Development of Rheological Test Methods for Cheese

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Rheological analysis of cheese can aid in prediction of textural quality while providing insight into the chemistry of this popular food

☐ THE RHEOLOGICAL characterization of cheese is important as a means of determining body and texture for quality and identity as well as a means of studying its structure as a function of composition, processing techniques, and storage conditions. Since rheology deals with the deformation and flow of matter, this characterization, when done instrumentally, is essentially a measurement of the mechanical properties of the cheese under various conditions. Like most solid foods, cheese is viscoelastic in nature, meaning that it exhibits both solid (elastic) and fluid (viscous) behavior. Energy dissipation, by means of the viscous portion, may be related to flow of the matrix, flow of liquid through the matrix, or relative movement of material elements causing friction (Luyten, 1988).

The major structural component of cheese is a continuous protein matrix, but the contribution of milkfat to product quality is significant. Reduction of milkfat content by 50% or more in Cheddar-type cheeses results in unacceptable flavor and physical properties (Olson and Johnson, 1990). With increased demands for "light" cheeses that simulate the traditional full-fat cheese products, evaluation by rheological methods has assumed even greater importance.

The ultimate goal of rheological research on cheese is the correlation of measured textural or mechanical properties with sensory characteristics. The goal of this review is to discuss both historical and modern rheological evaluations of various cheeses.

Development of Methodology

A variety of types of tests have been developed for measuring texture:

• **Empirical and Imitative Tests.** With the introduction of advanced instrumentation, rheological characteristics of cheese are now measured on a routine basis. Rheological investigations, however, have been conducted for more than 50 years, with most of the early work being empirical tests. Firmness and elasticity, for example, were evaluated by means of the cheese grader's thumb pressed on the surface of the cheese. The readiness of Cheddar curd for cutting was determined by the "cheesemaker," using a dairy thermometer to cut through the set curd. The development of simple instruments followed. These instruments had in common five components: (1) a means of mechanically deforming the cheese, (2) a means of recording the force, (3) a means of recording the deformation, (4) a means of measuring time during deformation, and (5) a test cell to hold the sample (Voisey, 1971). The grader's thumb was replaced by a ball compressor; its hemisphere was pressed into the surface of a cheese sample and the depth of penetration and recovery time were recorded (Caffyn and Baron, 1947).

A penetrometer was developed that provided force measurements as a needle was pushed into the cheese; results were similar to those obtained by the ball compressor (Prentice, 1987). The Cherry Burrell Curd Tension Meter (Emmons and Price, 1959), measured resistance to the passage of a wire through the curd or block of cheese. The major disadvantage of these tests was the influence of local variations and the need for multiple measurements to obtain a representative average value (Tunick and Nolan, 1991).

The first instrument to examine texture by imitation of the chewing of food, the Volodkevich bite tenderometer, was developed in the 1930s. The denture tenderometer, developed at Massachusetts Institute of Technology in the mid-1950s, contained motorized dentures and strain gauges (Proctor et al., 1955). The General Foods Texturometer appeared in the 1960s; this device cyclically compressed a bite-sized sample to 25% of its original height, thereby imitating jaw movement. Strain gauges and a strip-chart recorder produced a force–time curve from which a Texture Profile Analysis (TPA) could be derived (Friedman et al., 1963; Szczesniak et al., 1963). Bourne (1968) adapted the Instron Universal Testing Machine for TPA studies, and Shama and Sherman (1973a, b) published the first studies of this instrument with cheese.

• **Fundamental Tests.** The development of fundamental tests, those relating the nature of the food to basic rheological models, began in the 1930s, when Davis (1937) compressed cylinders of four types of English cheese under a constant load. These force–compression tests and the work of Scott Blair and Baron (1949) and Scott Blair (1958) led to significant increases in the application of rheological theory to food analysis (Bagley and Christianson, 1987).

• **Force–Compression.** Compressive deformation is frequently used in the textural evaluation of cheese, primarily because of its simplicity. In this test, a cheese sample (usually a cylinder of known dimensions) is compressed at a constant rate between two rigid plates, or platens, and the force and time recorded. The change in height resulting from the compression, when expressed as a proportion of the original height ($\Delta h/h_0$), defines the engineering strain and is a simplification of the more widely used Hencky strain ($-\ln \Delta h/h_0$). Stress is expressed as the force applied per unit of contact area. To reduce the effects of friction, minimize sample barreling and obtain more reproducible results, the sample–platen interface is usually lubricated (bonding is an alternate approach for eliminating friction).

Casiraghi et al. (1985) evaluated the behavior of Mozzarella, Cheddar, and processed cheese spread using lubrication and bonding with a cyanoacrylate ester adhesive and determined stress–strain relationships for both conditions. Plots of the stress for bonded and lubricated samples vs strain showed agreement that was dependent on cheese type.

A typical force–strain curve for Cheddar cheese undergoing uniaxial compression (force parallel to longitudinal axis of the cylinder) is shown in Fig. 1. When the structure begins to fail, an inflection point appears in the curve. As application of the force continues, the structure breaks down faster than the stress buildup. The stress at the point of fracture is the yield point. Force–compression relationships must be converted to stress–strain curves, since it is the shape of the stress–stain relationship that in principle represents the material properties.

• **Creep.** Imposing a stress at time zero and holding it constant thereafter are the necessary mechanisms for measuring creep compliance. The resultant

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curve shows strain as a function of time. In many cases, creep experiments are accompanied by a recovery test, in which the load is removed and the restoration or relaxation of the sample is measured. A typical creep curve for Mozzarella cheese is shown in Fig. 2. When the data are presented as strain per unit stress, the terminology creep compliance is used.

• **Stress Relaxation.** Stress relaxation may be described as the ability of a cheese to reduce an imposed stress over time at a constant strain or deformation. In ideal elastic bodies, all the energy is invested in the deformation and there is no relaxation. This behavior is Hookean and is mechanically spring-like. Ideal viscous bodies cannot maintain any stress in the absence of motion and will relax instantaneously. Mechanically, this behavior is Newtonian and is represented by a dash-pot. Mathemataical models describing this composite behavior using the spring/dash-pot concept in series (Maxwell model) or in parallel (Kelvin model) have been developed (Mohsenin, 1970; Shama and Sherman, 1973b). Strains must be of a sufficiently small magnitude, however, to ensure that measurements are made in the linear viscoelastic range for these models to be easily applied.

Stress relaxation curves are usually fit to exponential decay equations. To simplify these calculations, Peleg (1979) suggested an introspective empirical method in which the relaxation curves are normalized with respect to the initial force. Nolan (1987) modified this equation to present a linear relationship, but with the normalized force and time variables written as reciprocals, as shown for Cheddar cheese in Fig. 3. Applying this relationship to stirred-curd Cheddar cheese over a 14-mo storage period, he was able to identify two relaxation periods in curves generated through compression and subsequent relaxation using an Instron machine. There was a primary relaxation of about 2 min, followed by a secondary period. The secondary relaxation rate was substantially slower than the first, thereby providing a more sensitive tool for comparing aging effects in stored cheeses, especially when coupled with electrophoretic analysis.

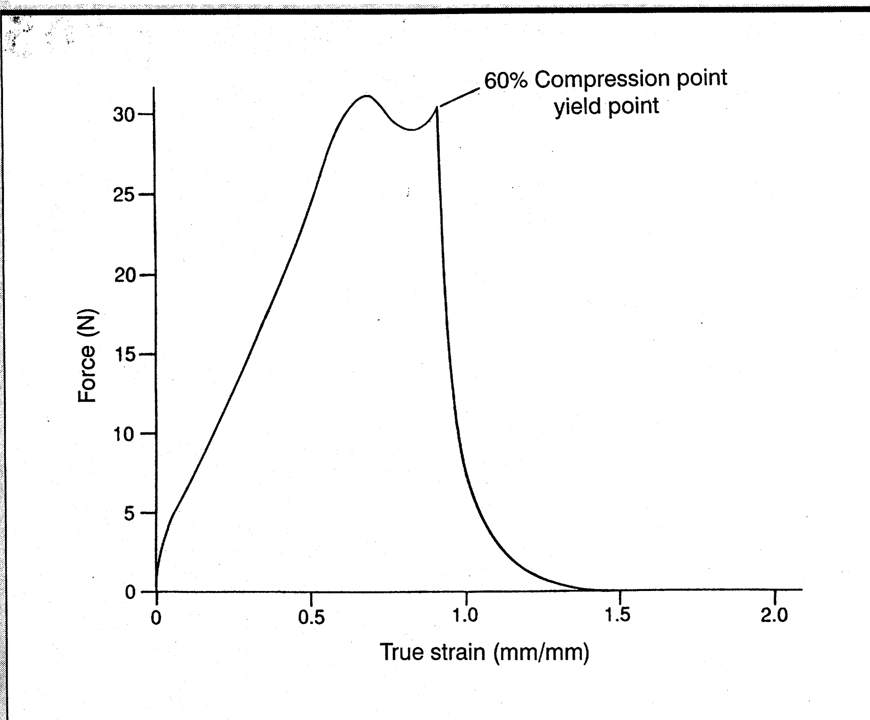

Fig. 1—**Force-Strain Curve** *of stirred curd Cheddar cheese in uniaxial compression*

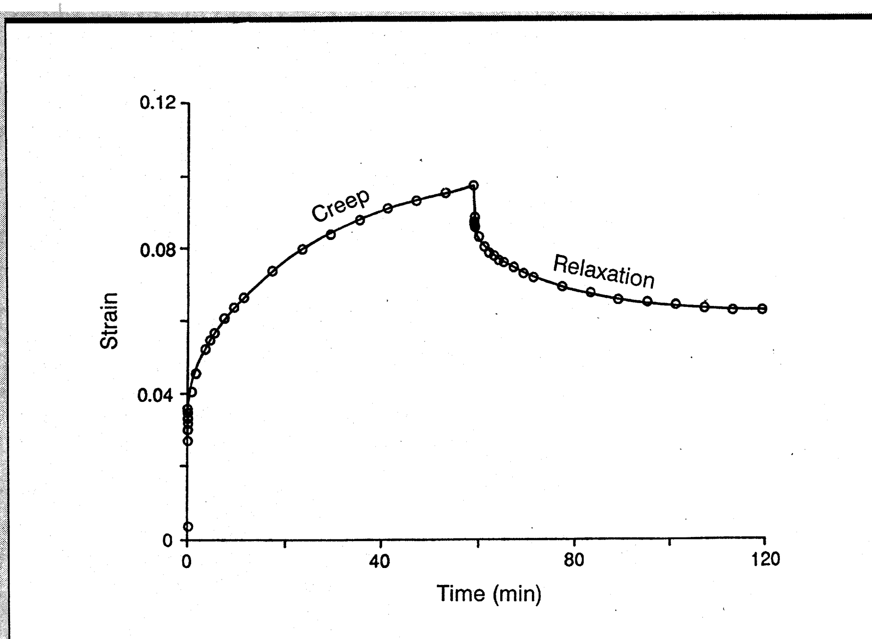

Fig. 2—**Creep-Relaxation Curve** *of Mozzarella cheese*

• **Small-Amplitude Oscillatory Shear.** The measurement of dynamic mechanical properties of food is a relatively new technique and has only recently been applied to cheese. Dynamic testing offers very rapid results with minimal chemical and physical changes. Mechanical properties such as Young's modulus may be determined at various frequencies and temperatures within a short time. Another advantage is the use of extremely small strains (usually within 1%) imposed on the sample; this assures linear stress–strain behavior and applicability of mathematical models.

In small-amplitude oscillatory shear experiments, the sample is contained in two parallel plates and undergoes sinusoidally oscillating deformation as the lower plate is rotated at a specified frequency and transient responses are recorded. The stress and strain vary harmonically with time.

The stress of an ideal elastic material depends on the degree of strain or deformation, which means that the stress and strain are in phase. For an ideally viscous material, the stress depends on strain velocity at maximum strain (which is zero, since the system is changing direction at this point). This means that stress and strain are 90° out of phase. In a viscoelastic material such as cheese, the phase angle δ will lie between 0 and 90°. This phase angle may be expressed in terms of the complex moduli as follows:

$$\cos \delta = G'/G^* \quad (1)$$

$$\sin \delta = G''/G^* \quad (2)$$

where G' is the elastic (or storage) modulus. G'' is the viscous (or loss) modulus, and G^* is the complex modulus. The absolute value of G^* equals the maximum stress divided by the maximum strain and provides information relative to the viscoelasticity of the sample. The coefficient of viscosity η is determined in an analogous manner.

Application to Cheese

In our laboratory, small-amplitude oscillatory shear has been used to study the viscoelastic properties of various cheeses. Nolan et al. (1989) studied the properties of low-moisture, part-skim-milk Mozzarella cheese, both natural and imitation. Measurements were made with an RDA 700 Dynamic Analyzer (Rheometrics, Inc., Piscataway, N.J.) in a parallel-plate configuration. In this study, sample slippage due to migration of milkfat to the sample surface required bonding the sample to the plates with cyanoacrylate resin. Dynamic viscosities and shear viscoelastic moduli were measured at temperatures up to 70°C and frequencies from 0.10 to 100 rad/sec. Imitation cheeses were made by adding 1 or 2% of calcium caseinate by weight of fluid milk to fresh raw milk before pasteurization. Viscosity (in Poise) of the imitation cheese proved sensitive to added calcium caseinate and followed an Arrhenius relationship with temperature. For imitation cheese with 1% added calcium caseinate, the relationship was:

$$\eta = 0.032\, e^{4100/T} \qquad (3)$$

where T = absolute temperature and η = coefficient of viscosity. The corresponding correlation with imitation cheese containing 2% added calcium caseinate was:

$$\eta = 0.005\, e^{4750/T} \qquad (4)$$

Addition of 1% calcium caseinate during processing increased viscosity by 30% at room temperature; addition of 2% calcium caseinate increased viscosity by about 50%.

The viscoelastic shear modulus (the ratio of shear stress to shear strain) is frequency dependent; the addition of 1% calcium caseinate increased the elastic and viscous moduli over the corresponding values of natural Mozzarella cheese at room temperature, whereas addition of 2% decreased the shear storage modulus G′ below that observed for natural Mozzarella under the same conditions. This effect may be related to non-uniform distribution of fat globules in the imitation cheeses. This has been shown to reduce the thermal stability of the imitation cheese (Tunick et al., 1989) and could have a similar effect on the viscoelastic modulus. The changes in the properties observed can help distinguish between natural and imitation Mozzarella cheese.

Nolan et al. (1990) compared some properties of Cheddar and pasteurized process American cheese by this technique. Experimental data showed that both cheeses exhibited nonlinear strain behavior at 100 rad/sec except within a narrow maximum-strain range of 0.55–0.70%. The viscosity of both cheeses followed an Arrhenius-type relation between 20 and 50°C; Fig. 4 shows a plot of the natural log of complex viscosity (ln η^*) of Cheddar cheese vs the reciprocal of absolute temperature at three different frequency values. A gradual decrease in "activation" energy E and a corresponding increase in pre-exponential factors occurred as the frequency increased from 1 to 100 rad/sec. The results suggested that the particular sample of Cheddar cheese studied, about 9 mo old, was crumbly and melted with difficulty.

Tunick et al. (1990) used this method to distinguish between Cheddar and Cheshire cheeses. Compositional differences between these cheeses are slight, so sophisticated methodology is necessary to prevent mislabeling. The results, shown in Table 1 for 20- and 60-week old cheeses, indicated that the viscosity and activation energy of Cheshire cheese decreased by about 20% from 20 to 60 weeks. The higher activation energy for Cheddar cheese at 60 weeks indicated that its body had broken down considerably less than that of the Cheshire cheese. Results suggested that commercially available Cheshire cheese would evidently have an activation energy much lower than that of Cheddar cheese of similar age, providing an approach to distinguish these types of cheeses from one another.

We are presently studying the effects of variations in fat and moisture content of Mozzarella cheese on its rheological properties. Tunick et al. (1991) conducted a TPA study of low-fat Mozza-

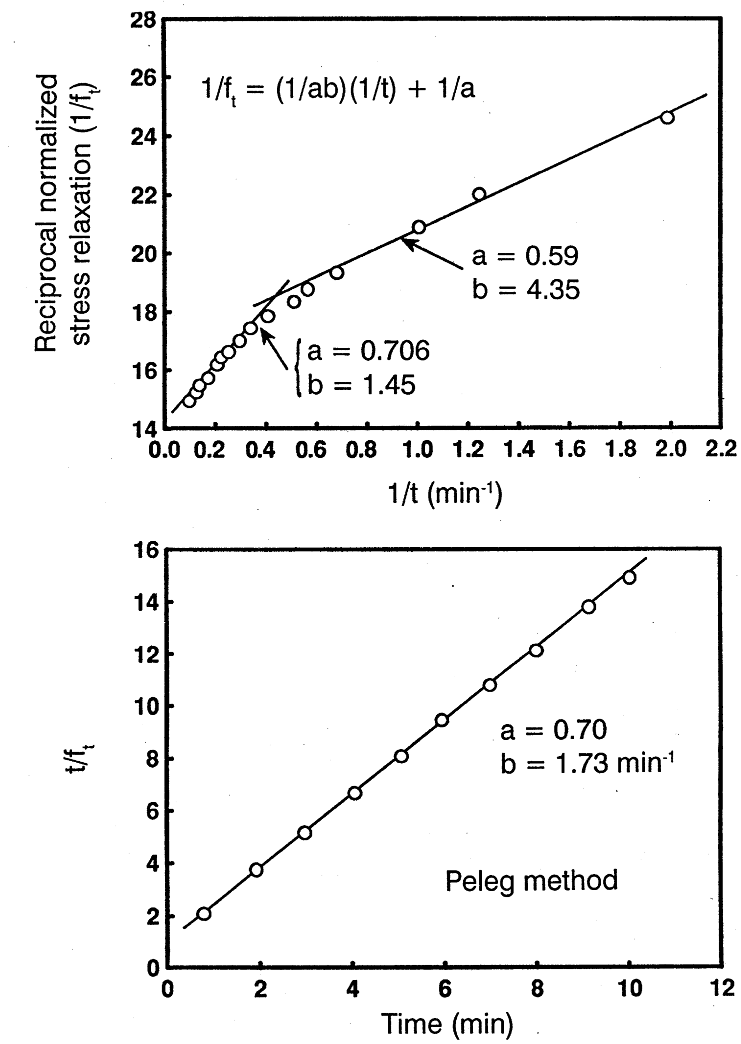

Fig. 3 A—**Reciprocal Baseline** *data-normalized stress relaxation* $(F_0 - F_t)/F_0$ *for stirred Cheddar curd; 6% compression. Stress level 0.322 kg/cm²; crosshead speed 50 mm/min; no treatment.* F_0 *= force at time zero;* F_t *= force at time t. Fig. 3B*—**Peleg Method**

rella cheese; a typical TPA curve is shown in Fig. 5. Reduced fat content resulted in higher values for hardness, springiness and cohesiveness, and reduced meltability. Reduced moisture content resulted in higher values for hardness and springiness and lower values for cohesiveness and meltability. However, after 6 weeks of refrigerated storage, low-fat (50% below the legal minimum of fat in dry matter), high-moisture samples had textural and meltability characteristics comparable to those of a full-fat, low-moisture Mozzarella. The lower cook temperature associated with the development of higher moisture in the finished cheese evidently promoted enzyme survival and subsequent proteolytic activity, resulting in a more desirable texture. We hope, by this approach, to gain greater insight into effects of varying composition and processing on texture to aid in the development of new reduced-fat cheese products.

Future Needs

Many different varieties of cheese have been subjected to some form of rheological analysis worldwide. Tunick and Nolan (1991) concluded their review by pointing out that for the future, we must have more reliable data along with standardized testing methods to aid in the invention of acceptable new cheeses. Difficulties in obtaining representative samples must be overcome, and new methods for analyzing more of the factors responsible for the texture and mouthfeel of cheeses must be developed. Meanwhile, rheological analysis can provide new information on the physics and chemistry of this popular food.

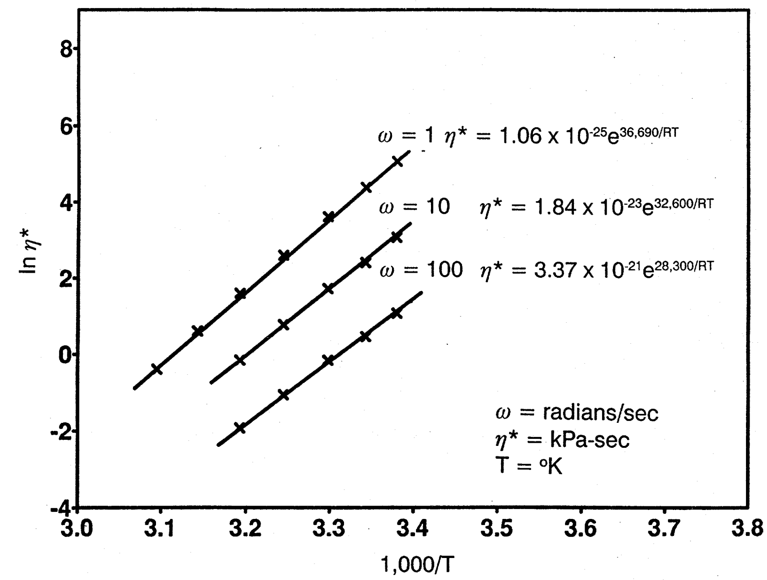

Fig. 4—**Variation of Natural Logarithm** *of the viscosity of Cheddar cheese with 1/T (° Kelvin)$^{-1}$; Strain = 0.68%*

Table 1—**Arrhenius Equations and Activation Energies** *(E_{visc}) of Cheddar and Cheshire cheeses of different ages*

Cheese sample	Equation	E_{visc} (cal/mole)
20-week Cheshire	$\log \eta^* = 5{,}331/T - 12.05$	24,400
60-week Cheshire	$\log \eta^* = 4{,}442/T - 9.20$	20,250
60-week Cheddar	$\log \eta^* = 7{,}156/T - 18.24$	32,750

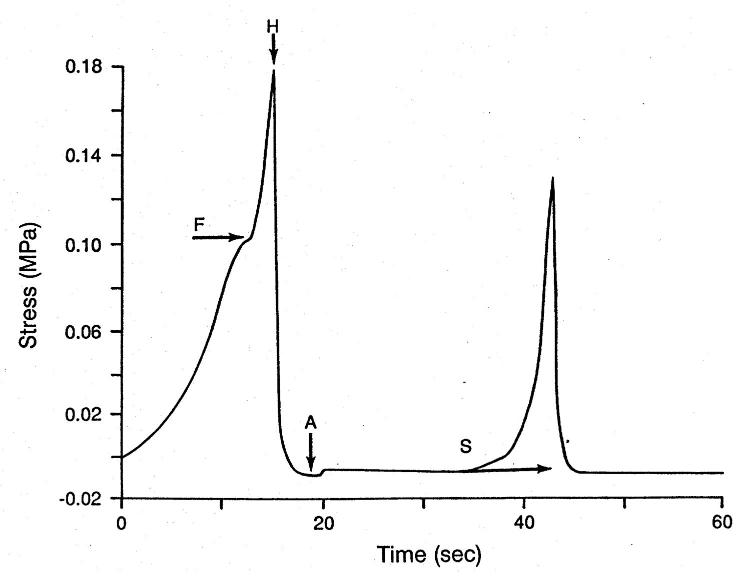

Fig. 5—**Texture Profile Analysis Curve** *of Mozzarella cheese, obtained from an Instron Universal Testing Machine. F = fracturability, the force at the first significant break in the curve; H = the maximum force during the first compression cycle or "first bite"; A = adhesiveness, the force area of any negative peak following the first compression cycle; S = springiness, the height that the specimen recovers between the end of the "first bite" and the start of the second; cohesiveness = the ratio of the positive force area of the second compression to that of the first; gumminess = the product of hardness and cohesiveness; and chewiness = the product of springiness and gumminess*

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