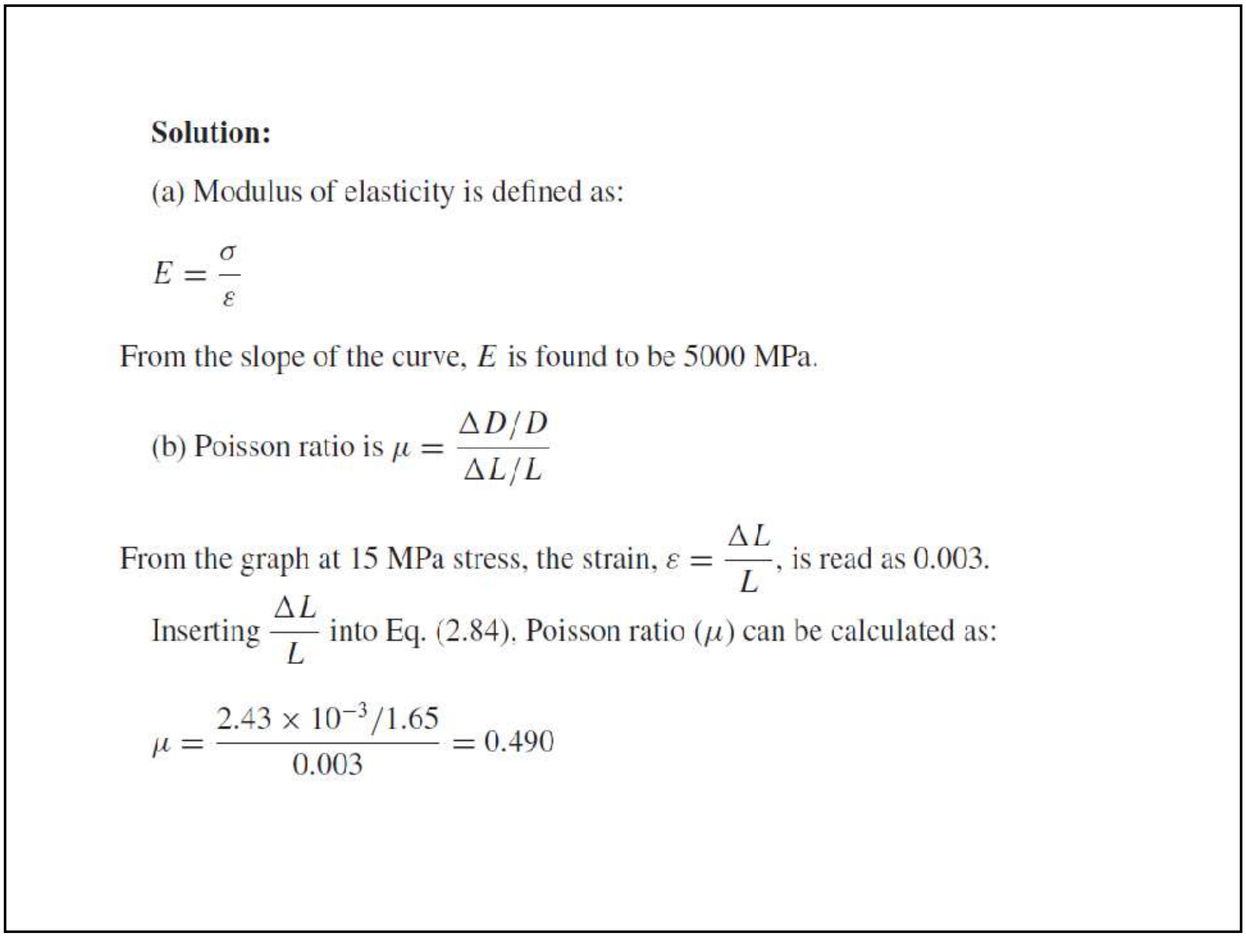


**Example 2.7.** Dry commercial semolina fibers with a diameter of 1.65 mm are used to examine the rheological properties of dry spaghetti.

(a) A tensile test is applied on fibers of 150 mm length and the result is given in Fig. E.2.7.1. Determine the value of the modulus of elasticity.

(b) What is the Poisson ratio if the fibers exhibit a diameter change of $2.43 \times 10^{-3}$ mm under the stress of 15 MPa?

**Figure E.2.7.1** Stress versus strain data obtained from a tensile test applied on semolina fibers.



**Solution:**

(a) Modulus of elasticity is defined as:

$$E = \frac{\sigma}{\varepsilon}$$

From the slope of the curve, $E$ is found to be 5000 MPa.

(b) Poisson ratio is $\mu = \dfrac{\Delta D / D}{\Delta L / L}$

From the graph at 15 MPa stress, the strain, $\varepsilon = \dfrac{\Delta L}{L}$, is read as 0.003.

Inserting $\dfrac{\Delta L}{L}$ into Eq. (2.84), Poisson ratio ($\mu$) can be calculated as:

$$\mu = \frac{2.43 \times 10^{-3} / 1.65}{0.003} = 0.490$$

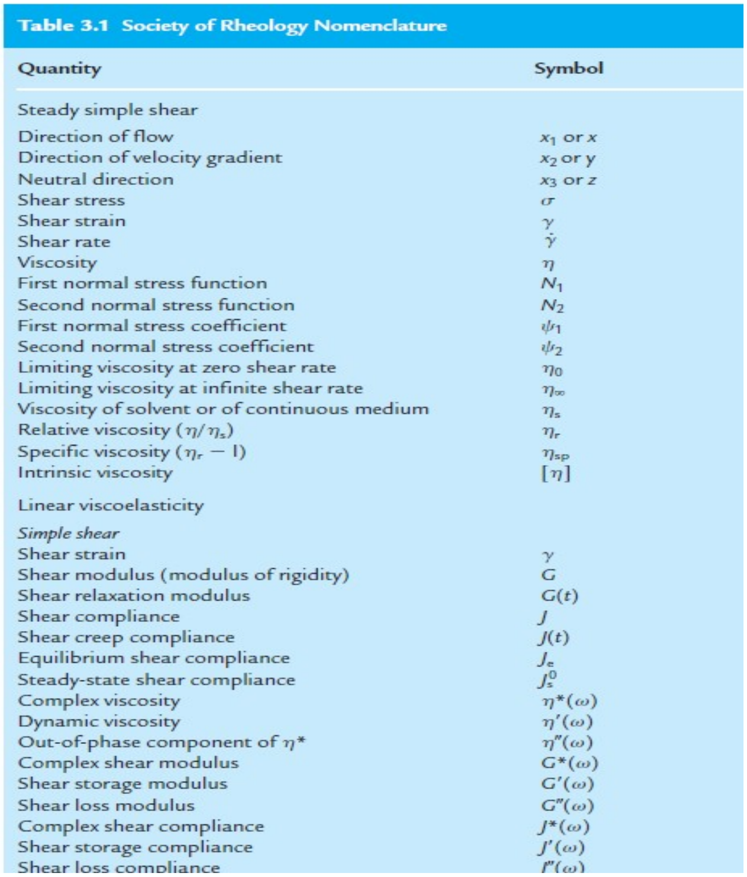


**Table 3.1 Society of Rheology Nomenclature**

| Quantity | Symbol |
|---|---|
| Steady simple shear | |
| Direction of flow | $x_1$ or $x$ |
| Direction of velocity gradient | $x_2$ or $y$ |
| Neutral direction | $x_3$ or $z$ |
| Shear stress | $\sigma$ |
| Shear strain | $\gamma$ |
| Shear rate | $\dot{\gamma}$ |
| Viscosity | $\eta$ |
| First normal stress function | $N_1$ |
| Second normal stress function | $N_2$ |
| First normal stress coefficient | $\psi_1$ |
| Second normal stress coefficient | $\psi_2$ |
| Limiting viscosity at zero shear rate | $\eta_0$ |
| Limiting viscosity at infinite shear rate | $\eta_\infty$ |
| Viscosity of solvent or of continuous medium | $\eta_s$ |
| Relative viscosity ($\eta/\eta_s$) | $\eta_r$ |
| Specific viscosity ($\eta_r - 1$) | $\eta_{sp}$ |
| Intrinsic viscosity | $[\eta]$ |
| Linear viscoelasticity | |
| *Simple shear* | |
| Shear strain | $\gamma$ |
| Shear modulus (modulus of rigidity) | $G$ |
| Shear relaxation modulus | $G(t)$ |
| Shear compliance | $J$ |
| Shear creep compliance | $J(t)$ |
| Equilibrium shear compliance | $J_e$ |
| Steady-state shear compliance | $J_s^0$ |
| Complex viscosity | $\eta^*(\omega)$ |
| Dynamic viscosity | $\eta'(\omega)$ |
| Out-of-phase component of $\eta^*$ | $\eta''(\omega)$ |
| Complex shear modulus | $G^*(\omega)$ |
| Shear storage modulus | $G'(\omega)$ |
| Shear loss modulus | $G''(\omega)$ |
| Complex shear compliance | $J^*(\omega)$ |
| Shear storage compliance | $J'(\omega)$ |
| Shear loss compliance | $J''(\omega)$ |

# VISCOELASTIC BEHAVIOR

- When a force is applied to a viscous fluid, it will start to deform and this deformation is proportional with the magnitude of force applied. It deforms continuously until the force is removed so that it cannot return to its original position. Viscous fluids generally exhibit viscosity while solids exhibit elasticity.
- Some foods show both viscous and elastic properties which are known as viscoelastic materials.
- The typical food example for viscoelastic fluids is wheat flour dough.

- Weissenberg effect

When a viscous fluid is agitated, the circular motion causes a vortex. If a viscoelastic fluid is stirred by a rotating rod it tends to climb the rod, which is known as the **Weissenberg effect (Fig. 2.14).** You might have observed this effect while mixing a cake batter or bread dough at home. This is due to the production of a normal force acting at right angles to the rotational forces, which in turn acts in a horizontal plane. The rotation tends to straighten out the polymer molecules in the direction of rotation but the molecules attempt to return to their original position.

When a Newtonian fluid emerges from a long, round tube into the air, the emerging jet will normally contract. It may expand to a diameter of 10% to 15% larger than the tube diameter at low Reynolds numbers. Normal stress differences present in a viscoelastic fluid, however, may cause jet expansion (called die swell) which are two or more times the diameter of the tube. In addition, highly elastic fluids may exhibit a tubeless siphon effect

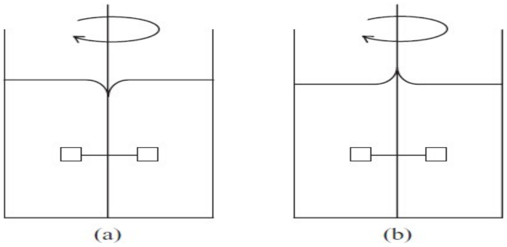
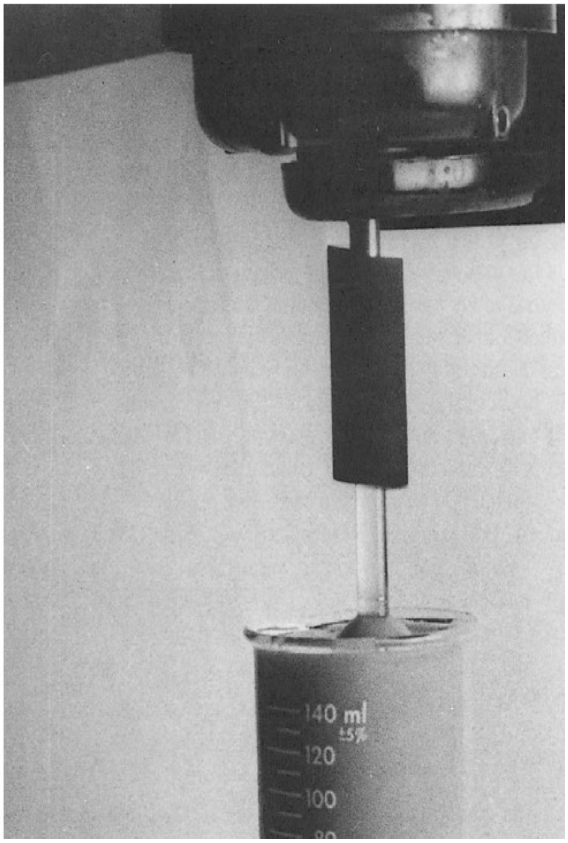
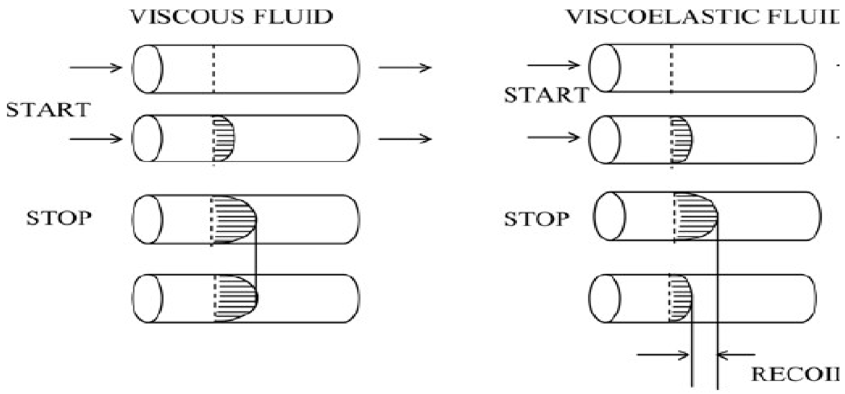


**Figure 3.26** The Weissenberg effect: the rotation of the glass rod causes the aged sweetened condensed milk to climb up the rod because of the normal force that is generated by the rotation. Many doughs also exhibit this phenomenon.



- Recoil phenomenon

Another phenomenon observed in the viscoelastic material is called the **recoil phenomenon. When** the flow of viscoelastic material is stopped, tensile forces in the fluid cause particles to move back. However, viscous fluids stay where they are when their motion is stopped (Steffe, 1996). This phenomenon is illustrated in Fig. 2.15.

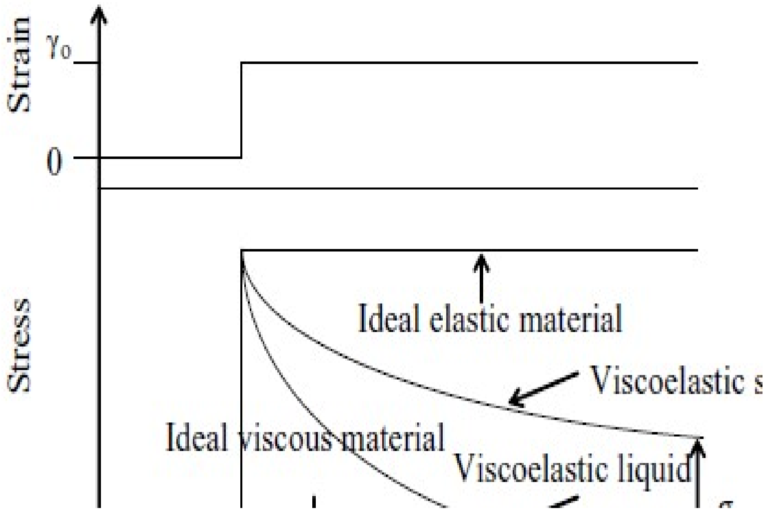


# Study viscoelastic

- There are three different methods to study viscoelastic materials: stress relaxation test, creep test, and dynamic test.

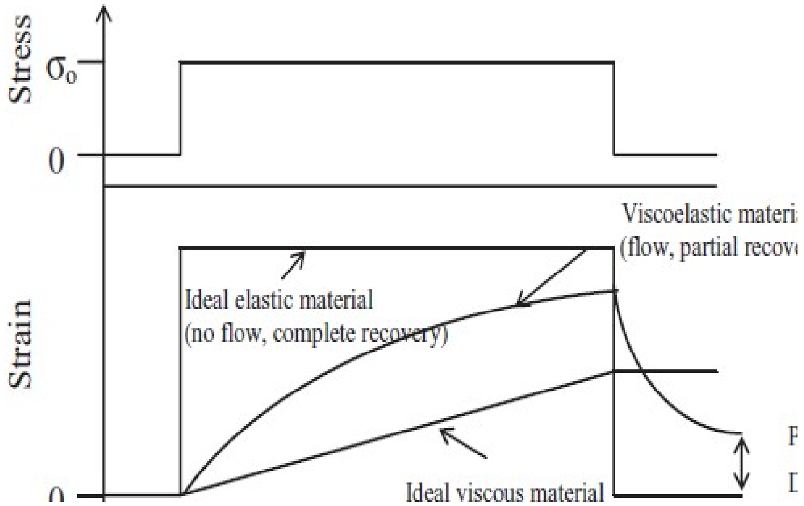
# Stress Relaxation Test

If food materials are deformed to a fixed strain and the strain is held constant, the stress required to maintain this strain decreases with time. This is called stress relaxation. In this test, stress is measured as a function of time as the material is subjected to a constant strain.



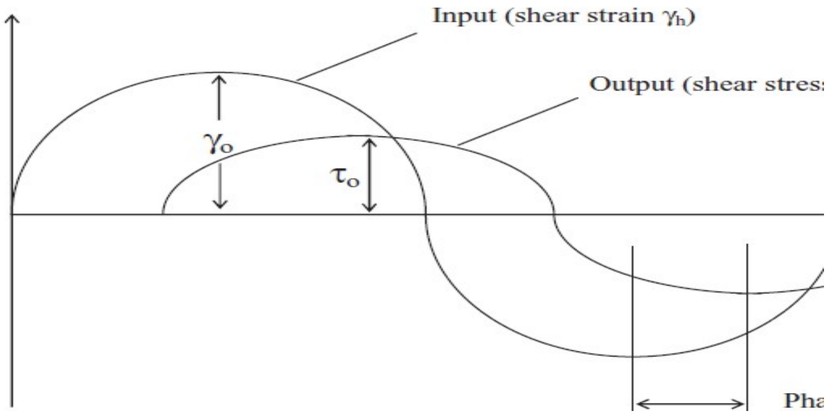
# Creep Test

If a constant load is applied to biological materials and if stresses are relatively large, the material will continue to deform with time. This is known as creep. In a creep test, an instantaneous constant stress is applied to the material and the resulting strain is measured as a function of time.



# Dynamic Test (Oscillatory Test)

In dynamic tests, either rate is controlled (stress is measured at a constant strain) or stress is controlled (deformation is measured at a constant stress amplitude). That is, materials are subjected to deformation or stress which varies harmonically with time. Usually, a sinusoidal strain is applied to the sample, causing some level of stress to be transmitted through the material. Then, the transmitted shear stress in the sample is measured(Fig. 2.18). Concentric cylinder, cone, and plate or parallel viscometers are suitable for this purpose. This test is suitable for undisturbed viscoelastic materials as a function of time.



The magnitude and the time lag (phase shift) of the transmission depend on the viscoelastic nature of the material. Much of the stress is transmitted in highly elastic materials while it is dissipated in frictional losses in highly viscous ones. The time lag is large for highly viscous materials but small for highly elastic materials.

A storage modulus ( $G'$ ) *that is high for elastic materials and loss modulus (* $G''$ *) that is high for* viscous materials are defined as follows:

$$G' = \frac{\tau_0 \cos\theta}{\gamma_0}$$

$$G'' = \frac{\tau_0 \sin\theta}{\gamma_0}$$

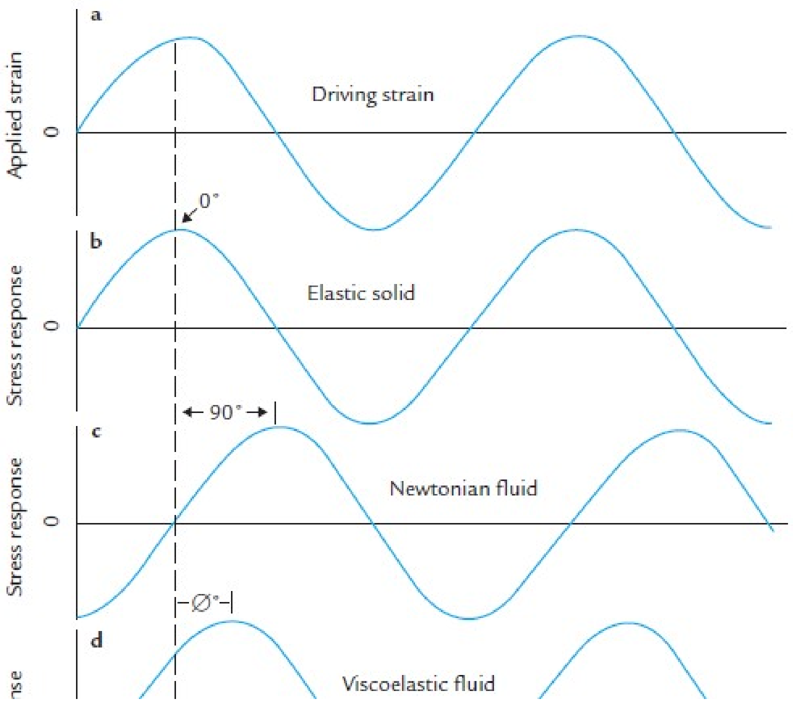
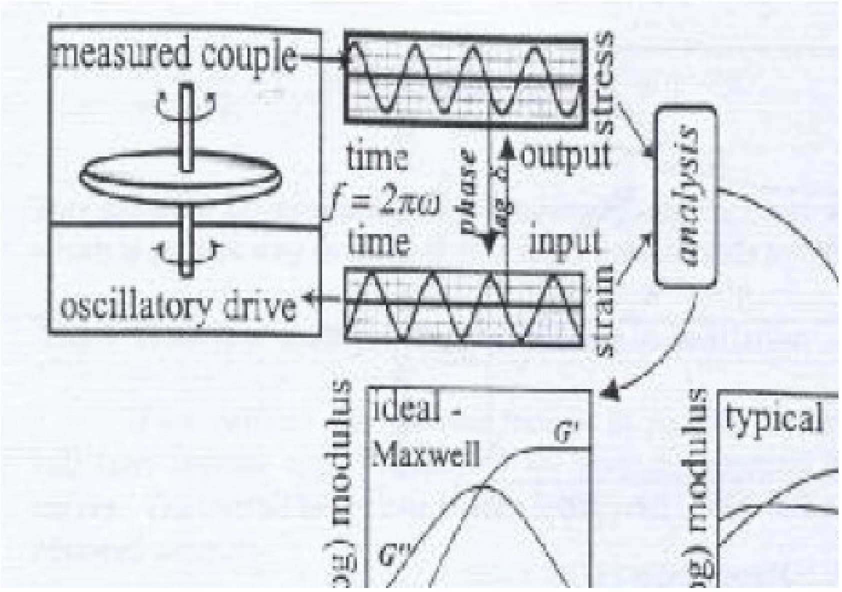


**Figure 3**
oscillatio
strain ver
resultant
is measu
(b), New
viscoelas
from Bou
Page 221
Methods
Foods, e
By court
Inc.)


measured couple
oscillatory drive
time
f = 2πω
time
phase lag
output
input
stress
strain
analysis
ideal - Maxwell
G'
G''
(log) modulus
typical
(log) modulus

complex modulus ($G^*$), complex viscosity ($\eta^*$), dynamic viscosity ($\eta'$), out of phase component of the complex viscosity ($\eta''$), complex compliance ($J^*$), storage compliance ($J'$), and the loss compliance ($J''$):

$$G^* = \frac{\sigma_o}{\gamma_o} = \sqrt{(G')^2 + (G'')^2} \qquad [5.38]$$

$$\eta^* = \frac{G^*}{\omega} = \sqrt{(\eta')^2 + (\eta'')^2} \qquad [5.39]$$

$$\eta' = \frac{G''}{\omega} \qquad [5.40]$$

$$\eta'' = \frac{G'}{\omega} \qquad [5.41]$$

$$J^* = \frac{1}{G^*} \qquad [5.42]$$

$$J' = \frac{G'}{(G')^2 + (G'')^2} \qquad [5.43]$$

$$J'' = \frac{G''}{(G')^2 + (G'')^2} \qquad [5.44]$$

Another popular material function used to describe viscoelastic behavior is the tangent of the phase shift or phase angle (called tan delta) which is also a function of frequency:

$$\tan(\delta) = \frac{G''}{G'} \qquad [5.46]$$

This parameter is directly related to the energy lost per cycle divided by the energy stored per cycle. Since $0 \le \delta \le \pi/2$, $\tan\delta$ can vary from zero to infinity. Observations of polymer systems give the following numerical ranges for $\tan\delta$: very high for dilute solutions, 0.2 to 0.3 for

amorphous polymers, low (near 0.01) for glassy crystalline polymers and gels. Values of $\tan\delta$ for typical food systems (dilute solution, concentrated solution, and gel)

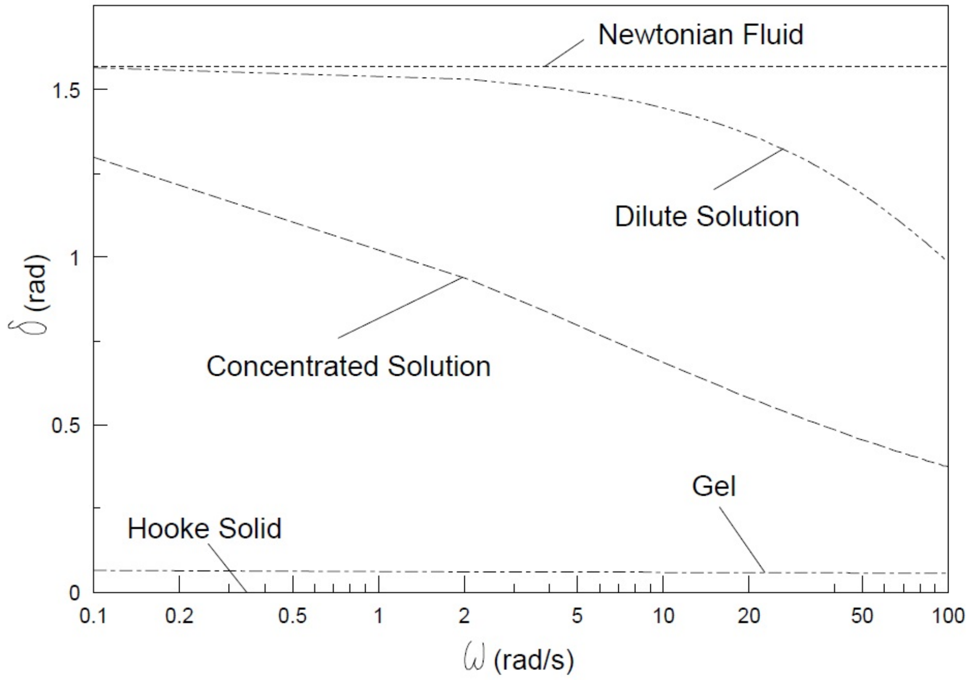
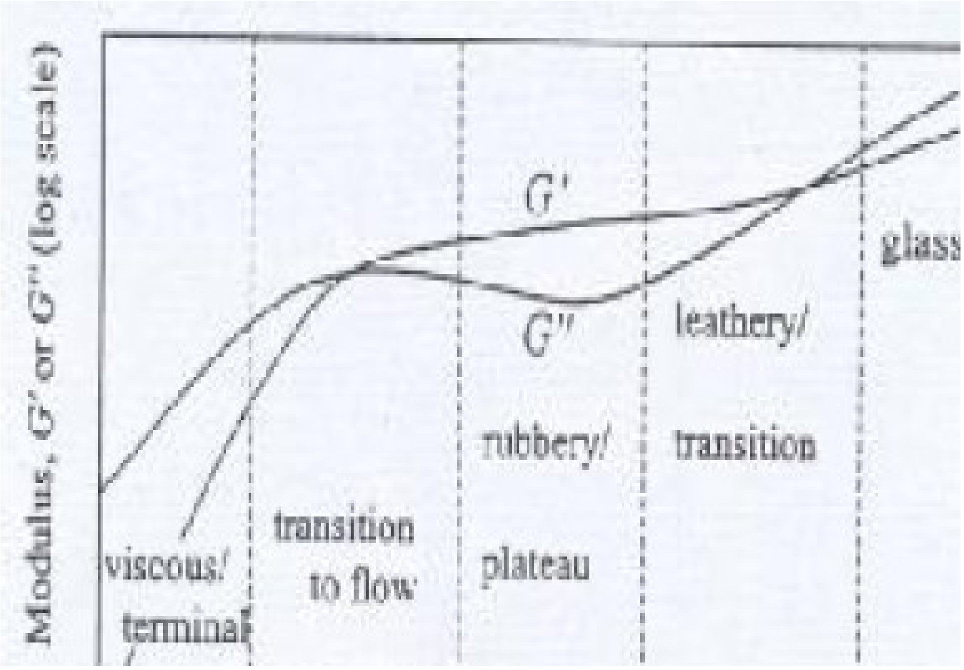
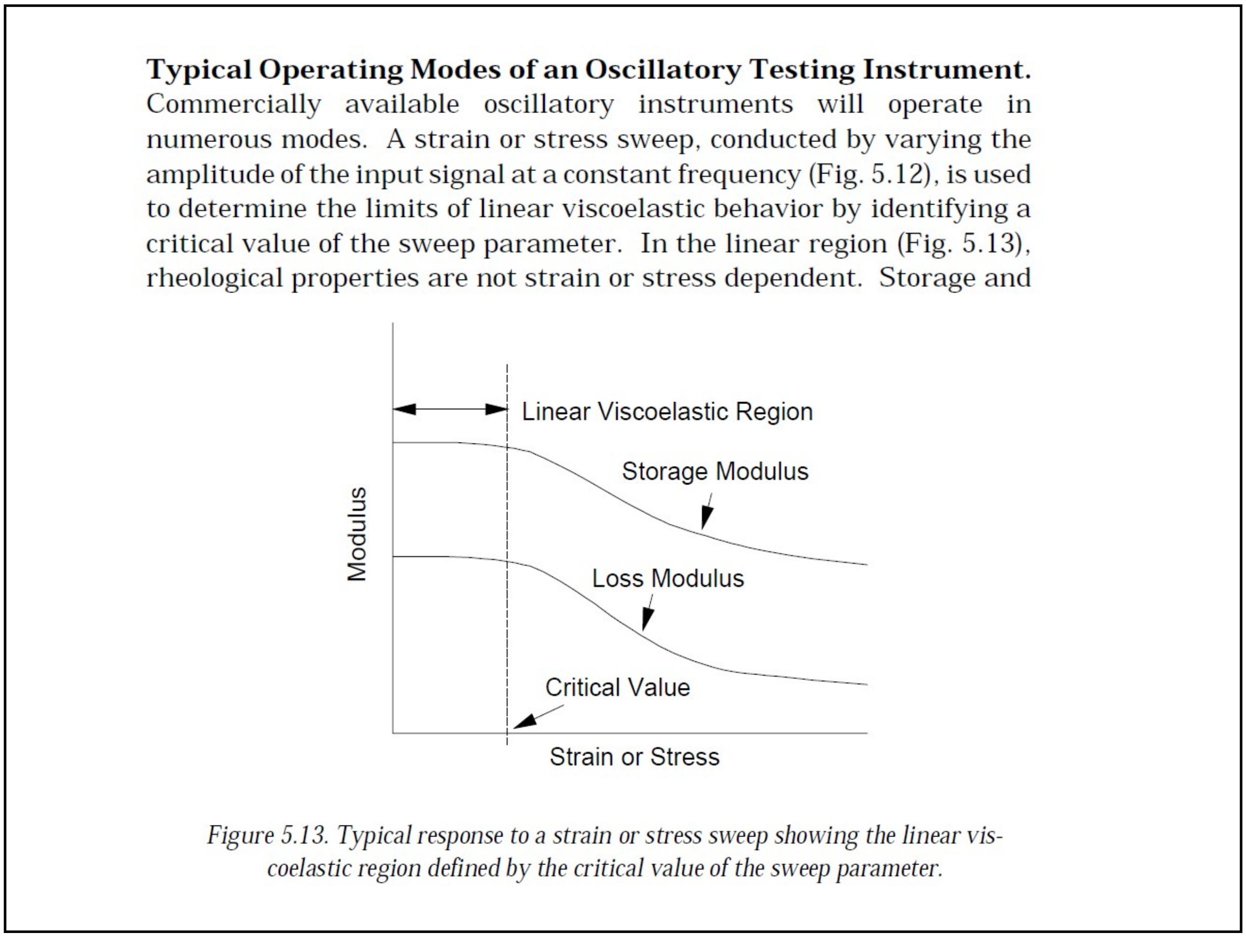


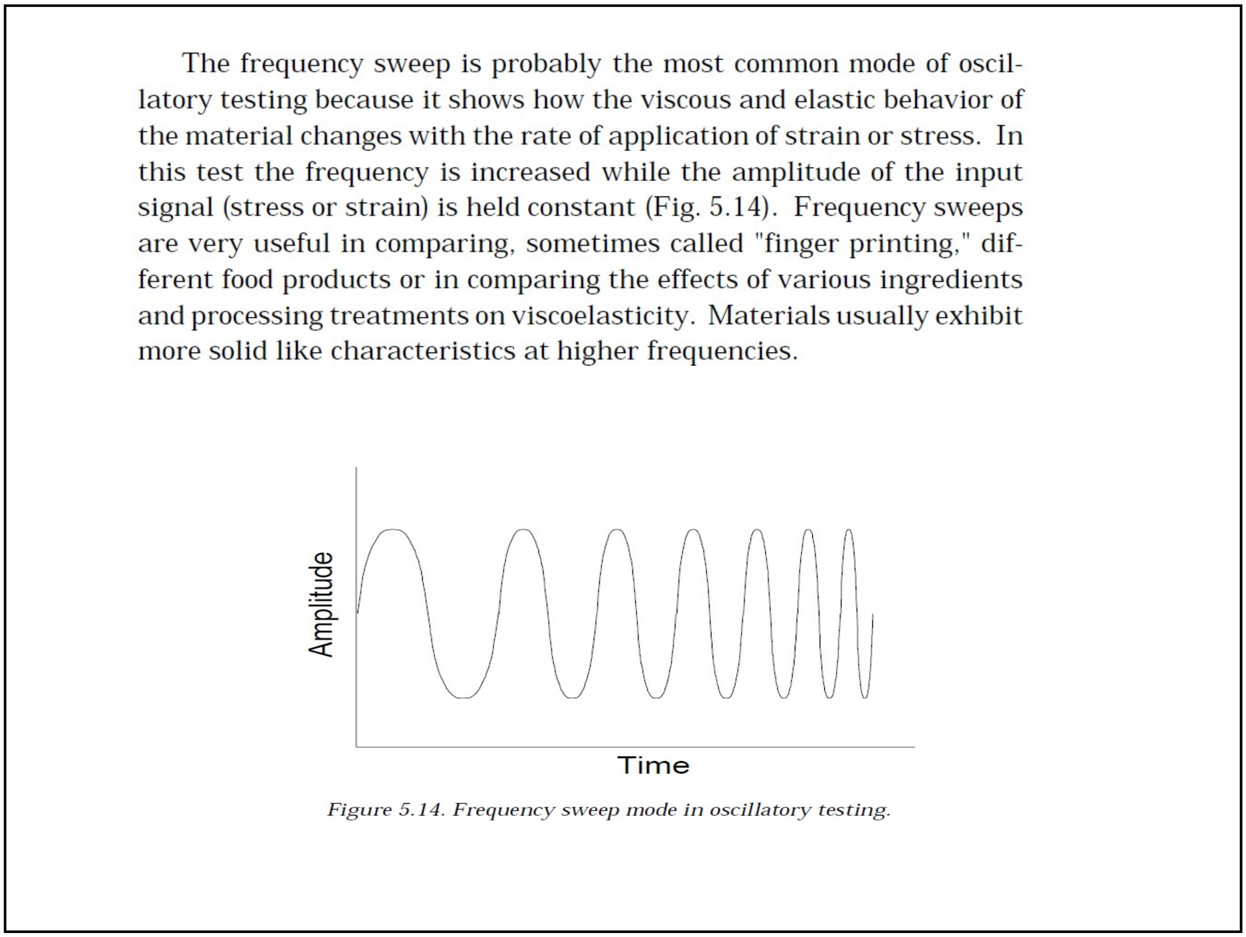
*Figure 5.24. Variation of the phase lag (δ) with frequency (ω) for typical materials. The upper limit is represented by a Newtonian fluid (δ = π/2) and the lower limit by a Hooke solid (δ = 0).*


Modulus, G' or G'' (log scale)
G'
G''
glass
leathery/
transition
rubbery/
plateau
transition
to flow
viscous/
terminal



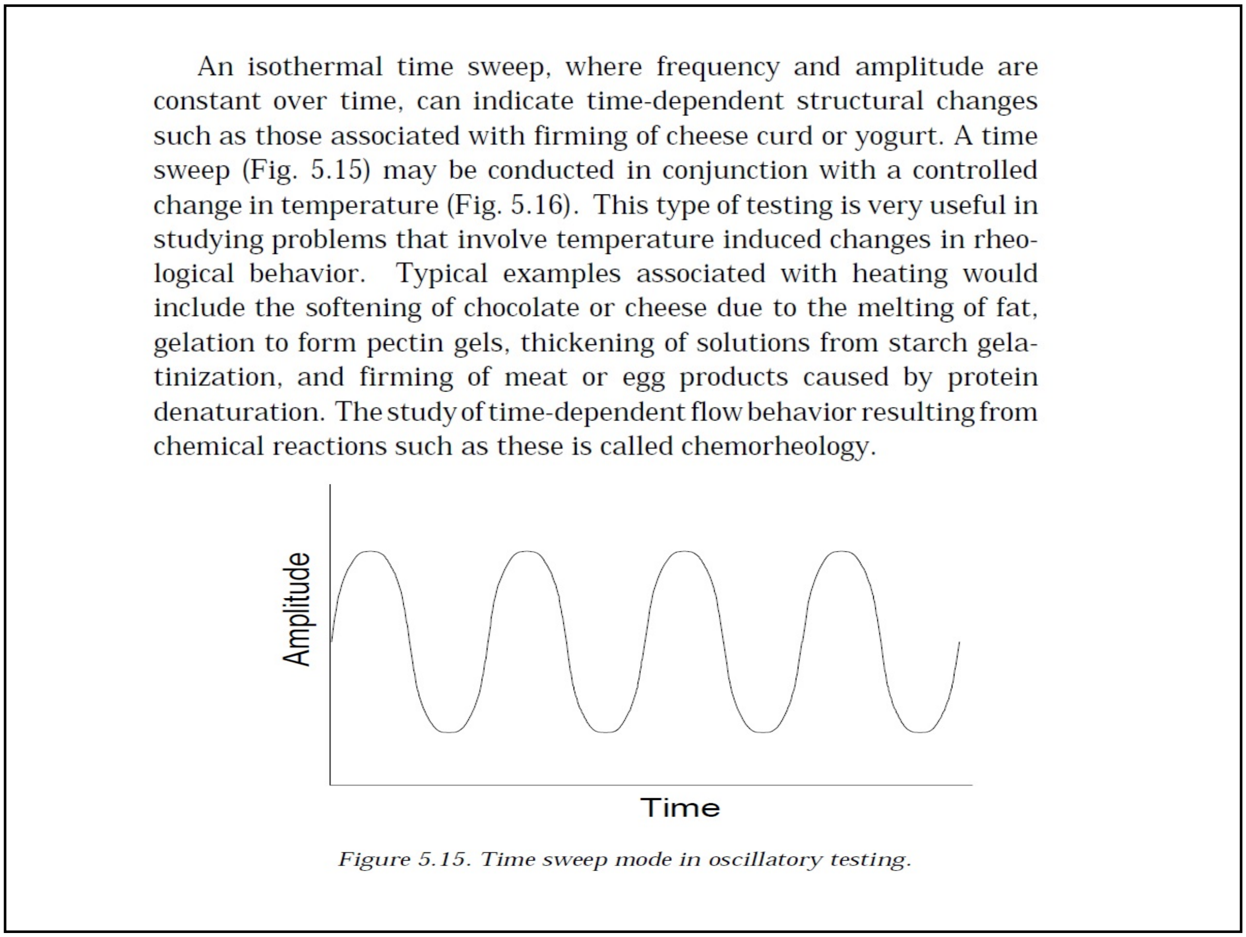
**Typical Operating Modes of an Oscillatory Testing Instrument.** Commercially available oscillatory instruments will operate in numerous modes. A strain or stress sweep, conducted by varying the amplitude of the input signal at a constant frequency (Fig. 5.12), is used to determine the limits of linear viscoelastic behavior by identifying a critical value of the sweep parameter. In the linear region (Fig. 5.13), rheological properties are not strain or stress dependent. Storage and

*Figure 5.13. Typical response to a strain or stress sweep showing the linear viscoelastic region defined by the critical value of the sweep parameter.*



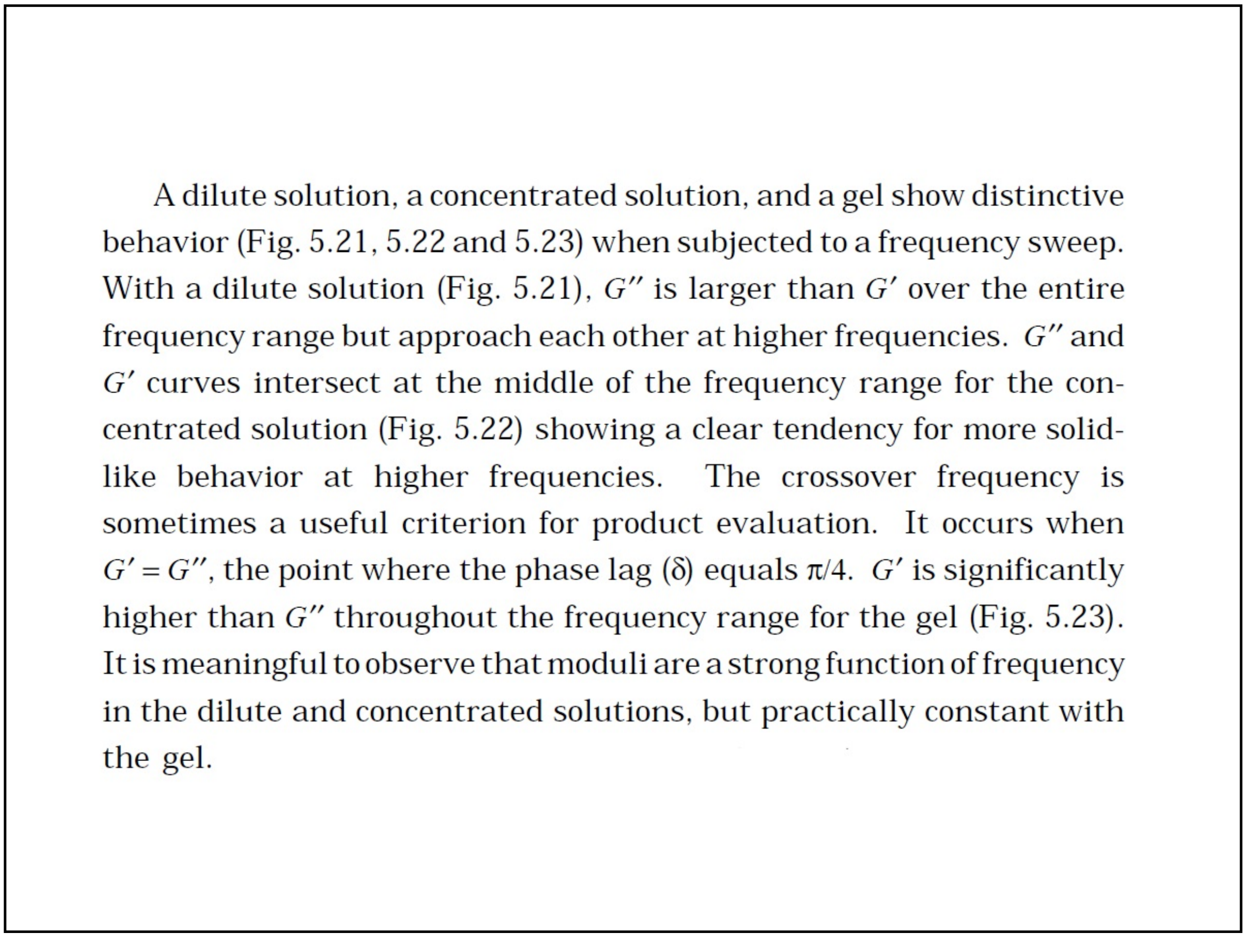
The frequency sweep is probably the most common mode of oscillatory testing because it shows how the viscous and elastic behavior of the material changes with the rate of application of strain or stress. In this test the frequency is increased while the amplitude of the input signal (stress or strain) is held constant (Fig. 5.14). Frequency sweeps are very useful in comparing, sometimes called "finger printing," different food products or in comparing the effects of various ingredients and processing treatments on viscoelasticity. Materials usually exhibit more solid like characteristics at higher frequencies.

*Figure 5.14. Frequency sweep mode in oscillatory testing.*



An isothermal time sweep, where frequency and amplitude are constant over time, can indicate time-dependent structural changes such as those associated with firming of cheese curd or yogurt. A time sweep (Fig. 5.15) may be conducted in conjunction with a controlled change in temperature (Fig. 5.16). This type of testing is very useful in studying problems that involve temperature induced changes in rheological behavior. Typical examples associated with heating would include the softening of chocolate or cheese due to the melting of fat, gelation to form pectin gels, thickening of solutions from starch gelatinization, and firming of meat or egg products caused by protein denaturation. The study of time-dependent flow behavior resulting from chemical reactions such as these is called chemorheology.

*Figure 5.15. Time sweep mode in oscillatory testing.*



A dilute solution, a concentrated solution, and a gel show distinctive behavior (Fig. 5.21, 5.22 and 5.23) when subjected to a frequency sweep. With a dilute solution (Fig. 5.21), $G''$ is larger than $G'$ over the entire frequency range but approach each other at higher frequencies. $G''$ and $G'$ curves intersect at the middle of the frequency range for the concentrated solution (Fig. 5.22) showing a clear tendency for more solid-like behavior at higher frequencies. The crossover frequency is sometimes a useful criterion for product evaluation. It occurs when $G' = G''$, the point where the phase lag ($\delta$) equals $\pi/4$. $G'$ is significantly higher than $G''$ throughout the frequency range for the gel (Fig. 5.23). It is meaningful to observe that moduli are a strong function of frequency in the dilute and concentrated solutions, but practically constant with the gel.

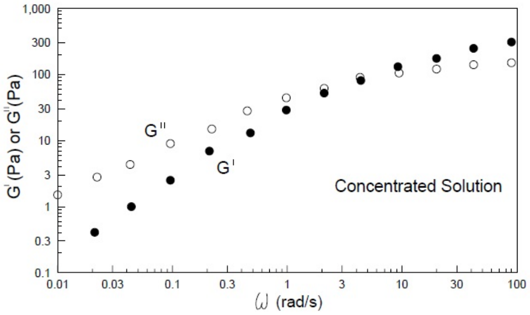


*Figure 5.22. Mechanical spectra for a concentrated solution made from 5% lambda carrageenan (Data from Ross-Murphy, 1988).*

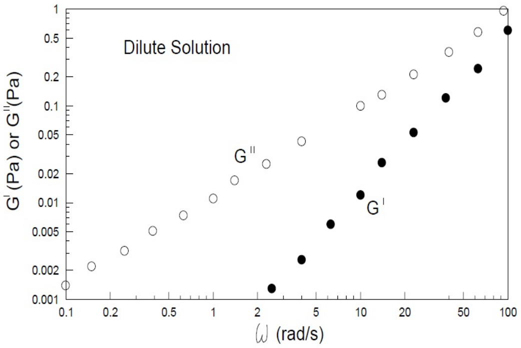


*Figure 5.21. Mechanical spectra for a dilute solution made from 5% dextrin (Data from Ross-Murphy, 1988).*

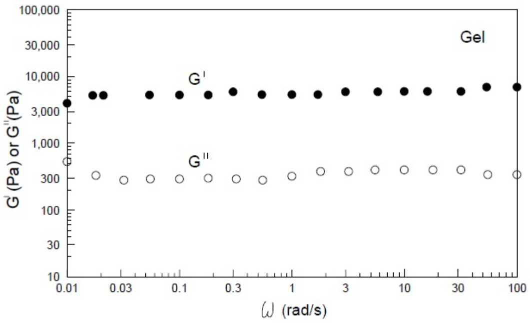
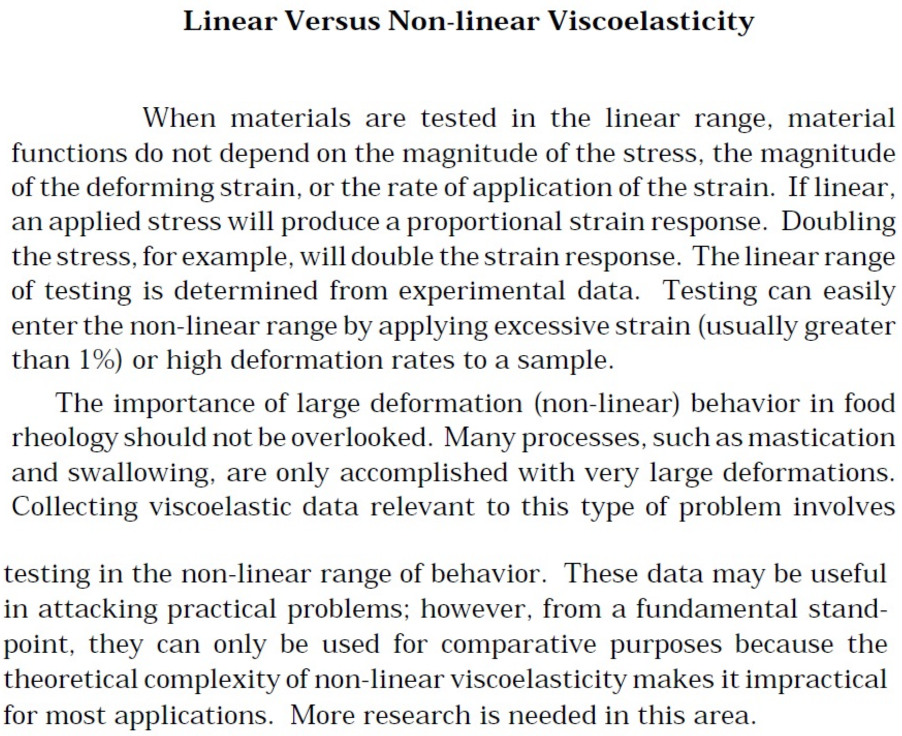


*Figure 5.23. Mechanical spectra for a gel made from 1% agar (Data from Ross-Murphy, 1988).*

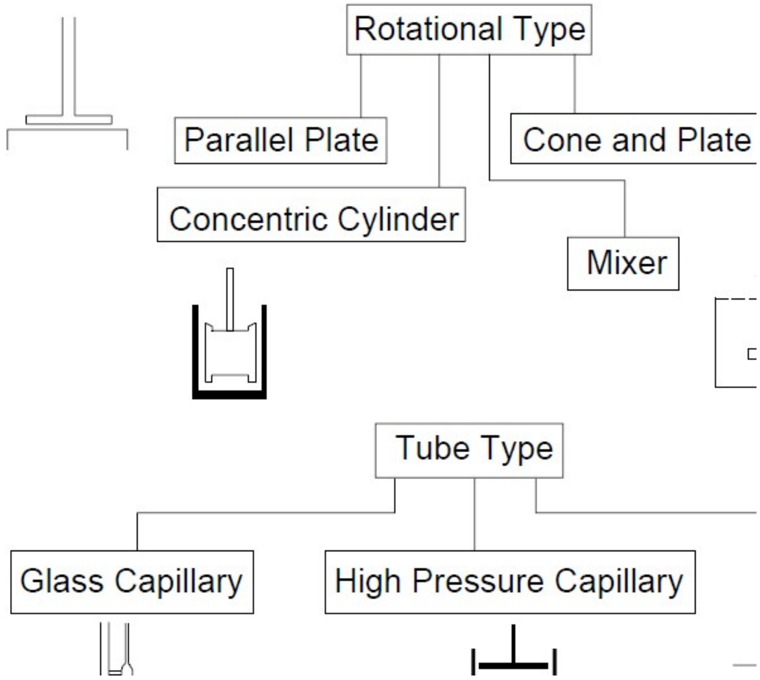


## Linear Versus Non-linear Viscoelasticity

When materials are tested in the linear range, material functions do not depend on the magnitude of the stress, the magnitude of the deforming strain, or the rate of application of the strain. If linear, an applied stress will produce a proportional strain response. Doubling the stress, for example, will double the strain response. The linear range of testing is determined from experimental data. Testing can easily enter the non-linear range by applying excessive strain (usually greater than 1%) or high deformation rates to a sample.

The importance of large deformation (non-linear) behavior in food rheology should not be overlooked. Many processes, such as mastication and swallowing, are only accomplished with very large deformations. Collecting viscoelastic data relevant to this type of problem involves testing in the non-linear range of behavior. These data may be useful in attacking practical problems; however, from a fundamental standpoint, they can only be used for comparative purposes because the theoretical complexity of non-linear viscoelasticity makes it impractical for most applications. More research is needed in this area.

1.2 Rheological Instruments for Fluids



Rotational Type

Parallel Plate

Cone and Plate

Concentric Cylinder

Mixer

Tube Type

Glass Capillary

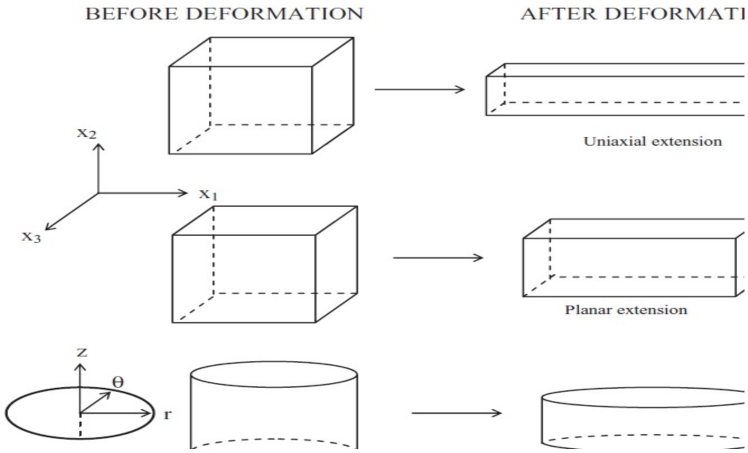
High Pressure Capillary

# EXTENSIONAL FLOW

Many food processes involve extensional deformation. Pure extensional flow does not involve shearing and sometimes called shear free flow. In extensional flow, molecular orientation is in the direction of the flow field since there are no competing forces to cause rotation. Extensional flow causes maximum stretching of molecules, producing a chain tension that may result in a large resistance to deformation.

Dough processing is an important food process in which extensional flow is significant. Another example for extensional flow is extrusion, which involves a combination of shear and extensional flow. Formation of carbon dioxide gas during fermentation of bread dough involves extensional deformation.
The extensograph is an important instrument used to study dough rheology which gives resistance to extension and stretchability.

There are three types of extensional flow: uniaxial, planar, and biaxial (Fig. 2.19).



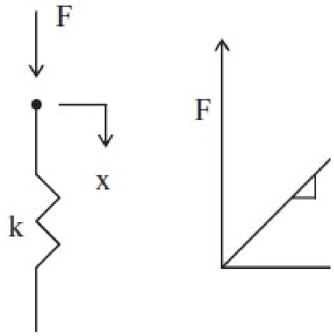
There are many test methods that measure the uniaxial extensional properties of dough such as the Brabender Extensograph and the Stable Microsystems Kieffer dough and gluten extensibility rig. However, these methods do not give rheological data in units of stress and strain since sample geometry is not defined or measured, and dimensions change nonuniformly during testing. Therefore, it is impossible to determine stress, strain, modulus, or viscosity by these methods.

# MECHANICAL MODELS

- To understand the rheological behavior of viscoelastic foods, some mechanical models are used.
- These models consist of springs and dashpots.
- **Elastic (Spring) Model**

law:

$$\tau = G\gamma$$



- **Viscous (Dashpot) Model**

$$F = C\frac{dx}{dt}$$

$$\tau = \mu\frac{d\gamma}{dt}$$

$$\tau = \mu\dot{\gamma}$$

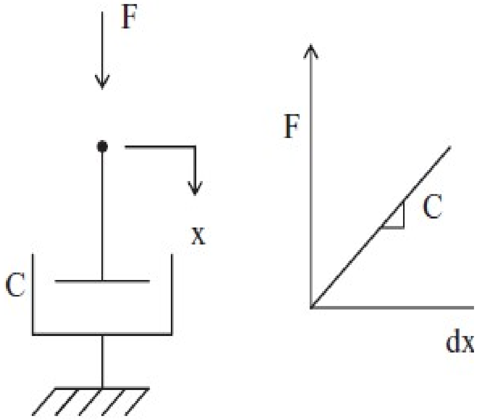
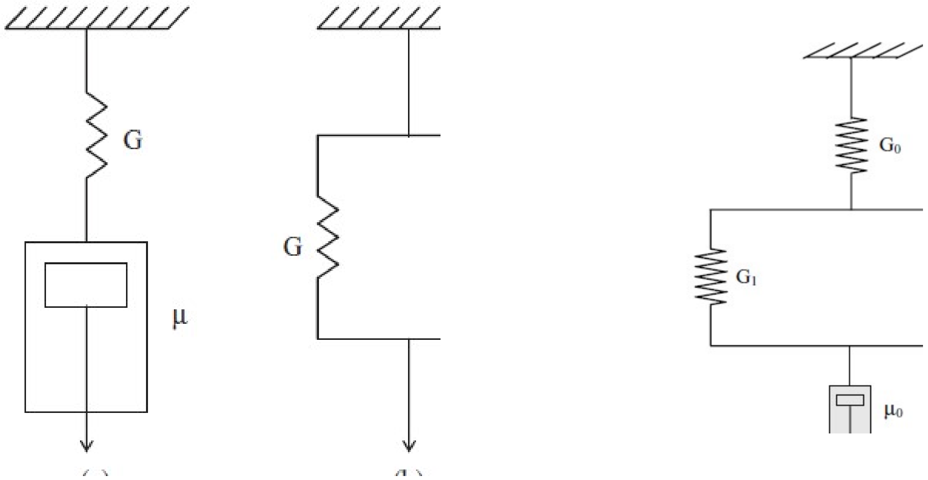


Figure 2.21 Viscous (dashpot) model.

# Combination Models



# Maxwell Model

The Maxwell model has been used to interpret stress relaxation of viscoelastic liquids, especially polymeric liquid. Since the arrangement is a series arrangement in Maxwell model, the total shear strain can be expressed as the summation of strain in the spring and dashpot:

$$\gamma = \gamma_{\text{spring}} + \gamma_{\text{dash}}$$

Differentiating Eq. (upper) with respect to time and using Eqs. (spring) and (dashpot), the following equation was obtained:

$$\frac{d\gamma}{dt} = \dot{\gamma} = \frac{1}{G}\left(\frac{d\tau}{dt}\right) +$$

# ***Kelvin-Voigt Model***

Creep behavior can be described by the Kelvin-Voigt model. This model contains a spring and a dashpot connected in parallel . Therefore, it is possible to express all strains as equal to each other.

$$\gamma = \gamma_{\text{spring}} = \gamma_{\text{dash}}$$

$$\tau = \tau_{\text{spring}} + \tau_{\text{dashpo}}$$

$$\tau = G\gamma + \mu$$

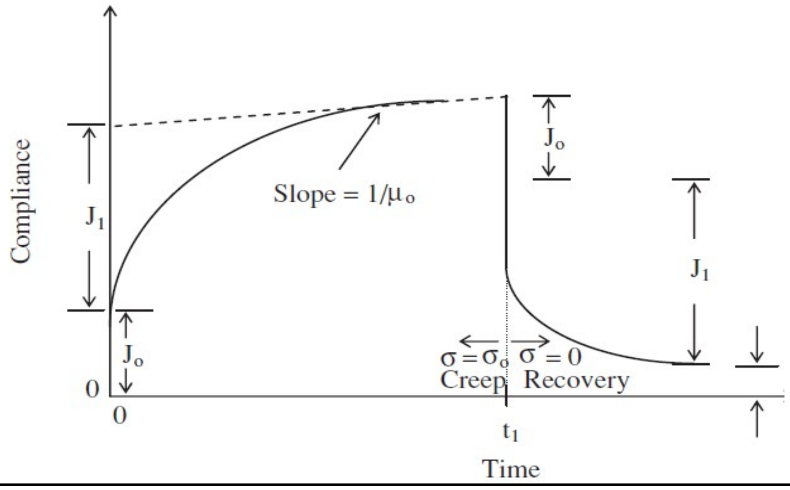
$$\gamma = \frac{\tau_0}{G}\left(1 - \exp\left(-\frac{t}{\lambda_{\text{r}}}\right.\right.$$

$$\lambda_{\text{ret}} = \frac{\mu}{G}$$

# Burger Model

The Kelvin model shows excellent retardation but this is not the case in many foods. Therefore, the Burger model is proposed, which is the series combination of the Kelvin and Maxwell models:

$$\gamma = \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1}\left(1 - \exp\left(\frac{-t}{\lambda_{ret}}\right)\right) \qquad \lambda_{ret} = \frac{\mu}{G}$$



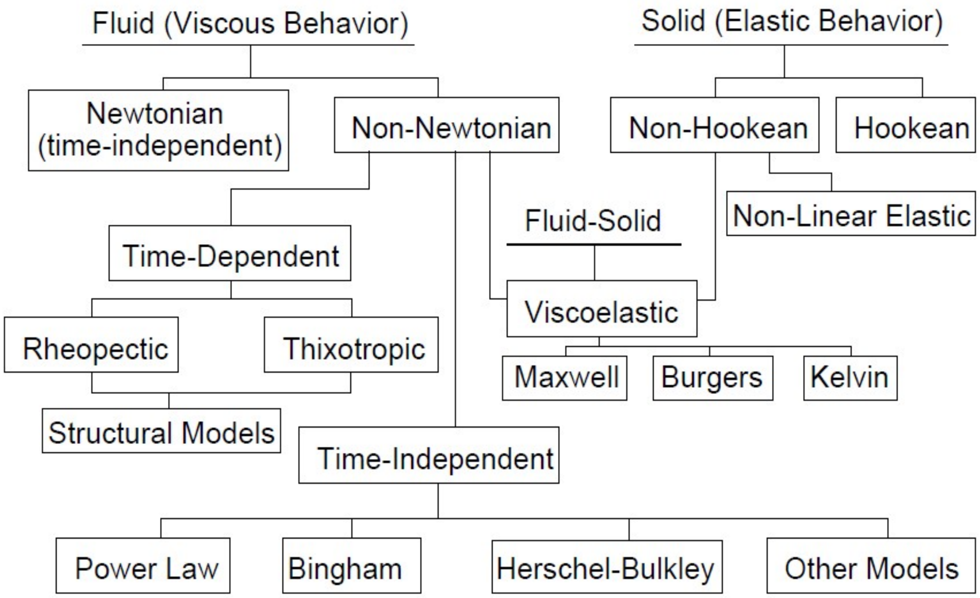


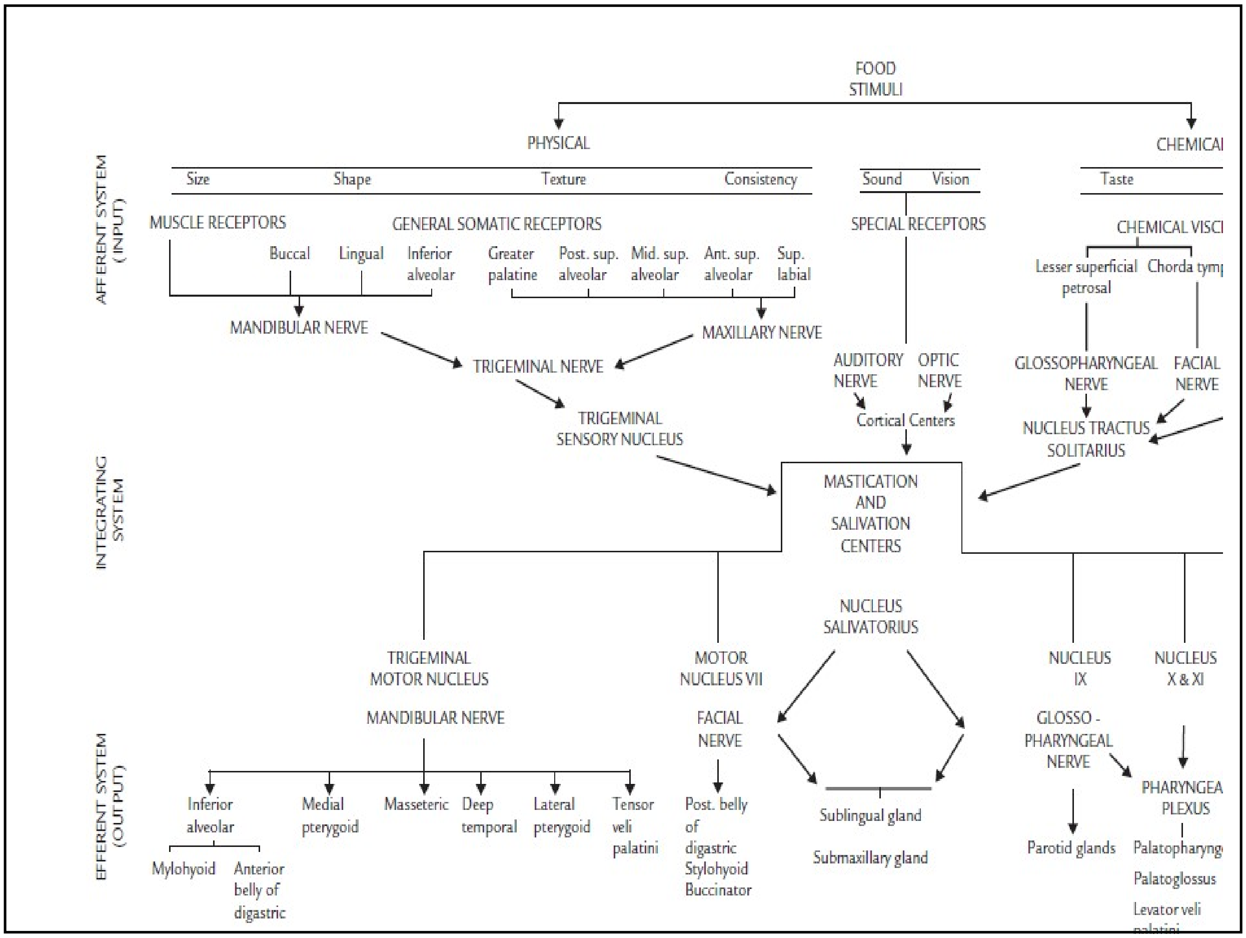
*Figure 1.25. Simple classification of rheological behavior.*

# Texture

- Although we do not have an entirely satisfactory definition of texture we can say with a high degree of certainty that texture of foods has the following characteristics.

1. It is a group of physical properties that derive from the structure of the food.
2. It belongs under the mechanical or rheological subheading of physical properties. Optical properties, electrical and magnetic properties, and temperature and thermal properties are physical properties that are excluded from the texture definition.
3. It consists of a *group of properties, not a single property.*
4. Texture is sensed primarily by the feeling of touch, usually in the mouth, but other parts of the body may be involved (frequently the hands).
5. It is not related to the chemical senses of taste or odor.
6. Objective measurement is by means of functions of mass, distance, and time only; for example, force has the dimensions *MLT2, work has the* dimensions *ML2T2, and flow has the dimensions L3T1.*

Texture is one of the most important quality characteristics of foods. Foods have different textural properties. These differences are caused by inherent differences due to the variety difference, differences due to maturity, and differences caused by processing methods. Food texture can be evaluated by sensory or instrumental methods. Sensory methods need a taste panel containing trained panelists. It is hard to repeat the results. Instrumental methods are less expensive and less time consuming as compared to sensory methods. There are various instrumental methods to determine the texture of foods.


FOOD
STIMULI
PHYSICAL
CHEMICAl
AFFERENT SYSTEM (INPUT)
Size
Shape
Texture
Consistency
Sound
Vision
Taste
MUSCLE RECEPTORS
GENERAL SOMATIC RECEPTORS
SPECIAL RECEPTORS
CHEMICAL VISCI
Buccal
Lingual
Inferior alveolar
Greater palatine
Post. sup. alveolar
Mid. sup. alveolar
Ant. sup. alveolar
Sup. labial
Lesser superficial petrosal
Chorda tymp
MANDIBULAR NERVE
MAXILLARY NERVE
TRIGEMINAL NERVE
TRIGEMINAL SENSORY NUCLEUS
AUDITORY NERVE
OPTIC NERVE
Cortical Centers
GLOSSOPHARYNGEAL NERVE
FACIAL NERVE
NUCLEUS TRACTUS SOLITARIUS
INTEGRATING SYSTEM
MASTICATION AND SALIVATION CENTERS
NUCLEUS SALIVATORIUS
TRIGEMINAL MOTOR NUCLEUS
MOTOR NUCLEUS VII
NUCLEUS IX
NUCLEUS X & XI
EFFERENT SYSTEM (OUTPUT)
MANDIBULAR NERVE
FACIAL NERVE
GLOSSO - PHARYNGEAL NERVE
PHARYNGEA PLEXUS
Inferior alveolar
Medial pterygoid
Masseteric
Deep temporal
Lateral pterygoid
Tensor veli palatini
Post. belly of digastric
Stylohyoid
Buccinator
Sublingual gland
Submaxillary gland
Parotid glands
Palatopharyng
Palatoglossus
Levator veli palatini
Mylohyoid
Anterior belly of digastric

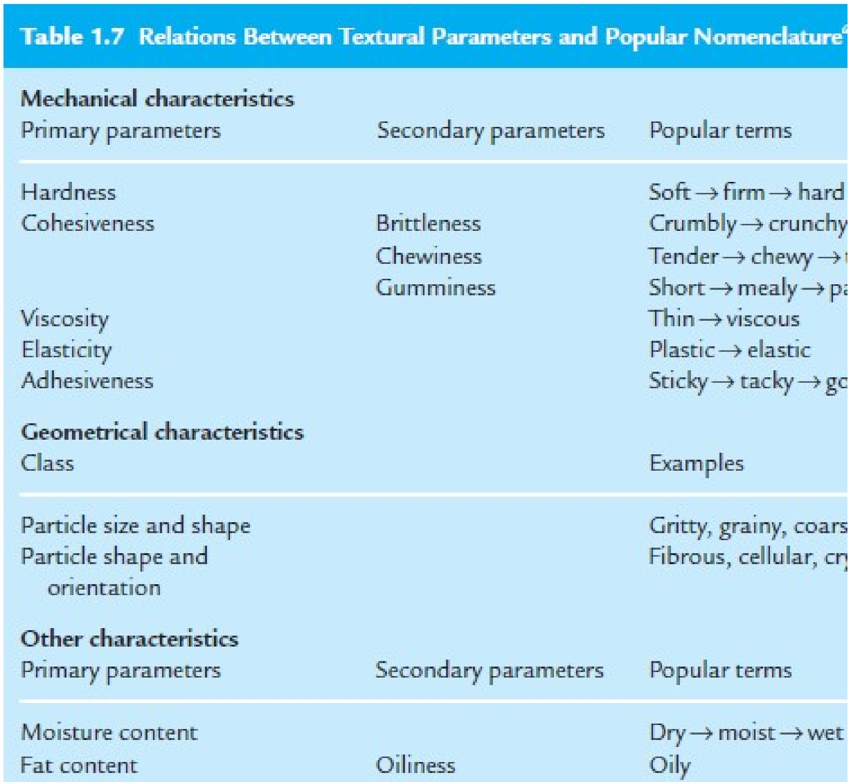


**Table 1.7 Relations Between Textural Parameters and Popular Nomenclature**

| **Mechanical characteristics** | | |
|---|---|---|
| Primary parameters | Secondary parameters | Popular terms |
| Hardness | | Soft → firm → hard |
| Cohesiveness | Brittleness | Crumbly → crunchy |
| | Chewiness | Tender → chewy → |
| | Gumminess | Short → mealy → p |
| Viscosity | | Thin → viscous |
| Elasticity | | Plastic → elastic |
| Adhesiveness | | Sticky → tacky → go |
| **Geometrical characteristics** | | |
| Class | | Examples |
| Particle size and shape | | Gritty, grainy, coars |
| Particle shape and orientation | | Fibrous, cellular, cr |
| **Other characteristics** | | |
| Primary parameters | Secondary parameters | Popular terms |
| Moisture content | | Dry → moist → wet |
| Fat content | Oiliness | Oily |

# Texture Measurement

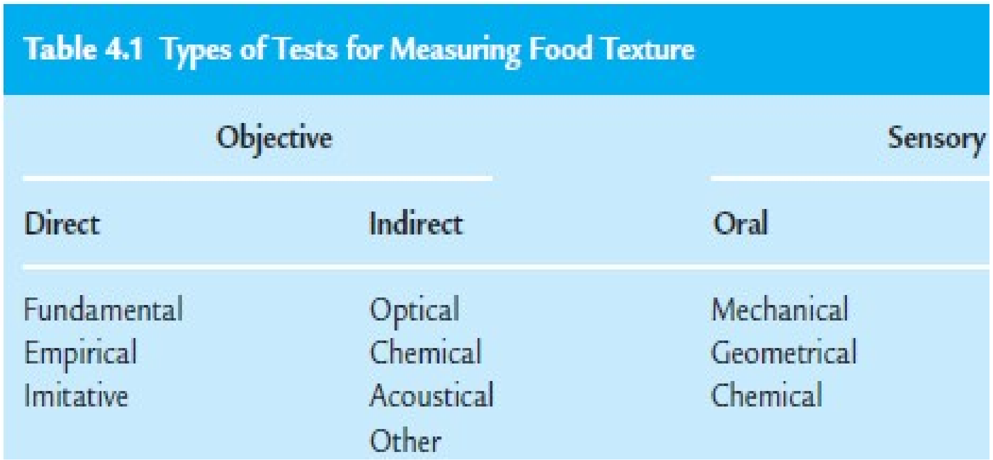
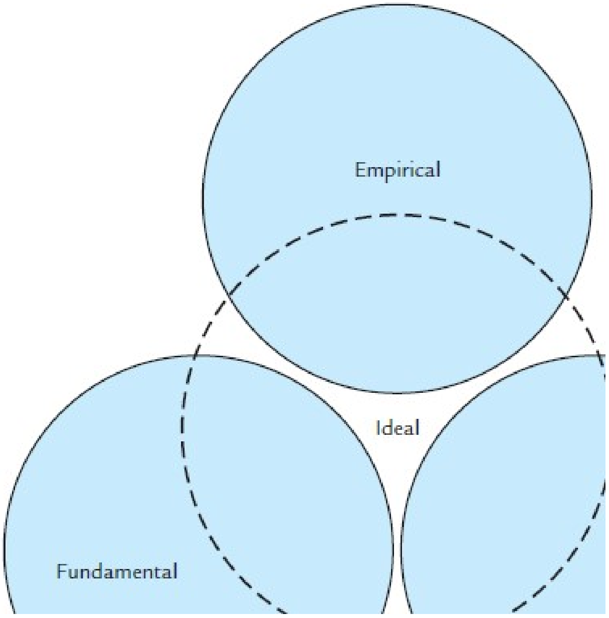


Table 4.1 Types of Tests for Measuring Food Texture

| Objective | | Sensory |
|---|---|---|
| Direct | Indirect | Oral |
| Fundamental<br>Empirical<br>Imitative | Optical<br>Chemical<br>Acoustical<br>Other | Mechanical<br>Geometrical<br>Chemical |

**Figure 4.1** Schematic representation of the ideal texture measuring apparatus and its derivation from empirical, fundamental, and imitative instruments. (From Bourne, 1975b; reprinted with permission from D. Reidel Publ. Co.)



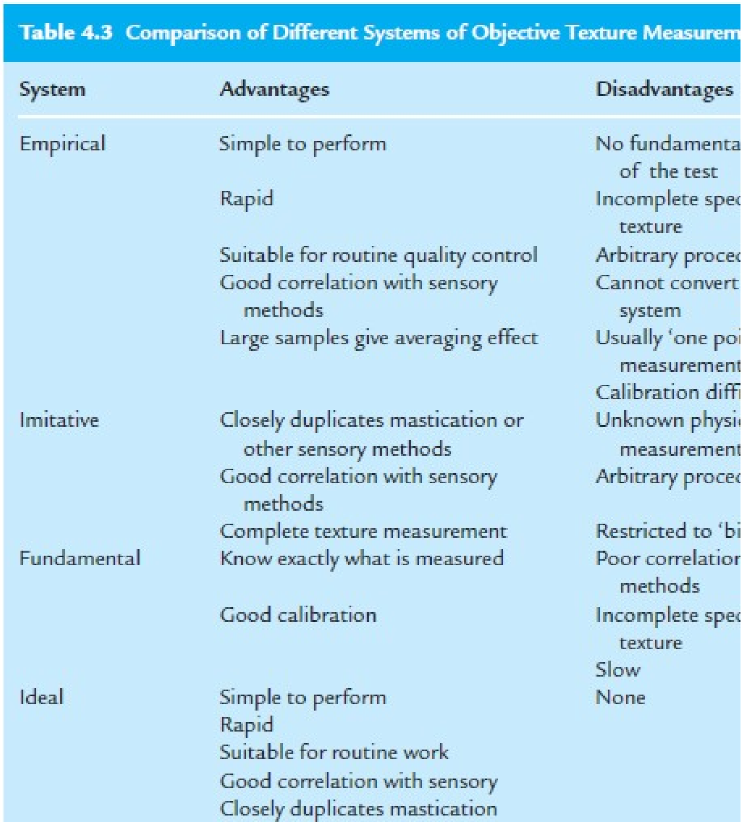


**Table 4.3 Comparison of Different Systems of Objective Texture Measurem**

| System | Advantages | Disadvantages |
|---|---|---|
| Empirical | Simple to perform | No fundamenta of the test |
| | Rapid | Incomplete spe texture |
| | Suitable for routine quality control | Arbitrary proce |
| | Good correlation with sensory methods | Cannot convert system |
| | Large samples give averaging effect | Usually 'one poi measurement |
| | | Calibration diffi |
| Imitative | Closely duplicates mastication or other sensory methods | Unknown physi measurement |
| | Good correlation with sensory methods | Arbitrary proce |
| | Complete texture measurement | Restricted to 'bi |
| Fundamental | Know exactly what is measured | Poor correlatio methods |
| | Good calibration | Incomplete spe texture |
| | | Slow |
| Ideal | Simple to perform | None |
| | Rapid | |
| | Suitable for routine work | |
| | Good correlation with sensory | |
| | Closely duplicates mastication | |

- Another method of classification of food texture instruments is on the basis of the variable or variables that are measured in the test.

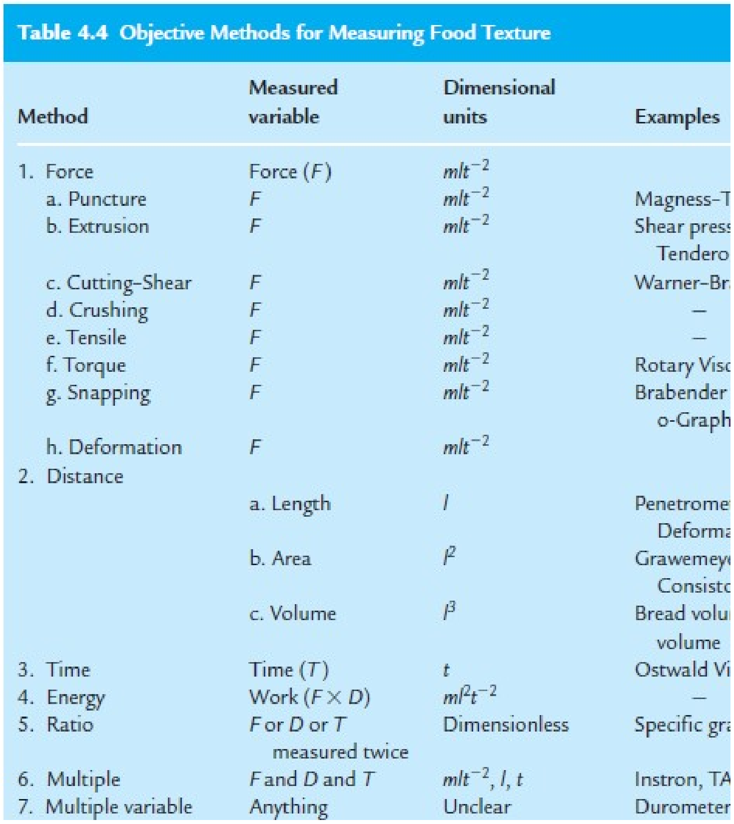


**Table 4.4 Objective Methods for Measuring Food Texture**

| Method | Measured variable | Dimensional units | Examples |
|---|---|---|---|
| 1. Force | Force ($F$) | $mlt^{-2}$ | |
| a. Puncture | $F$ | $mlt^{-2}$ | Magness–T |
| b. Extrusion | $F$ | $mlt^{-2}$ | Shear press Tendero |
| c. Cutting–Shear | $F$ | $mlt^{-2}$ | Warner–Br |
| d. Crushing | $F$ | $mlt^{-2}$ | – |
| e. Tensile | $F$ | $mlt^{-2}$ | – |
| f. Torque | $F$ | $mlt^{-2}$ | Rotary Visc |
| g. Snapping | $F$ | $mlt^{-2}$ | Brabender o-Graph |
| h. Deformation | $F$ | $mlt^{-2}$ | |
| 2. Distance | | | |
| | a. Length | $l$ | Penetrome Deforma |
| | b. Area | $l^2$ | Grawemey Consistc |
| | c. Volume | $l^3$ | Bread volu volume |
| 3. Time | Time ($T$) | $t$ | Ostwald Vi |
| 4. Energy | Work ($F \times D$) | $ml^2t^{-2}$ | – |
| 5. Ratio | $F$ or $D$ or $T$ measured twice | Dimensionless | Specific gr |
| 6. Multiple | $F$ and $D$ and $T$ | $mlt^{-2}$, $l$, $t$ | Instron, TA |
| 7. Multiple variable | Anything | Unclear | Durometer |

# Force Measuring Instruments

## 1- Puncture Test

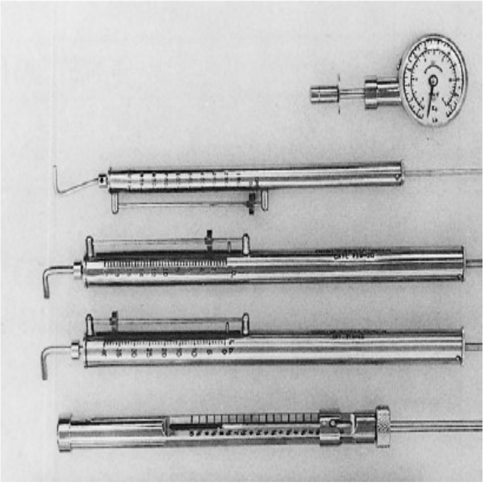
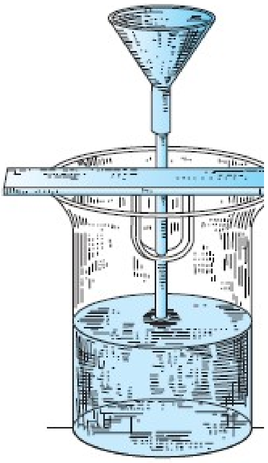
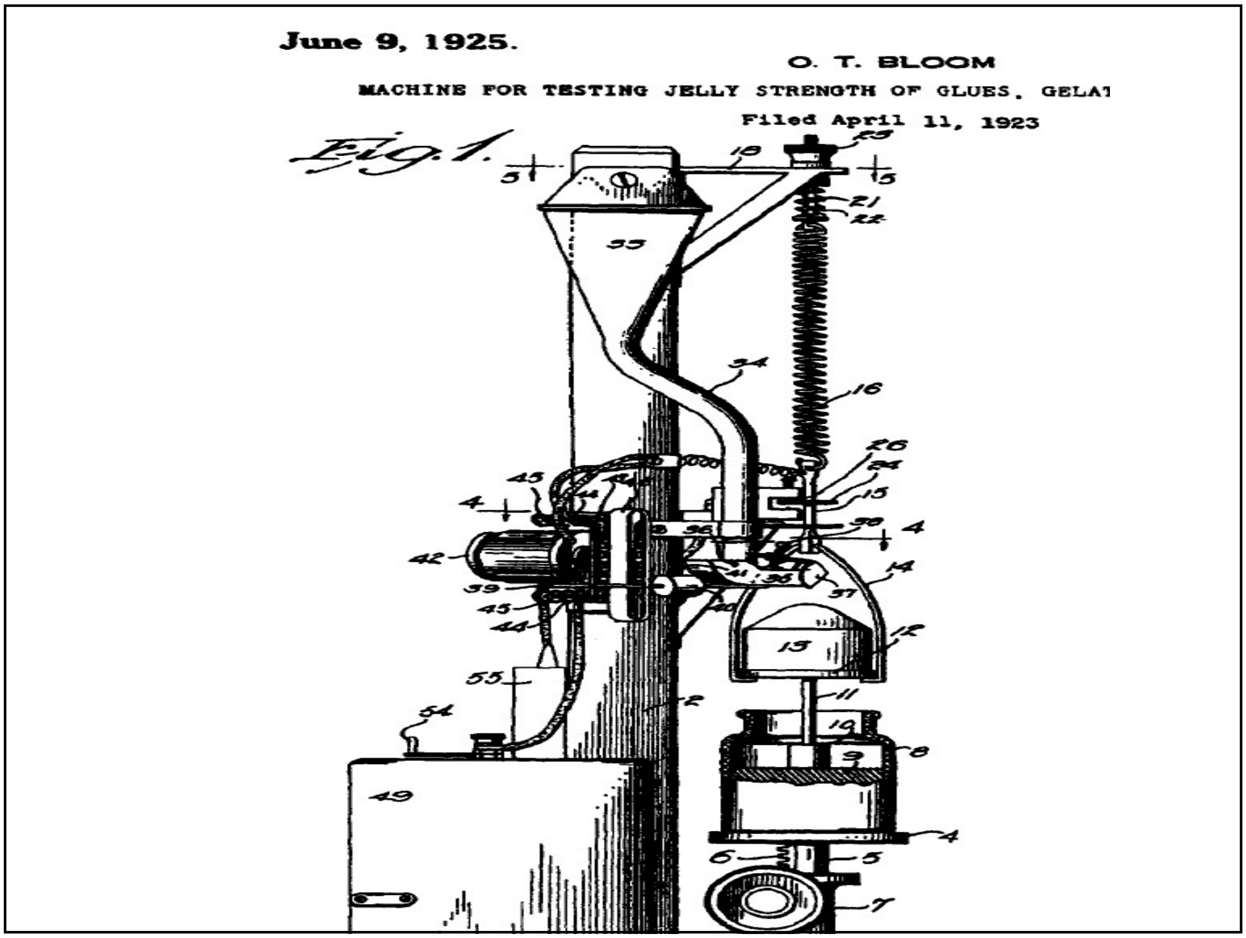


**Figure 5.1** Hand-operated puncture testers of the Magness–Taylor type. From the bottom up: 30-lb Ballauf with 7/16-in.-diam punch, 10-lb Ballauf with 5/16-in.-diam punch, 40-lb Chatillon with 7/16-in.-diam punch, 20-lb Chatillon with 5/16-in.-diam punch, 1000 g Chatillon with 0.058-in.-diam punch, and Effi-Gi with 7/16-in.-diam punch.



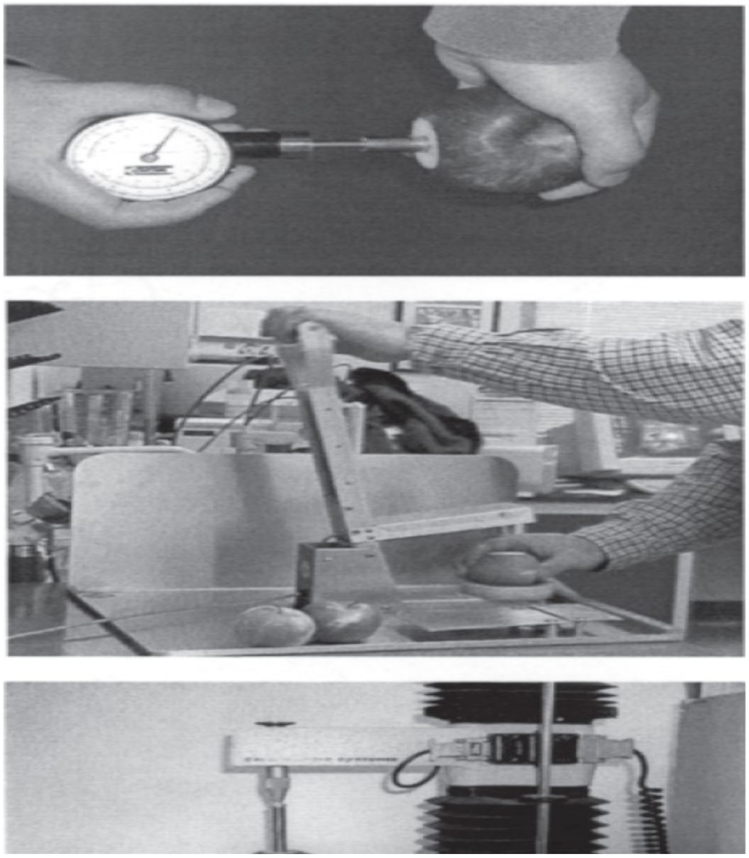


June 9, 1925.

O. T. BLOOM

MACHINE FOR TESTING JELLY STRENGTH OF GLUES, GELA

Filed April 11, 1923



# 2- **Compression–Extrusion Test**

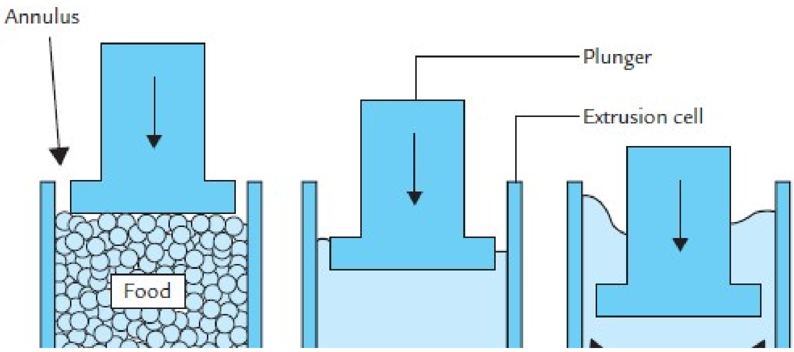
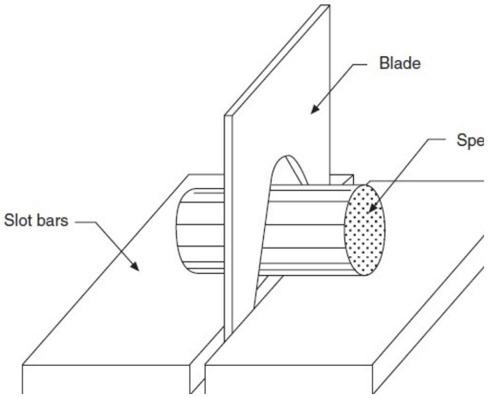
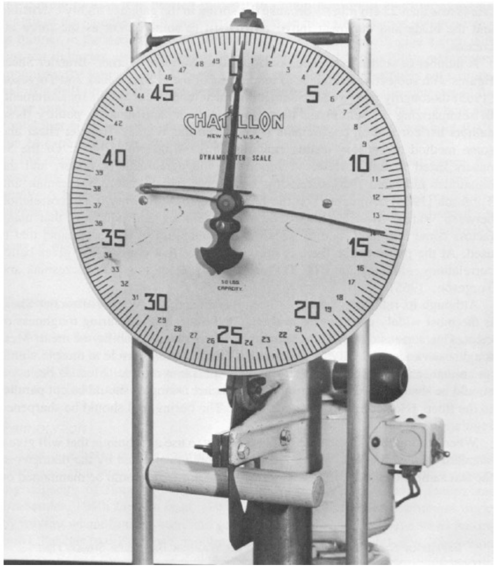


**Figure 4.1**
diagram of
extrusion t
goes down
the surface
food is pac
liquid may
(c) The foo
the annulu

# 3- **Cutting–Shear Test**





## 4- Compression Tests

## 5- Bending and Snapping Test

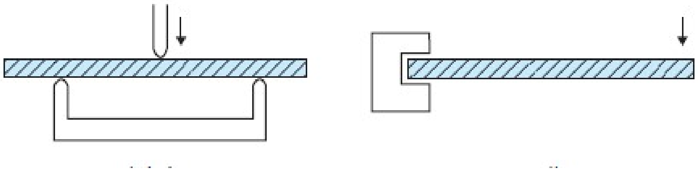


Figure 4.
perform b
tests.

# Distance Measuring Instruments

## 1- **Linear Measuring Instruments**

**Figure 5.8** The Bostwick Consistometer: (a) sample is in first compartment with gate closed; (b) gate is open and sample has flowed along the second compartment.

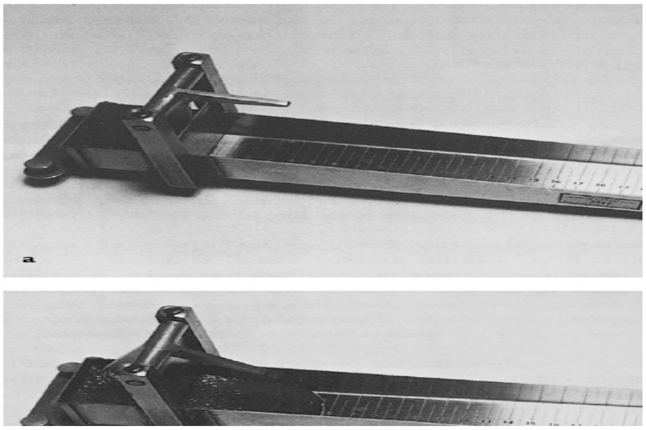
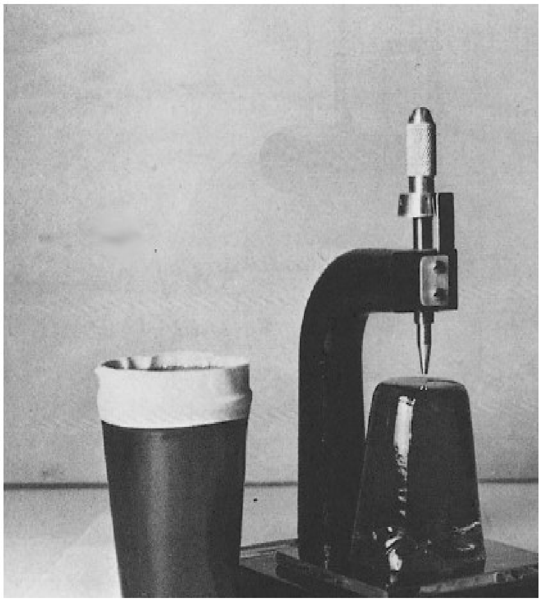
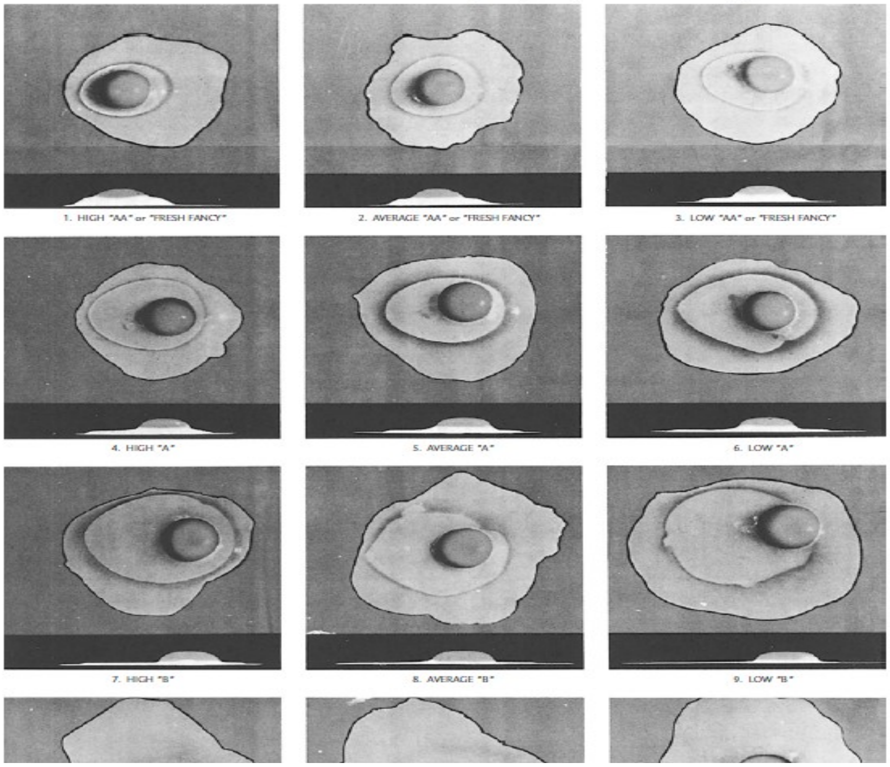


**Figure 5.9** The Ridgelimeter.



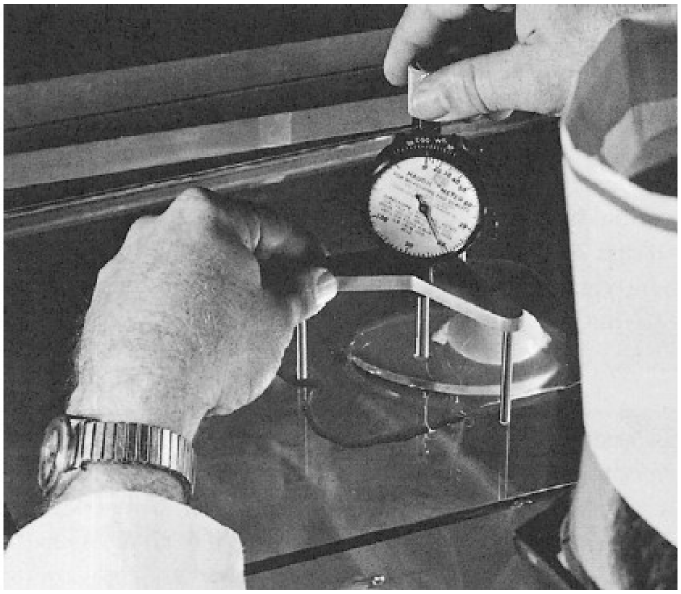
## INTERIOR QUALITY OF EGGS
(Recommended standards for scoring the quality of broken-out eggs)



1. HIGH "AA" or "FRESH FANCY"
2. AVERAGE "AA" or "FRESH FANCY"
3. LOW "AA" or "FRESH FANCY"
4. HIGH "A"
5. AVERAGE "A"
6. LOW "A"
7. HIGH "B"
8. AVERAGE "B"
9. LOW "B"

**Figure 5.1**
between alb
quality (US

**Figure 5.13** The Haugh meter (USDA photo).



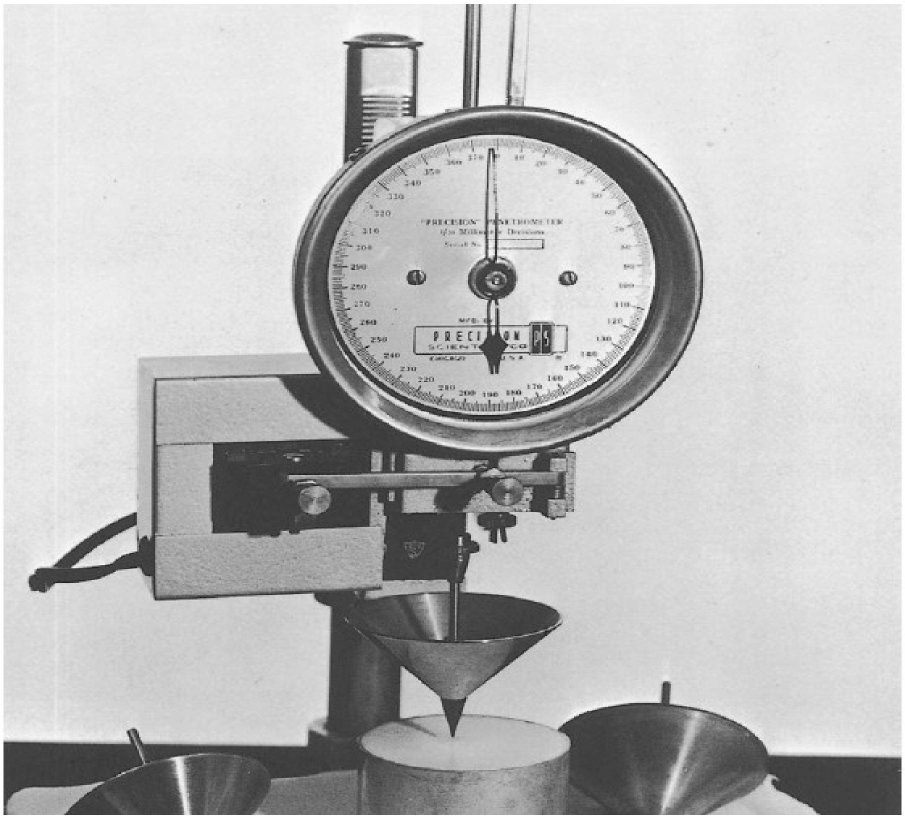
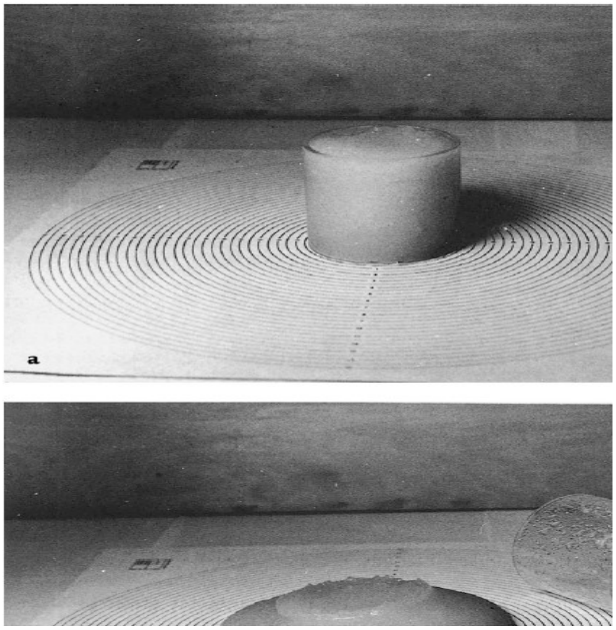


**Figure 5.**
different t
needles a
white clot

# 2- **Area Measuring Instruments**

**Figure 5.14** The USDA Consistometer: (a) cylinder is filled with applesauce; (b) cylinder is removed, allowing sauce to flow out.



# Multiple Variable Instruments

1-**GF Texturometer**
**2- FTC Texture Test System**
**3- Ottawa Texture Measuring System (OTMS)**
**4- Universal Testing Machines (UTM)**
**4-1- Instron**
**4-2- TA.XT2 Texture Analyzer**
**4-3- QTS Texture Analyzers**
**4-4- Lloyd Texture Analyzer**
**4-5- Tensipresser**

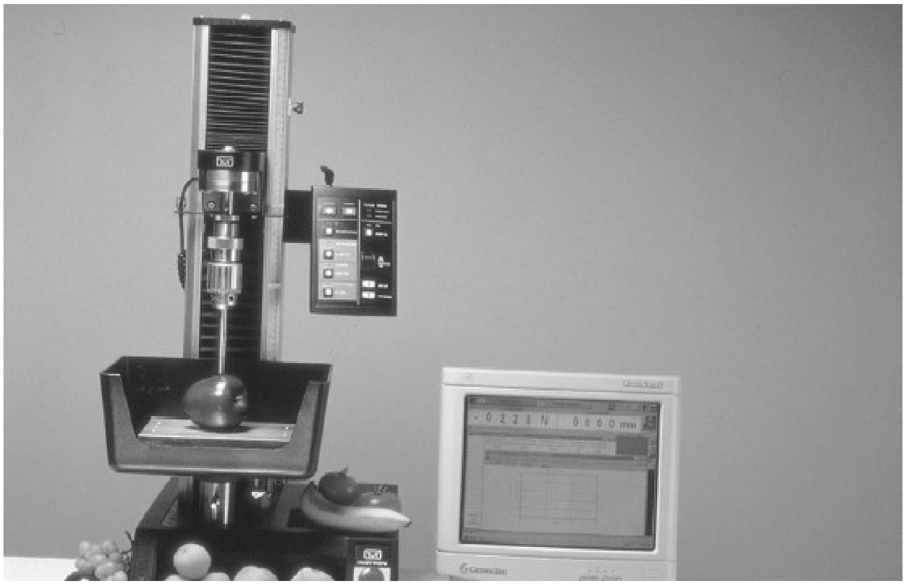
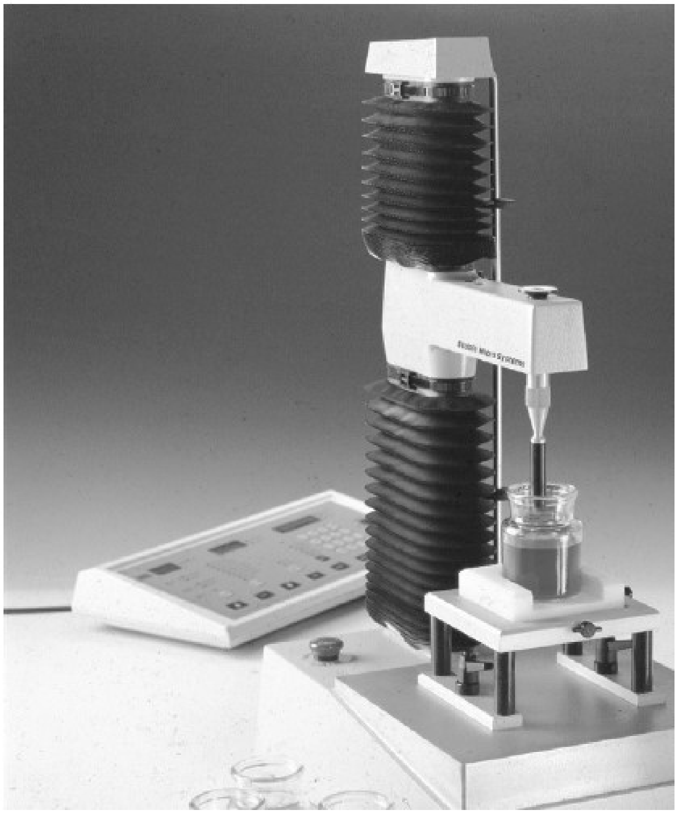


**Figure**
Instron
(Courte
Corpor

**Figure 5.17** The TA.XT2 Texture Analyzer. (Courtesy of Stable Microsystems Ltd.)



# SANTAM

Materials Testing Equipment

STM-50
Manual Wedge Grips WG

MOODY
INTERNATIONAL CERTIFICATION
ISO 9001:2000
Approved Company

UKAS
QUALITY MANAGEMENT

## Universal Testing Machine

Servo Electero-Mechanical Model

*STM Series 50 kN Capacity*

SANTAM

www.santamco.com ◆ info@santamco.com

# Texture Profile Analysis (TPA)

- A group at the General Foods Corporation Technical Center pioneered the test that compresses a bite-size piece of food two times in a reciprocating motion that imitates the action of the jaw, and extracted from the resulting force–time curve a number of textural parameters that correlate well with sensory evaluation of those parameters *The* instrument devised especially for this purpose is the General Foods Texturometer.

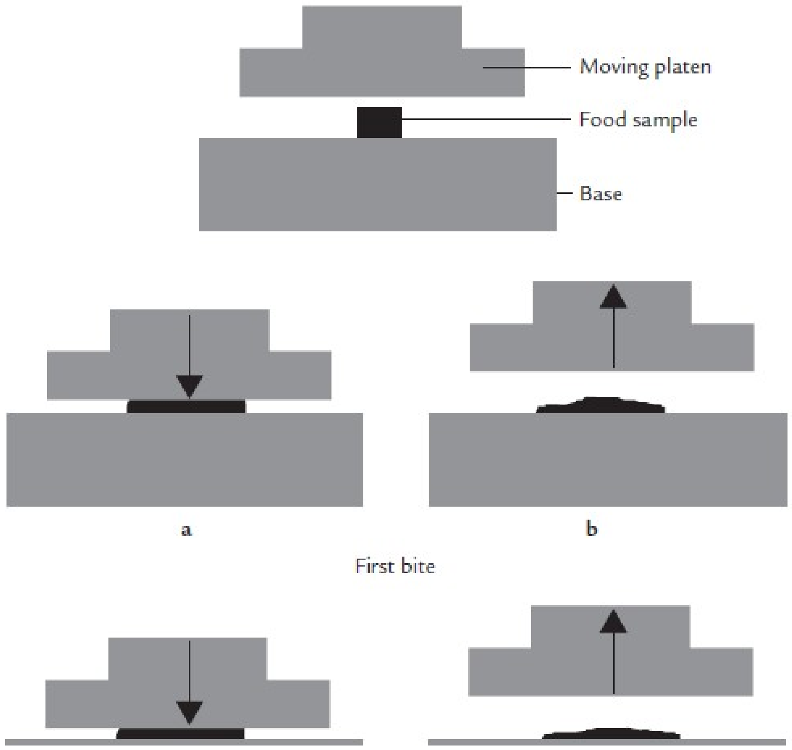
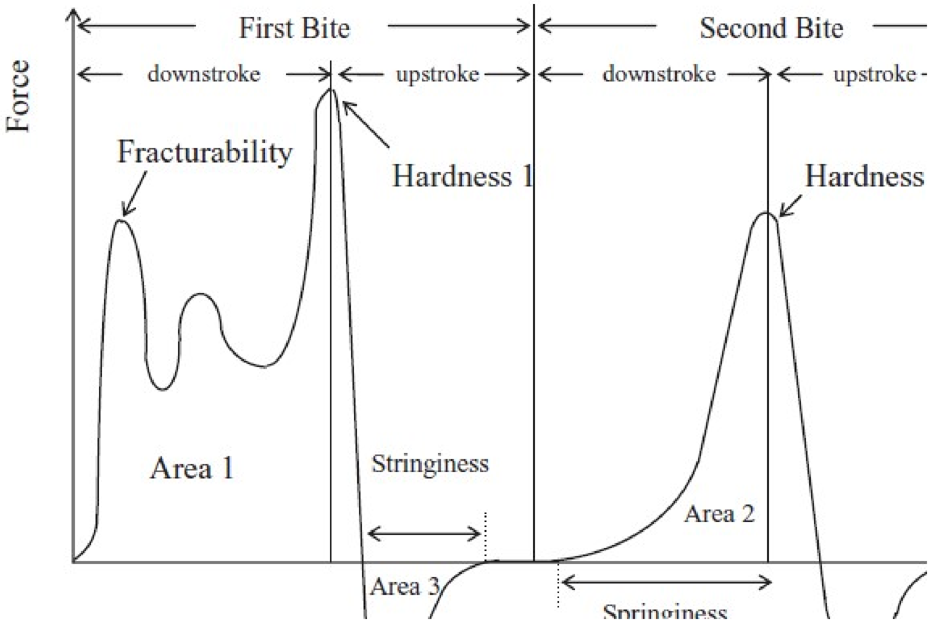


**Figure 4.**
diagram o
required f
analysis te
actions du
second bit
actions du
second bit


First Bite
Second Bite
downstroke
upstroke
downstroke
upstroke
Force
Fracturability
Hardness 1
Hardness
Area 1
Stringiness
Area 2
Area 3
Springiness

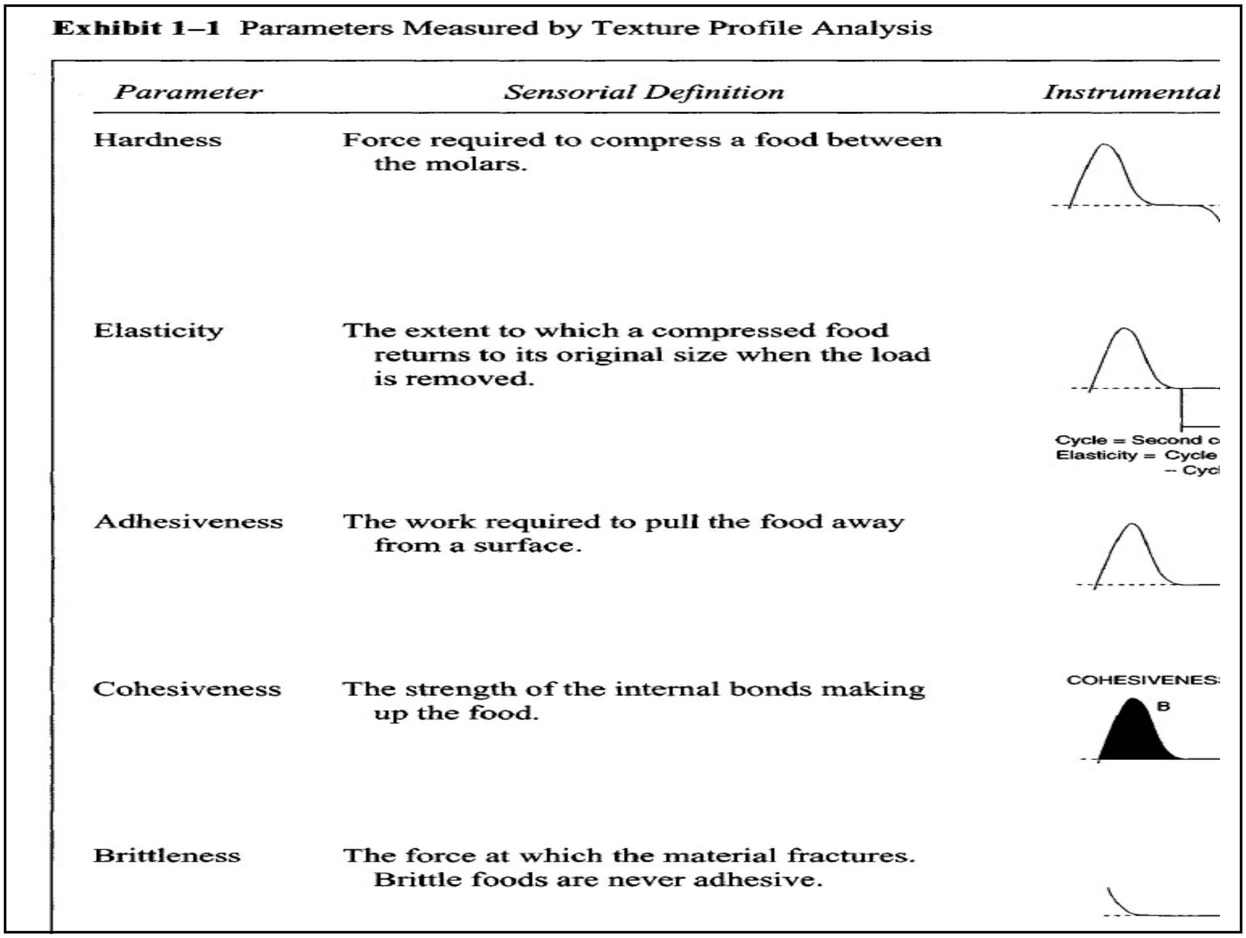


**Exhibit 1–1** Parameters Measured by Texture Profile Analysis

| *Parameter* | *Sensorial Definition* | *Instrumental* |
|---|---|---|
| Hardness | Force required to compress a food between the molars. | |
| Elasticity | The extent to which a compressed food returns to its original size when the load is removed. | Cycle = Second c<br>Elasticity = Cycle<br>– Cycl |
| Adhesiveness | The work required to pull the food away from a surface. | |
| Cohesiveness | The strength of the internal bonds making up the food. | COHESIVENES<br>B |
| Brittleness | The force at which the material fractures. Brittle foods are never adhesive. | |

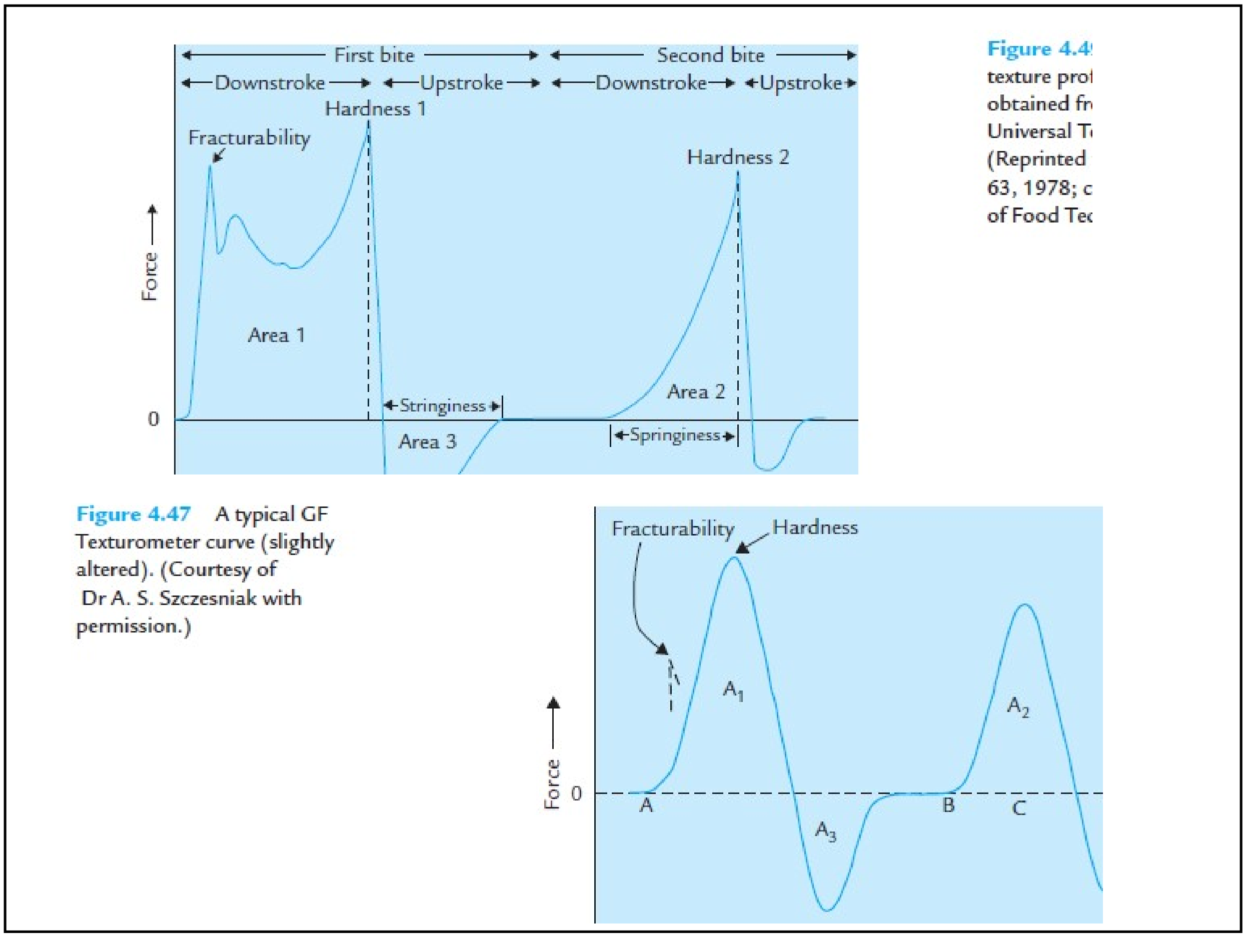
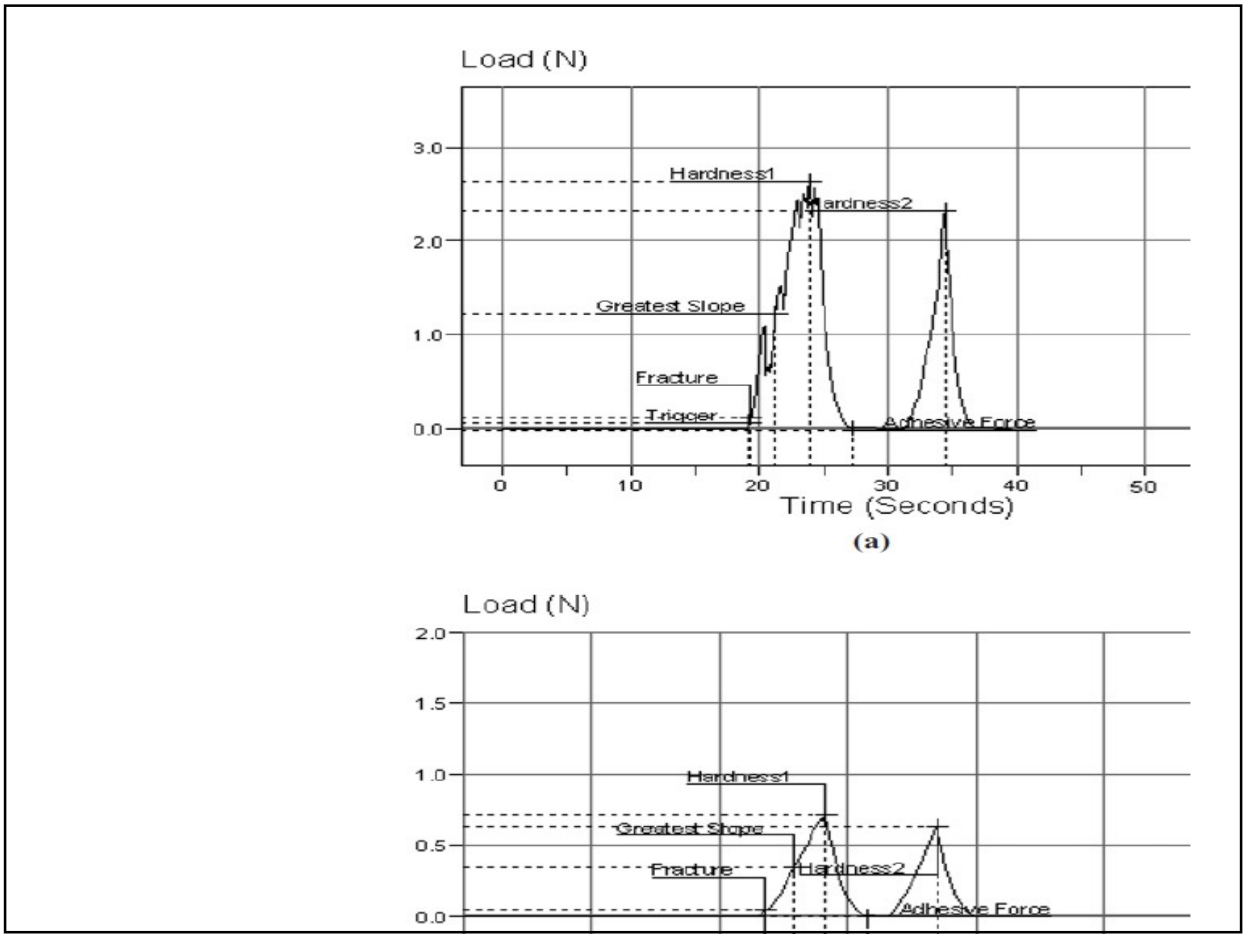


**Figure 4.4**
texture pro
obtained fr
Universal T
(Reprinted
63, 1978; c
of Food Te

**Figure 4.47** A typical GF Texturometer curve (slightly altered). (Courtesy of Dr A. S. Szczesniak with permission.)


Load (N)
3.0
2.0
1.0
0.0
Hardness1
Hardness2
Greatest Slope
Fracture
Trigger
Adhesive Force
0
10
20
30
40
50
Time (Seconds)
(a)
Load (N)
2.0
1.5
1.0
0.5
0.0
Hardness1
Greatest Slope
Fracture
Hardness2
Adhesive Force