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PHYSICAL CHEMISTRY OF FOOD PROCESSES *VOLUME I*

Fundamental Aspects

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Rheology of Cheese

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WHY RHEOLOGY IS USED IN CHEESE ANALYSIS

The instrumental measurement of the rheological properties of cheese is performed for two reasons: as a *quality control* method for cheesemakers, and as a technique for scientists to study *cheese structure*. The rheological properties of cheese can be as important as flavor, and are a large part of the total score awarded by the cheese grader (Farkye and Fox, 1990). Consequently, an objective instrumental method of determining rheological properties of cheese would be quite valuable. This also holds true for scientific studies of cheese. The pH at whey draining affects the size and shape of protein aggregates and has a large effect on the textural properties of cheese (Fox, Lucey, and Cogan, 1990). Low-pH curds result in a crumbly texture, such as in Cheshire cheese, whereas high-pH curds lead to more elastic cheeses, such as Swiss or Gouda. The extent of proteolysis and the amounts of water, protein, fat, and salt in cheese also affect texture, resulting in profound differences between cheese types. Research into the origins of cheese texture is an important part of dairy science, and investigations into cheese rheology have been conducted for over half a century. Correlating the results of various instrumental tests to each other and to subjective evaluations by sensory panels and consumers is a goal that is constantly being strived for (Szczesniak, 1987).

BRIEF HISTORY OF RHEOLOGICAL MEASUREMENTS OF CHEESE

The three general categories of food texture measurement are empirical, imitative, and fundamental tests (Scott Blair, 1958). The idea behind empirical tests is the measurement of parameters that experience indicates are related to texture. The first measurements of cheese rheology were empirical tests performed by hand without instruments: the cheese grader would press into the surface with his thumb to judge firmness and elasticity. Simple instruments followed, such as the ball compressor, in which a hemisphere presses into the surface of the specimen, and the depth of compression and amount of recovery with time is noted (Caffyn and Baron, 1947; Cox and Baron, 1955). Another instrument, the penetrometer, produces force measurements as a needle is pushed into the cheese (Prentice, 1987). A third device, the Cherry-Burrell Curd Tension Meter, measures the resistance to the passage of a wire through cheese curd or a block of cheese (Emmons and Price, 1959). Other tests include rate of penetration of a standard borer under a standard load, pressure on a standard cheese skewer pushed into cheese by hand, and rate of increase of indentation caused by increasing load on a sphere (Scott Blair and Baron, 1949). Szczesniak (1963) reviewed many of these devices. With all of these methods, several measurements must be taken over the sample surface in order to obtain an accurate average. The results can be useful if only one type of cheese is being tested, but these instruments are not always satisfactory for rigorous theoretical studies due to the arbitrary test conditions (Voisey, 1976).

In the 1930s, the first instrument to examine texture by imitating the chewing of food was developed: the Volodkevich bite tenderometer. A wedge, imitating teeth on the upper jaw, was brought down toward a second wedge, exerting a biting and squeezing action on the sample held between the wedges (Volodkevich, 1938). The next significant development in imitative tests came in the mid-1950s with the MIT denture tenderometer, which contained motorized dentures and strain gauges (Proctor et al., 1955). In the early 1960s, the General Foods Texturometer made its appearance (Friedman, Whitney, and Szczesniak, 1963). This device compresses a bite-sized sample to 25% of its original height, releases, and repeats, thus imitating jaw movement. Its strain gauges and a strip chart recorder produce a force-time curve from which a texture profile analysis (TPA) can be derived. Several years later, Bourne adapted the Instron Universal Testing Machine for TPA studies (Bourne, 1968), and the first studies of cheese with this instrument soon followed (Shama and Sherman, 1973a, 1973b). Theoretical analyses may be difficult when using imitative tests due to the various motions and stresses involved (Voisey, 1976).

Fundamental tests measure rheological properties such as viscous and elastic moduli, with the intention of relating the nature of the specimen to basic rheological models. Specimens used in these experiments are of a specific shape and are deformed in a specific manner; therefore, all of the test parameters are known, the results can be analyzed systematically, and predictions are more readily made. The earliest fundamental tests of cheese were performed in the 1930s when Davis compressed cylinders of four types of English cheese under constant load (Davis, 1937). These force-compression tests are the forerunners of much of the serious cheese rheology research in recent years. Scott Blair and his colleagues performed a great deal of fundamental work on cheese and other foods, emphasizing viscoelastic properties, which led to an increase in applications of rheological theory to food analysis (Bagley and Christianson, 1987).

METHODS USED

Fundamental Experiments

Force-Compression

Cheese presents classic viscoelastic behavior, that is, somewhere between the response of a viscous material and an elastic material. The theories behind fundamental measurements are covered by Collyer and Clegg (1988), with applications to food being described by Shoemaker, Lewis, and Tamura (1987) and Bagley and Christianson (1987). In fundamental rheological tests of cheese, there are several parameters that are measured, and several others that are calculated from them. The *stress* σ applied to a small sample, typically, a cylinder, is defined as the force per unit area of the specimen. Stress applied in a downward direction is known as *uniaxial compression.* The deformation resulting from uniaxial compression will cause a slight bulging of the specimen, and the original height of the sample h_0 will be changed by an amount Δh. The change $\Delta h / h_0$ is defined as *engineering strain*, a simplification of the more widely used *Hencky strain in compression*, defined by $-\ln (h/h_0)$ (Ward, 1971; Chatraei, Makosko, and Winter, 1981).

During force-compression tests, one usually lubricates the sample–platen interface to minimize frictional effects. The stress σ_L (the subscript L refers to the lubricated condition) at a strain $\epsilon = \Delta h / h_0$ is calculated on the assumption that a cylinder of original radius r_0 and height h_0 will be deformed to a cylinder of radius r and height h. Assuming no volume change occurs,

$$\pi r_0^2 h_0 = \pi r^2 h,$$

and the resulting stress is given by

$$\sigma_L = \frac{F}{\pi r^2} = \frac{F}{\pi r_0^2} \frac{h}{h_0}$$

where F is the total force applied to the sample. If the specimens are bonded to the platens, the sample cross-sectional area in contact with the platens is constant, and therefore the stress (when bonded) is given by

$$\sigma_b = \frac{F}{\pi r_0^2}$$

where the subscript b refers to the bonded state (Casiraghi, Bagley, and Christianson, 1985). Christianson, Casiraghi, and Bagley (1985) show that a modified form of an equation proposed by Gent and Lindley (1959) may then be used to compare bonded and lubricated results. This equation yields a corrected bonded stress

$$\sigma_{bc} = \sigma_b \left(1 + \frac{r_0^2}{2h^2}\right)^{-1}$$

Casiraghi, Bagley, and Christianson (1985) found that this relation is very satisfactory for Mozzarella cheese, up to about 60% deformation; the structure collapses above 60% in the bonded sample, invalidating the comparison. The aforementioned correction also gave good results in the case of Cheddar cheese under uniaxial compression before structural collapse, which occurred between strains of 0.4–0.8.

When the structure begins to break down, an inflection point appears in the *force-strain curve* (Fig. 8-1). Further along the curve, the structure collapses faster than the stress buildup. We define the stress at the point of fracture as the *yield point*.

Creep

Further experimentation that may be conducted to characterize cheese involves the application of a constant stress imposed suddenly at time zero and held constant thereafter; the resulting deformation strain is then measured as a function of time. The corresponding plot is called a *creep curve*. When the force is removed, strain decreases, producing a *recovery curve*. Recovery from this compression is known as *relaxation*. A typical *creep-relaxation curve* for Mozzarella is shown in Figure 8-2.

If the cheese behaves as a linear viscoelastic solid during the creep experiment, the creep strain ϵ_{xy} increases with time t, and is related to the stress σ by σ_{xy}

$$\epsilon_{xy} = J(t)\sigma_{xy}$$

where $J(t)$ is the *creep compliance function*. The subscript x refers to the direction of the perpendicular to the plane of the stress, and y refers to the direction of the stress component. It is possible to rearrange the creep compliance function into three parts, each of which corresponds to particular phases of creep: instantaneous deformation, retarded elastic deformation, and flow, that is,

$$J(t) = J_0 + J\Phi(t) + \frac{t}{\eta_3}$$

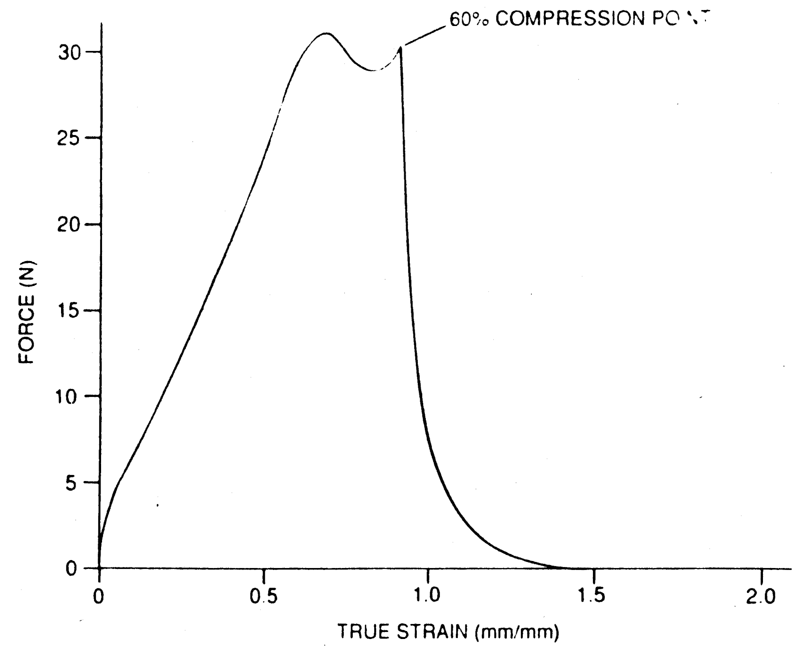
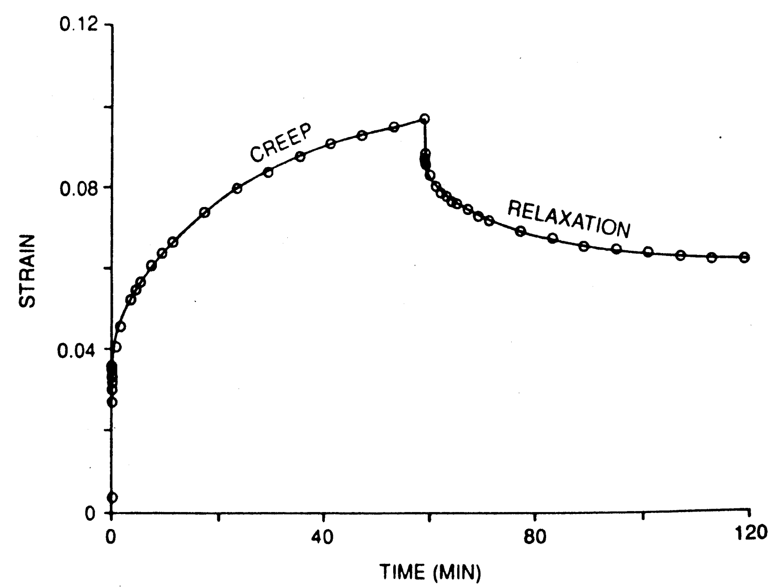


FIGURE 8-1 Force-strain curve of stirred curd Cheddar in uniaxial compression.



where J_0 is compliance at time zero. J is the *decay compliance*. $\Phi(t)$ is a *retardation function* with initial value $\Phi(0) = 0$ and final value $\Phi(\infty) = 1$, and η_3 is the coefficient of viscosity in steady flow.

It is frequently adequate to represent experimental cheese creep data by describing the viscoelastic behavior using mechanical models (Fig. 8-3*a* and *b*). These models are comprised of elastic springs, which obey Hooke's law, and viscous dashpots, which obey the Newtonian viscosity law. Although the simplest possible models consist of a single spring and dashpot in series (Maxwell model) or in parallel (Voight or Kelvin model), neither is normally suitable for yielding a reasonable prediction of the behavior of cheese during creep. However, combining the springs and dashpots into a four-element model (Fig. 8-3*c*) gives a reasonable representation of cheese behavior during creep experiments (Chang et al., 1986). The total deformation represented by this combination of Maxwell and Kelvin models is the sum of the deformation for each individual element:

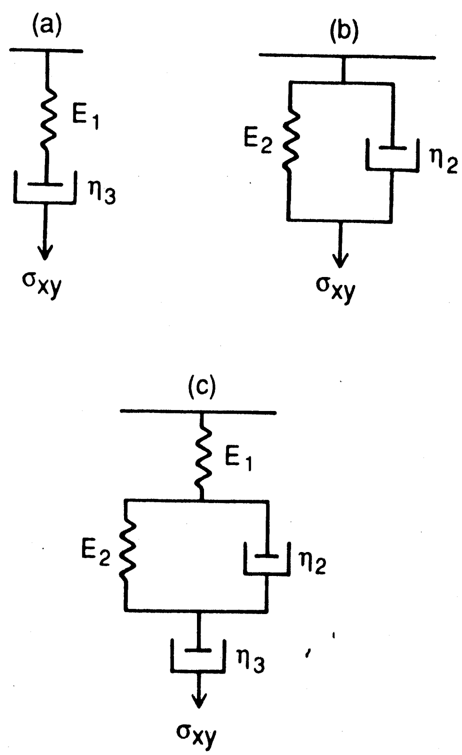


FIGURE 8-3 Mechanical models that describe viscoelastic behavior. (*a*) Maxwell model. (*b*) Voight or Kelvin model. (*c*) Four-element model.

$$\epsilon_{\text{total}} = \epsilon_1 + \epsilon_2 + \epsilon_3$$

where ϵ_1 is *instantaneous deformation*, ϵ_2 is *retarded elastic deformation*, and ϵ_3 is Newtonian flow (Lodge, 1964). Application of a stress σ_{xy} gives

$$\sigma_{xy} = E_1\epsilon_1 \qquad \text{(elastic)}$$

$$\sigma_{xy} = \frac{E_2\lambda d\epsilon_2}{dt} + E_2\epsilon_2 \qquad (\lambda = \text{retardation time, } \eta_2/E_2)$$

$$\sigma_{xy} = \frac{\eta_3 d\epsilon_3}{dt} \qquad \text{(Newtonian flow)}$$

where E_1 and E_2 are constants. Differentiation of these equations with respect to time and subsequent elimination of the individual strains leads to the general equation for the four-element model during constant imposed stress σ_0:

$$\ddot{\epsilon} + \frac{\dot{\epsilon}}{\lambda} = \frac{\sigma_0}{\lambda\eta_3}$$

with the complementary solution

$$\epsilon = C_1 + C_2 \exp\frac{-t}{\lambda}$$

and particular integral

$$\epsilon = \frac{\sigma_0 t}{\eta_3}$$

The constants C_1 and C_2 are determined from the conditions

$$\epsilon = \frac{\sigma_0}{E_1} \qquad \text{at } t = 0$$

$$\epsilon \to \frac{\sigma_0}{E_2} \qquad \text{as } t \to \infty$$

finally giving the general solution

$$\epsilon = \frac{\sigma_0}{E_1} + \frac{\sigma_0[1 - \exp(-t/\lambda)]}{E_2} + \frac{\sigma_0 t}{\eta_3}$$

or in terms of compliance

$$\epsilon = J_0\sigma_0 + J_e\sigma_0\left[1 - \exp\left(\frac{-t}{\lambda}\right)\right] + \frac{\sigma_0 t}{\eta_3}$$

the subscript e representing the equilibrium value. Chang et al. (1986) analyzed the plotted creep data as follows: at zero time, the strain gives E_1; the extrapolated curve at long times gives a straight line that yields η_3; and the difference between the extrapolated portion of the creep curve and the creep curve itself gives rise to a curve from which E_2, η_2, and λ may be determined by curve fit.

Stress Relaxation

As noted earlier, relaxation ensues when a force is removed at the culmination of a creep experiment. A satisfactory method for modeling the behavior of cheese during this period is to employ a number of Maxwell elements in parallel, combined with a free spring. Ward (1971) has shown that the differential equation relating stress and strain in the deformation of viscoelastic materials is

$$a_0\sigma + \frac{a_1 d\sigma}{dt} + \frac{a_2 d^2\sigma}{dt^2} + \cdots = b_0 e + \frac{b_1 de}{dt} + \frac{b_2 d^2 e}{dt^2} + \cdots$$

When one includes only one or two terms of this equation, there results an equivalence to the corresponding behavior of elastic springs and viscous dashpots, obeying Hooke's law and Newton's law respectively. For example, stress relaxation occurs during a constant rate of strain; hence, de/dt is zero, as are the higher order derivatives of the strain. Consequently, an exponential response (Bland, 1960) is observed:

$$\sigma = \epsilon_0\left(E_0 + \sum_{m=1}^{n} E_m \exp\frac{-tE_m}{\eta_m}\right) u(t)$$

where η_m/E_m is the *relaxation time* and $u(t)$ is the *unit step function*:

$$u(t) = 0 \quad \text{when } t < 0$$

$$u(t) = 1 \quad \text{when } t > 0$$

The summation is based on the number of Maxwell elements in parallel, and E_0 is a free spring corresponding to the equilibrium value as $t \to \infty$. Generally, two or three terms are necessary to represent the experimental data obtained during relaxation. When using the foregoing model, the corresponding coefficients, the "elasticities" and "viscosities," are obtained by a curve fit to the experimental data, and may be used to compare particular cheese characteristics.

Steady Shear

In steady shear experiments, the sample is subjected to a *constant shear* in a rotational rheometer. The viscometer is used with a very small gap thickness to ensure that the velocity field is *linear*, or nearly so; this considerably simplifies the experimental determination. Transient stresses vanish during steady shear flow and the steady-state stresses depend only on the rate of shear $\dot{\gamma}$. A viscosity function dependent on shear rate, $\eta(\dot{\gamma})$, can be defined in analogy to the Newtonian viscosity (Bird, Armstrong, and Hassager, 1987):

$$\sigma_{yx} = -\eta(\dot{\gamma})\dot{\gamma}_{yx}$$

Normal stress coefficients $Z(\gamma)$ and $B(\gamma)$ are related by the equations

$$\sigma_{xx} - \sigma_{yy} = -Z(\dot{\gamma})(\dot{\gamma}_{yx})^2$$

$$\sigma_{yy} - \sigma_{zz} = -B(\dot{\gamma})(\dot{\gamma}_{yx})^2$$

Z, B, and $\eta(\dot{\gamma})$ completely determine the stress state in steady shear flow, and are consequently called *viscometric functions* (Vinogradov and Malkin, 1980). The quantities Z and B are called the *first and second normal stress coefficients*.

The viscosity functions are usually measured initially when examining oils or soft cheeses. Particular instrumentation must be used for measuring the first and second stresses in order to completely characterize the stress state. The fixture holding the sample may be two round parallel plates, *a cone and plate* (with the angle of the cone being less than about 3°), or two concentric cylinders (a *Couette configuration*). One piece of the fixture—the lower plate, the cone, or a cylinder—rotates at a constant angular velocity while the other piece is stationary. The resistance of the specimen to the steady shear is measured by a transducer.

Parallel plates allow for samples of different thickness and for testing for sample slip. Cone and plate fixtures are useful for transient measurements such as stress relaxation and give a constant shear rate across the entire sample geometry. Dickie and Kokini (1982), for instance, measured shear stress and time-dependent flow of whipped cream cheese under steady shear with a cone and plate fixture. Concentric cylinders are best used for low-viscosity samples, such as cheese spreads.

Small Amplitude Oscillatory Shear

In *oscillatory shear* experiments, stress and strain vary *harmonically* with time. When stress and strain rates are small enough to stay within the linear range of viscoelasticity, the applicable mathematical equations are relatively simple. This type of technique is often described as *mechanical spectroscopy*, since it is analogous to other spectroscopic methods. Small-amplitude oscillatory shear measurements determine the transient response of a sample contained between two parallel plates separated by a distance h. The lower plate undergoes small-amplitude oscillations of frequency ω. The velocity profile is very nearly linear if

$$\frac{\omega\rho h^2}{2\eta_0} \ll 1$$

where ρ is the density and η_0 is the zero shear rate viscosity (Bird, Armstrong, and Hassager, 1987). During small-amplitude oscillatory shear measurements on cheese, the shear strain γ and shear rate $\dot{\gamma}$ are related by

$$\gamma = \mathring{\gamma} \sin(\omega t)$$

$$\dot{\gamma} = \mathring{\gamma}\omega \cos(\omega t)$$

where $\mathring{\gamma}$ is the amplitude.

The shear stress is *in phase* with the shear rate in Newtonian fluids, but not in cheese or most other foods. The stress of an ideally elastic material (Fig. 8-4) depends on the degree of deformation, which means that stress and strain are in phase. The stress of an ideally viscous material depends on deformation velocity; at maximum strain, the strain velocity is zero, since the oscillating system is changing direction. Therefore, stress and strain are 90° out of phase. This *phase angle*, δ, will lie between 0° and 90° in a viscoelastic substance. In the linear viscoelastic region the stress is related to the strain and a *frequency-dependent modulus M*:

$$\sigma = -M(\omega)\, \mathring{\gamma} \sin(\omega t + \delta)$$

where $0 \leq \delta \leq \pi/2$, and identically

$$\sigma = -M(\omega)\mathring{\gamma}\, [\sin(\omega t)\, \underline{\cos(\delta)} + \underline{\sin(\delta)}\, \cos(\omega t)].$$

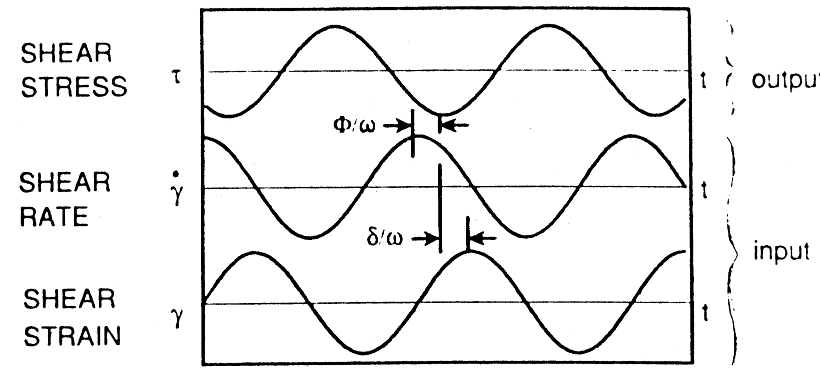
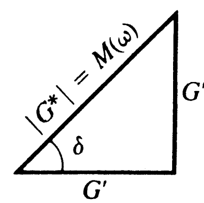


FIGURE 8-4 Waveforms describing small-amplitude oscillatory shear (based on Lodge 1964).

The phase angle δ may be expressed in terms of complex moduli, as shown below:



$$\cos(\delta) = \frac{G'}{G^*} \qquad \sin(\delta) = \frac{G''}{G^*} \qquad \tan(\delta) = \frac{G''}{G'}$$

leading to the equation

$$|G^*|^2 = (G')^2 + (G'')^2$$

The absolute value of the complex modulus G^*, which provides all of the information about the viscoelasticity of a sample, equals the maximum stress divided by maximum strain. The *elastic modulus* (or *storage* modulus) G' is $|G^*| \cos \delta$, and is a measure of the energy stored in the sample. The *viscous modulus* (or *loss* modulus) G'' is $|G^*| \sin \delta$, a measure of the energy lost as heat.

The viscosity coefficient may be determined in an analogous manner. The shear stress is related to the shear rate by

$$\sigma = -N(\omega)\dot{\gamma}$$

where $N(\omega)$ is a complex coefficient of viscosity. The *phase shift* Φ is related to the phase angle by

$$\Phi = \frac{\pi}{2} - \delta$$

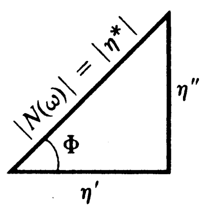
In turn,

$$\sigma = -N(\omega)(\dot{\gamma})^{\circ} \cos(\omega t - \Phi)$$

where $0 \leq \Phi \leq \pi/2$. The shear rate amplitude is $(\dot{\gamma})^{\circ}$, so identically,

$$\sigma = -N(\omega)(\dot{\gamma})^{\circ} [\cos(\omega t) \underline{\cos(\Phi)} + \underline{\sin(\Phi)} \sin(\omega t)]$$

As can be seen below:



$$\cos(\Phi) = \frac{\eta'}{|\eta^*|} = \frac{\eta'}{|N(\omega)|} \equiv \sin(\delta)$$

$$\sin(\Phi) = \frac{\eta''}{|\eta^*|} = \frac{\eta''}{|N(\omega)|} \equiv \cos(\delta)$$

and

$$\tan \Phi = \frac{\eta''}{\eta'} \equiv \cot(\delta)$$

leading to the equation

$$|\eta^*|^2 = (\eta')^2 + (\eta'')^2$$

which gives the relationship of the complex viscosity η^* to the component viscosities η' and η''. These viscosities are related to the storage and loss moduli by

$$G' = \omega\eta'' \quad \text{and} \quad G'' = \omega\eta'$$

and are the relationships most often used by cheese rheologists.

The theories behind viscoelasticity are thoroughly covered by Ferry (1980), Christensen (1982), Aklonis and MacKnight (1983), and Sperling (1986). The measurement of viscoelasticity is performed under *dynamic* conditions, with the specimen undergoing *sinusoidally oscillating* deformation. Photographs of an oscillatory shear rheometer are shown in Figure 8-5. A study of Mozzarella on this apparatus by Nolan, Holsinger, and Shieh (1989) included tests for slippage caused by milk fat diffusing to the specimen surface. Differences in stress waveforms with two different sample thicknesses at the same strain and frequency provide evidence for slip, which was eliminated by bonding the specimen to the plates with cyanoacrylate glue.

The linear viscoelastic range of a material may be found by measuring the moduli under varying strain while holding the frequency constant—a *strain sweep* (Fig. 8-6). Above this range, the structure of the sample breaks down. Information about the moduli at constant strain may be obtained by varying the frequency—a *frequency sweep*. The strain selected must be in the linear viscoelastic region.

Texture Profile Analysis

The theory behind the methods used in TPA has been reviewed by Voisey (1976), Voisey and deMan (1976), and Prentice (1987). The General Foods Texturometer was the first instrument that could produce texture profiles of food, but the Instron Universal Testing Machine has been the instrument of choice by most rheologists since it was first used to analyze food in 1968 (Breene, 1975).

In the General Foods Texturometer, a sample is placed on a flat plate (or a shallow dish if the sample is a liquid) and a plunger is brought down onto it. The plunger decelerates as it reaches the end of the compression stroke, stops, and then accelerates upward. This produces a *sinusoidal deformation* motion that closely approximates the action of the human jaw, but also causes the viscoelastic reaction of the sample to vary during the analysis (Voisey and deMan, 1976). A force-time curve is produced, but the variable speed prevents conversion to force-distance (Bourne, 1976). In the Instron machine, a crosshead is sent down a vertical column, causing a flat plate to deform a specimen that has been placed on a lower plate. The Instron reaches the end of the compression stroke at full speed, stops abruptly, and accelerates upward at full speed, producing sharper peaks than the Texturometer. In addition, the constant speed leads to both force-time and force-distance curves; the work done can then be calculated since work is a force-distance integral (Bourne, 1976). Photographs of an Instron are shown in Figure 8-7.

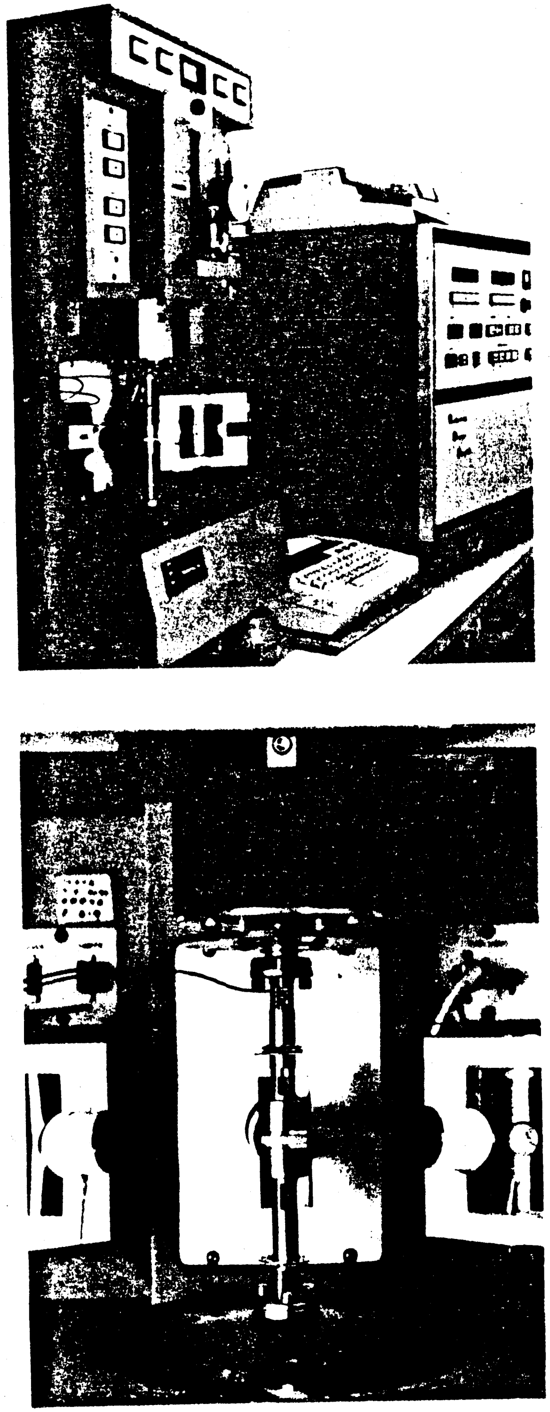


FIGURE 8-5 *Top:* Rheometrics RDA-700 oscillatory shear rheometer. *Bottom:* Cheese sample held between parallel plates.

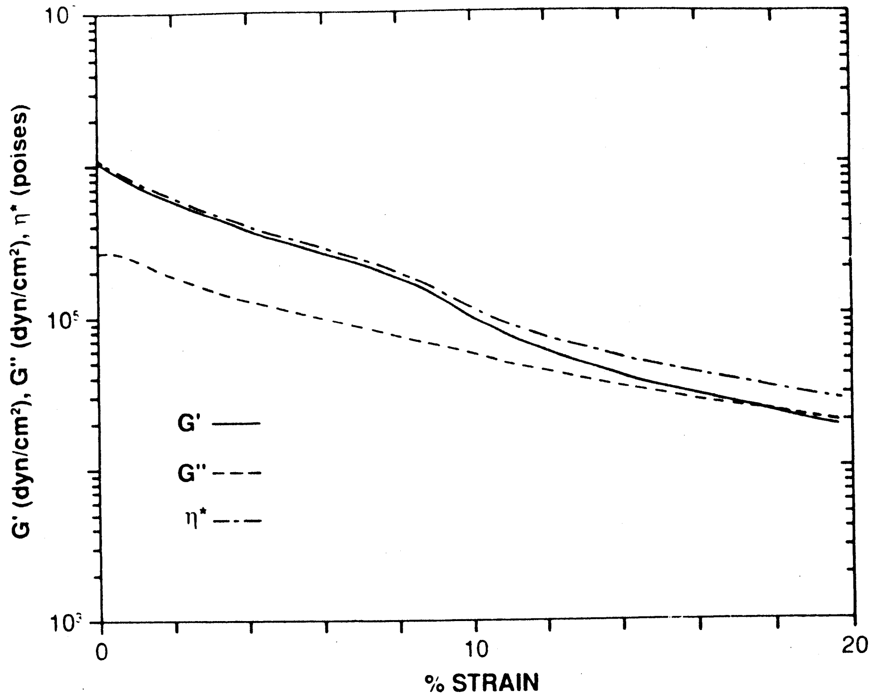


FIGURE 8-6 Strain sweep of Cheshire cheese aged 60 weeks.

Seven textural parameters have been extracted from the force–time curve obtained in TPA (Bourne, 1978):

1. *Fracturability* (originally brittleness), the force at the first significant break in the curve. The shoulder on the first peak in the curve in Figure 8-8 is the point to which fracturability is measured.
2. *Hardness*, the maximum force during the first compression cycle, or "first bite." This corresponds to the top of the first peak in Figure 8-8.
3. *Adhesiveness*, the force area of any negative peak following the first compression cycle (visible in Fig. 8-8). This variable represents the work required to pull the plunger or plate away from the sample.
4. *Cohesiveness*, the (dimensionless) ratio of the positive force area of the second compression to that of the first.
5. *Springiness* (originally elasticity), the height that the specimen recovers between the end of the first bite and the start of the second. In Figure 8-8, springiness is measured along the baseline from the start of the second peak

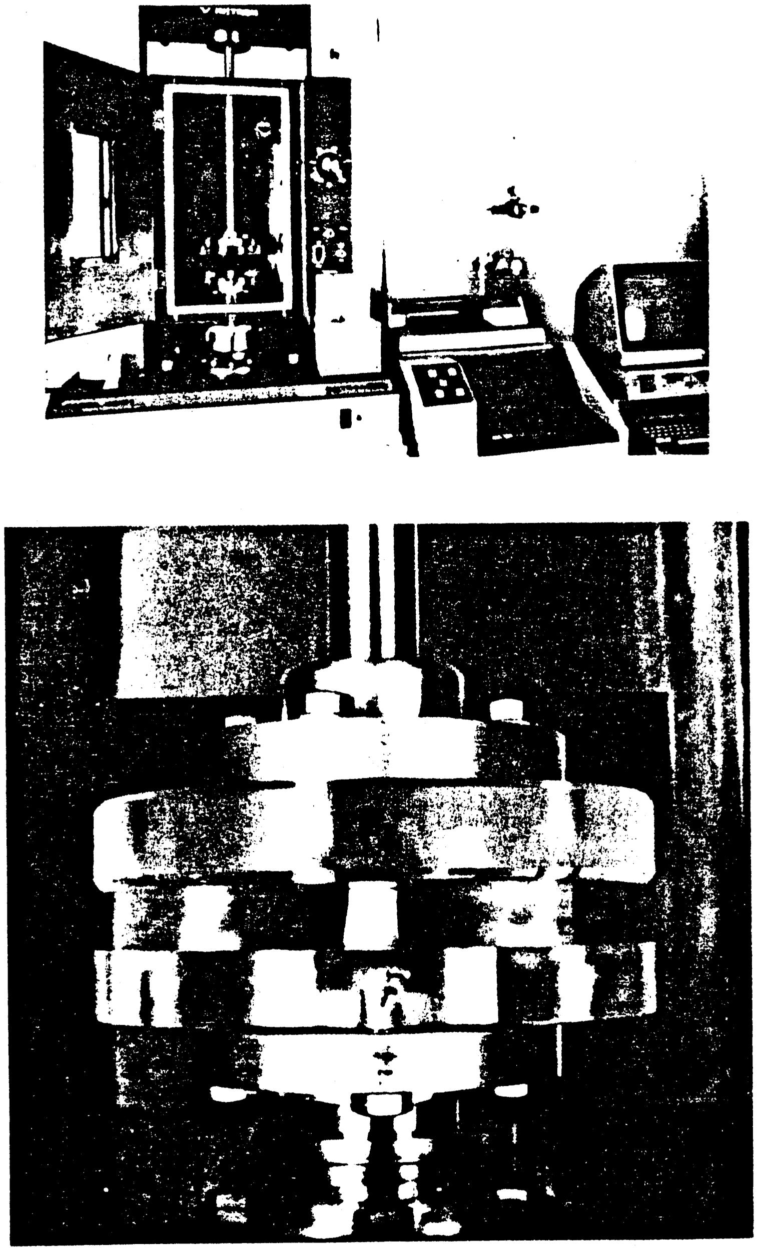


FIGURE 8-7 *Top:* Instron Universal Testing Machine. *Bottom:* Cheese sample held between plates.

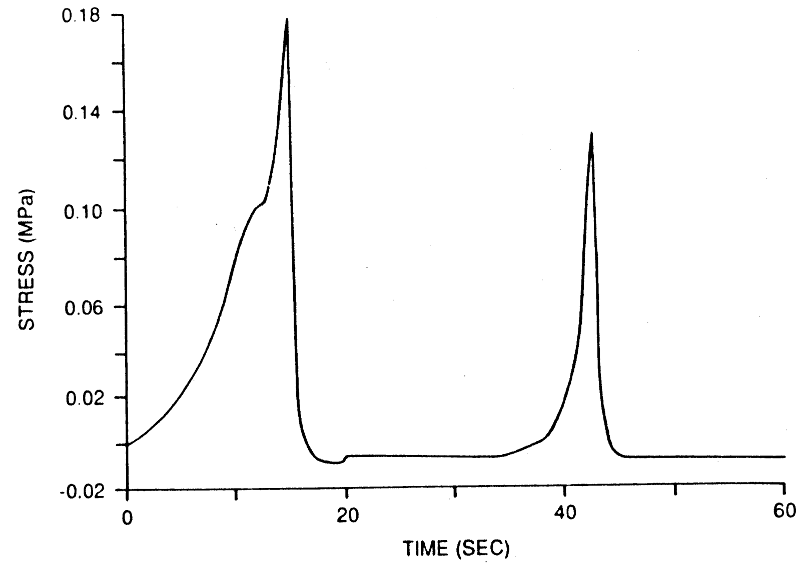


FIGURE 8-8 TPA curve of Mozzarella, obtained from an Instron instrument.

to the spot directly under the top of the peak. The measurement is then converted from seconds to units of length.

6. *Gumminess*, the product of hardness and cohesiveness.
7. *Chewiness*, the product of springiness and gumminess.

The Instron can also be used to measure stress relaxation, yield points, and other rheological parameters.

ANALYSES OF CHEESE VARIETIES

English Cheeses

Much rheological research has dealt with Cheddar and other English varieties of cheese, starting with Davis in the 1930s (Davis, 1937). He compressed cylinders of Cheddar, Cheshire, Lancashire, and Leicester under loads of 50, 100, and 200 g, and the resulting deformation-time curves were used to calculate moduli, viscosities, and relaxation times. Ball compressor tests on Cheshire and Cheddar were compared to graders' scores in a four-year study by Wearmouth (1954). More recently, force-compression tests using an Instron Universal Testing Machine have been run on Cheddar by several groups. Information obtained includes hardness, chewiness, springiness, and adhesiveness (Lee, Imoto, and

Rha, 1978); stress-strain relationships (Rosenau, Calzada, and Peleg, 1978; Casiraghi, Bagley, and Christianson, 1985); compression ratios (Imoto, Lee, and Rha, 1979); yield points (Dickinson and Goulding, 1980); and firmness and elasticity relationships with fat content (Emmons et al., 1980).

Creamer and Olson (1982) used an MTS Tensile Testing Machine to equate force-compression and yield point with casein proteolysis. They found that yield strain decreased linearly with the logarithm of days aged. Fedrick and Dulley (1984) used an Instron to determine that hardness and springiness decreased, and fracturability increased, with proteolysis. Amantea, Skura, and Nakai (1986) also compared ripening Cheddar samples with an Instron, finding that force-compression relationships are most affected by proteolysis, age, and type of starter culture.

An Instron compression test was used by Weaver, Kroger, and Thompson (1978) to determine toughness, hysteresis, stiffness, and degree of elasticity of Cheddar during ripening. Chen et al. (1979) attached a plunger to an Instron to penetrate samples (a "punch test"), and examined textural parameters of Cheddar and nine other varieties. Green et al. (1986) determined stiffness and work of fracture by cutting with a wire guillotine attached to an Instron. Nolan (1987) subjected stirred curd Cheddar to constant strain in an Instron and allowed the specimens to "relax," determining that a primary relaxation period occurred for 2 min, followed by a secondary period.

Fukushima, Taneya, and Sone (1964) obtained hardness data by slicing with a wire, yield stress by cone penetration, and other viscoelastic parameters by compression between parallel plates. Purkayastha et al. (1985) obtained a model of creep behavior of Cheddar using a homemade device.

Force-compression tests were used by Shama and Sherman (1973a, 1973b) to analyze Caerphilly, Double Gloucester, Lancashire, and White Stilton; by Carter and Sherman (1978) to analyze Leicester for firmness; and by Dickinson and Goulding (1980) to analyze yield points of Cheshire and Leicester. Green, Marshall, and Brooker (1985) compared ball compressor results for Cheddar and Cheshire to sensory panels.

Tunick et al. (1990) compared the viscoelastic properties of Cheddar and Cheshire with a *Rheometrics Dynamic Analyzer*. A straight line that followed the Arrhenius equation was obtained by plotting complex viscosity versus reciprocal of temperature at constant strain and frequency. The slope of the line was proportional to the activation energy, which was substantially different for the two varieties of cheese.

Italian Cheeses

The Instron has been used to examine Mozzarella hardness, chewiness, springiness, and adhesiveness (Lee, Imoto, and Rha, 1978); compression ratios (Imoto, Lee, and Rha, 1979); and stress-strain relationships (Casiraghi, Bagley, and Christianson, 1985). Smith, Rosenau, and Peleg (1980) measured flowability of melted Mozzarella with a piston-driven capillary rheometer. Taranto and Yang (1981) and Yang and Taranto (1982) obtained texture profiles from imitation Mozzarella cheese made from soybean oil. Cervantes, Lund, and Olson (1983) used an MTS Tensile Testing Machine for compression and deformation tests on Mozzarella. Nolan, Holsinger, and Shieh (1989) determined shear moduli and Arrhenius relationships of natural and imitation Mozzarella using a Rheometrics Dynamic Analyzer. Izutsu et al. (1990) determined apparent viscosity, relaxation time, and other parameters for Mozzarella as they relate to stretching of the curd.

Tunick et al. (1991) ran TPA on Mozzarella, varying fat content, moisture content, and type of storage. Hardness, gumminess, and chewiness all increased, and springiness decreased, when the fat or moisture contents were lowered. The same textural parameters were higher in one-week-old samples than in six-week-old or frozen samples, due to proteolysis.

Masi (1989) ran compression–relaxation tests on Galbanino cheese, and determined relaxation rate constants on seven other Italian cheeses. Masi and Addeo (1984) ran compression, stress relaxation, and TPA on Caciocavallo, Caciotta, Mozzarella (buffalo and cow milk), Provoloncino, Salamino, and Silano using a General Foods Texturometer. Casiraghi, Lucisano, and Pompei (1989) studied texture profiles of Grano Padino, Italico, Montasio, Pecorino, and Sbrinz.

Dutch Cheeses

Force-compression tests of Edam and Gouda were performed with an Instron by Shama and Sherman (1973a), who also investigated the stress relaxation characteristics of Edam (1973b). DeJong (1976) found that the firmness of Meshanger, as measured by the Instron, was related to breakdown of α_{s1}-casein to the α_{s1}-I peptide. Firmness of Gouda was evaluated by Instron force-compression tests by Culioli and Sherman (1976), who noted that samples near the edge of a block may require twice the stress for failure as samples at the center due to moisture gradients. Stress relaxation of Gouda was examined by Goh and Sherman (1987). Luyten (1988) used an Overload Dynamics material testing instrument to determine viscoelastic and fracture properties of Gouda as they varied with composition and aging. Fukushima, Taneya, and Sone (1964) analyzed rheological properties of Gouda in the same manner as they did with Cheddar.

French, German, and Swiss Cheeses

Compression and relaxation studies of Camembert were performed with an Instron by Mpagana and Hardy (1985, 1986). Yield point, deformation, and relaxation characteristics of Camembert and St. Paulin were examined with an Instron by Kfoury, Mpagana, and Hardy (1989). Several commercial acid-type French cheeses were analyzed for apparent viscosity and strain with a coaxial cylinder viscometer (Korolczuk and Mahaut, 1989), and for stress relaxation with a cone penetrometer (Korolczuk and Mahaut, 1990). Molander, Kristiansen, and Werner (1990) ran compression tests on Brie.

Eberhard and Flückiger (1981) differentiated between Appenzell, Emmental, Gruyère, Sbrinz, and Tilsit by examining their force-deformation curves with an Instron. Eberhard (1985) determined compression strength, deformation, and elasticity of Emmental as it aged. Lee, Imoto, and Rha (1978) and Imoto, Lee, and Rha (1979) ran force-deformation tests on Muenster and Swiss.

Cottage and Cream Cheeses

The textural evaluation of soft cheeses has been primarily by empirical means. An Instron was used to measure textural parameters by Lee, Imoto, and Rha (1978) and Imoto, Lee, and Rha (1979). An Instron was adapted to measure firmness of cottage cheese by Perry and Carroad (1980). Hori (1982) used a TOM compression testing machine to determine yield point data, stiffness, and deformability of cream cheese after freezing and thawing the curds. Dickie and Kokini (1982) measured shear stress under steady shear of whipped cream cheese.

Other Cheeses

Chen and Rosenberg (1977) devised a model simulating the yield behavior of American cheese using Instron data. Textural parameters of American cheese samples were examined by Lee, Imoto, and Rha (1978) and Imoto, Lee, and Rha (1979) using an Instron. Campanella et al. (1987) obtained an indication of American cheese meltability by compressing melting samples in an Instron and measuring elongational viscosity. Chang et al. (1986) developed a college laboratory experiment in which the viscoelasticity of processed cheese, especially in creep, was measured. Marshall (1990) measured work of fracture of processed cheese analogues by using a wire guillotine in an Instron in the same manner as Green et al. (1986). Fukushima, Sone, and Fukada (1965) determined viscosity and dynamic elastic moduli of processed cheese using a viscometer.

THE FUTURE

The factors affecting the rheological properties of cheese must be known if acceptable new products are to be developed. Many of the rheological tests that are performed in the cheese industry are empirical in nature, and more reliable data are needed along with standardized testing methods. Difficulties in obtaining representative samples from crumbly cheeses, such as Cheshire, or cheeses with eyes, such as Swiss, will have to be overcome. At present, there is no method capable of analyzing all of the parameters responsible for texture and mouthfeel of food. When such a technique is developed, rheological analyses will accurately predict the quality of cheese while providing insight into the chemistry of this popular food.

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