

Rheology for the food industry

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Abstract

Rheological measurements are quite relevant in the food industry as a tool for physical characterization of raw material prior to processing, for intermediate products during manufacturing, and for finished foods. There are several approaches to conduct these rheological characterizations, and the selected technique pretty much depend on the specific product and the functional characteristics in need to be analyzed. Several different types of equipments are available to scientists as a tool in food rheological studies leading to acceptable results in most design situations. This paper will focus on the review and discussion of some of the most relevant rheological tests of current interest to the food industry in selected examples, i.e. gels and emulsions.

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1. Introduction

The science of rheology has many applications in the fields of food acceptability, food processing, and food handling (Barbosa-Cánovas, Kokini, Ma, & Ibarz, 1996). Foods, however, are complex materials structurally and rheologically and, in many cases, they consist of mixtures of solids as well as fluid structural components (Finney, 1972).

Rheology concerns the flow and deformation of substances and, in particular, to their behavior in the transient area between solids and fluids. Moreover, rheology attempts to define a relationship between the stress acting on a given material and the resulting deformation and/or flow that takes place.

Rheological properties are determined by measuring force and deformation as a function of time. The difference between fundamental and empirical rheological

methods is that, unlike the latter, the former accounts for the magnitude and direction of forces and deformations, placing restrictions on acceptance of sample shapes and compositions. Fundamental tests have the advantage of being based on known concepts and equations of physics. Empirical methods are often used when sample composition or geometry is too complex to account for forces and deformations. These methods are of value if they correlate with a property of interest, whereas fundamental tests determine true physical properties.

Rheology is concerned with how all materials respond to applied forces and deformations. Basic concepts of stress (force per area) and strain (deformation per length) are key to all rheological evaluations. Stress (σ) is always a measurement of force per unit of surface area and is expressed in units of Pascals (Pa). The direction of the force with respect to the impacted surface area determines the type of stress. Normal stress occurs when the force is directly perpendicular to a surface and can be achieved during tension or compression. Shear stress occurs when the forces act in parallel to a surface.

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On the other hand, strain represents a dimensionless quantity of relative deformation of a material. The direction of the applied stress with respect to the material surface will determine the type of strain. Normal strain (ϵ) occurs when the stress is normal to a sample surface. Foods show normal strain when compressed (compressive stress) or pulled apart (tensile stress) (Nielsen, 1998).

Unique rheological properties of various foods have been reported and summarized in many publications (Rao & Steffe, 1992; Steffe, 1996; Steffe, Mohamed, & Ford, 1986; Weipert, Tscheuschner, & Windhad, 1993). However, published values for foods may not be accurate since factors such as variety, ripeness, processing methods, compositions, temperature, time, analytical assumptions, instrumental techniques, and analytical methods may influence rheological properties.

2. Rheological characterization of food gels

Some of the most popular foods, such as gelatin deserts, cooked egg whites, frankfurters, surimi based seafood analogs, and fruit jellies, can be considered gels. A gel is a solid-in-liquid colloid in which the solid phase forms a network structure that immobilizes the liquid and produces solid-like properties. A gel can also be described as a substantially diluted system that exhibits no steady state flow. The initial state can be a solution, dispersion, or suspension. Some food gels are formed irreversibly by cooking, while others like gelatin form reversible gels. Gelation arises either from chemical cross-linking by way of covalent reactions or from physical cross-linking through polymer-polymer interactions. The macromolecular substances responsible for network formation in food systems are primarily polysaccharides and proteins. The unifying property among these foods is that they are mostly fluids but respond as viscoelastic solids with a high degree of elasticity (Hamann, 1992; Hvidt & Heller, 1990; Nijenhuis, 1990). They usually fracture rather than flow when deformed. Fracture is inherent in sensory biting and mastication of foods so it is important to relate the fracture character of gels to their sensory texture.

Fracture properties are determined by deforming a sample to the point of abrupt mechanical yield (sometimes referred to as failure or ultimate properties). Deforming forces can be applied to gels during shear, compression, or tension. Shear changes the shape of a specimen but does not change volume. Tension tends to increase volume and compression tends to decrease volume. When compressive or tensile forces on a specimen are limited to a single direction they are termed 'uniaxial', differentiating them from forces causing bulk changes such as hydrostatic pressure (equal force per unit area applied perpendicularly to the specimen sur-

face at all points on the specimen surface), which changes the volume but not the shape of a specimen. Uniaxial tension or uniaxial compression can change both shape and volume.

There are methods for determining fracture properties of foods based on uniaxial compression, uniaxial tension, or torsion. Of these methods, uniaxial compression is the most commonly used method because it does not require attachment of the specimen to the testing machine and several suitable commercial machines are available to perform the test. Most machines capable of uniaxial compression testing can also be used to deform samples in uniaxial tension; however, tension requires a strong attachment of the specimen to the machine, which can be difficult with food samples. Torsional testing of fracture properties also requires a strong attachment of the material to the machine and, until recently, no commercially produced machine has been available specifically designed for torsion testing of food samples. Commercial availability of testing machines and minimal sample preparation have made uniaxial compression testing methods dominant in determining fracture properties. However, the limitations of uniaxial compression testing may make it advantageous in some situations to utilize methods that deform samples in tension or torsion.

During processing, manufacture, and consumption of food, these gelled systems are subjected to large deformations that may cause the food either to deform irreversibly or to fail in fracture. This calls for a profound knowledge of their mechanical properties, as well as appropriate quality control measurement systems (Pons & Fiszman, 1996). Traditionally, single point measurements such as "gel strength" have been used by suppliers and users to characterize gel systems. However, these single point measurements, often based on rupture tests, are not representative of the overall mechanical behavior of gels. Gels are differentiated from other structured network systems, in which small portions of solids are dispersed in relatively large proportions of liquid, by the property of mechanical rigidity or the ability to support shearing stress at rest. Gel, which consists mostly of fluid, has the remarkable ability to behave as a solid while retaining many characteristics of the properties of the fluid components (Mulvihill & Kinsella, 1987). To evaluate the rheological properties of gels many considerations should be taken into account; one is related to composition. For example, in the case of gels formed from protein-polysaccharide mixtures, they are dependent on thermodynamic and structural compatibility between both macromolecules. Depending on the experimental conditions, both macromolecules can gel separately in a single phase (mixed gel) or one of the macromolecules gels and the other component can be dispersed as a filler (filled gel) (Embola, Swanson, Barbosa-Cánovas, & Luedecke, 1996).

2.1. Classification of gels

Biopolymer gels can be classified based on the level of order of the macromolecule, both before and during the network formation: (1) gels formed from disordered biopolymers, such as carragenans, pectins, starch, gelatin, and (2) gel networks that involve specific interactions between denser and less flexible particles, such as thermally denatured globular proteins and aggregated proteins from enzymatic or chemical action. Also, based on the macroscopic behavior of gelled system, true gels are a consequence of the development of the three dimensional networks, and weak gels are characterized by a tenuous gel-like network that is easily broken when submitted to a high enough stress (Lopes da Silva & Rao, 1999).

Stress–strain tests are useful in studying the behavior of food gels and generally can be categorized as two types, small-strain testing and large-strain testing. Small-strain testing refers to deforming a sample when only a small percentage of the deformation is required to break the sample, which often is performed by fundamental tests. Large-strain testing refers to deforming a sample to the point of permanent structural change. Moreover, large-strain testing often yields information that correlates with sensory evaluation (Hamann & MacDonald, 1992).

2.2. Large-strain testing

2.2.1. Puncture test

This is one of the simplest methods to obtain a stress–strain curve. It is widely used in both solid and semi-solid foods. To perform the puncture test, a probe penetrates the sample to a required depth. The data can be interpreted in terms of gel strength, which results from the multiplication of force by the distance of the penetration (Fig. 1).

2.2.2. Uniaxial compression test

Similar to the penetration test, it can measure either the force needed to produce a given deformation or

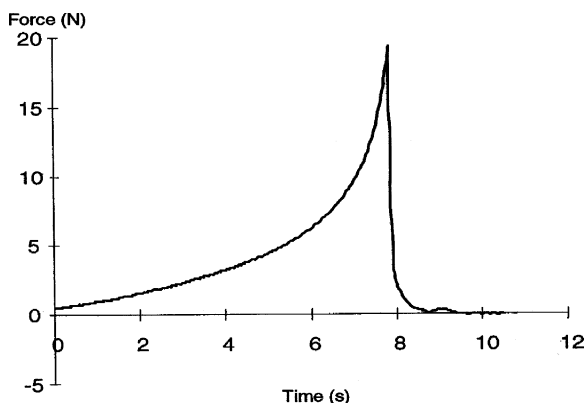


Fig. 1. Typical puncture curve of a surimi gel.

the deformation caused by a given force. The deformation of the test can be either a given point of deformation or a failure point of the gel. Most uniaxial compression tests are performed with a cylindrical sample. For example, in surimi samples, because the gel is a very deformable material; the uniaxial compression of a cylindrical specimen between parallel plates causes the gel height to decrease and the diameter to increase. Thus, the diameter length at which surimi gel can maintain stability during the uniaxial compression test is recommended as 1 (Lopes da Silva & Rao, 1999).

2.2.3. The torsion test

This is a method that applies shear stress to the sample in a twisting fashion. This is a convenient method to measure shear stress directly for the calculation of shear moduli. The advantages of this test are: (a) there is no change in the sample, thus the produced stress is “pure shear” and no geometric change is involved, (b) shear stress and strain are true values up to twist angles of about 45°, (c) material can fail in shear torsion, compression, or a combination mode, and (d) friction between the specimen and fixture can be neglected. Some limitations of this test are: (a) the torsion test requires a strong attachment of the specimen to the machine and (b) specimen shaping and preparation is usually more complex than that required for uniaxial compression (Hamann, 1992).

2.2.4. Folding test

This test can be used to measure the binding structure of gel, especially used in surimi gels, and can be interpreted in terms of cohesiveness. The folding test is conducted by slowly folding a 3-mm thick slice of gel in half, and then in half again to examine the structural failure of the surimi gel. The number of folds required to crack the surimi specimen is then scored from 1 to 5 and related in 5 classes designated AA, A, B, C, and D, which range from good to poor quality as related to the surimi gel’s cracking due to folding (NFI, 1991).

Compression, tension, and torsion tests can determine different values and patterns of gel fracture properties. One advantage of torsion testing is that the specimen is free to fracture along planes of maximum tension, maximum shear, or maximum compression. Another advantage is that neither the specimen volume nor shape changes, even at large strains, so that assumptions made in developing the stress and strain equations are valid for larger strain conditions.

2.3. Small-strain testing

2.3.1. Oscillatory test

Because gels are viscoelastic materials, dynamic rheological tests to evaluate properties of gel systems are well suited for studying the characteristics of gels as well as

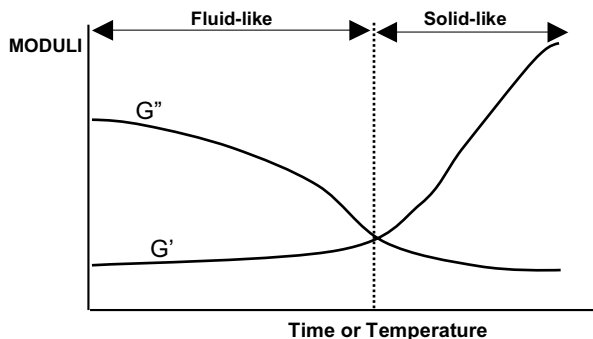


Fig. 2. Viscoelastic response of a material undergoing gelation.

gelation and melting (Fig. 2). From dynamic rheological tests in the linear viscoelastic range, the storage modulus, G' , and the loss modulus G'' , and $\tan \delta = (G''/G')$, the loss factor, can be obtained. G' value is a measure of the deformation energy stored in the sample during the shear process, representing the elastic behavior of a sample. In contrary, G'' value is a measure of the deformation energy used up in the sample during the shear and lost to the sample afterwards, representing the viscous behavior of a sample (Mezger, 2002). If G' is much greater than G'' , the material will behave more like a solid; that is, the deformations will be essentially elastic or recoverable. However, if G'' is much greater than G' , the energy used to deform the material is dissipated viscously and the material's behavior is liquid-like (Rao, 1999). On the other hand, the loss factor (or damping factor) reveals the ratio of the viscous to the elastic portion of the deformation behavior. A phase angle $\delta = 0^\circ$ or $\tan \delta = 0$ corresponds to an elastic response and $\delta = 90^\circ$ or $\tan \delta = \infty$ is a viscous response. If the phase angle is within the limits of $0 < \delta < 90^\circ$, the material is called viscoelastic (Schramm, 1994; Steffe, 1996; Mezger, 2002). Moreover, the complex viscosity $\eta^* = (G^*/\omega)$ is another useful parameter, where ω is the frequency of oscillation (rads^{-1}) and $G^* = \sqrt{(G')^2 + (G'')^2}$.

Three types of dynamic tests can be conducted to obtain useful properties of gels, gelation, and melting: (1) frequency sweep studies in which G' and G'' are determined as a function of frequency (ω) at fixed temperatures, (2) temperature sweep in which G' and G'' are determined as a function of temperature at fixed ω , and (3) time sweep in which G' and G'' are determined as a function of time at fixed ω and temperature (Lopes da Silva & Rao, 1999).

2.3.2. Stress relaxation test

In the stress relaxation test, an instantaneous deformation is applied to a body (Fig. 3). This can be done while in compression, extension, or shear. A level of strain is picked to maximize sensitivity and minimize

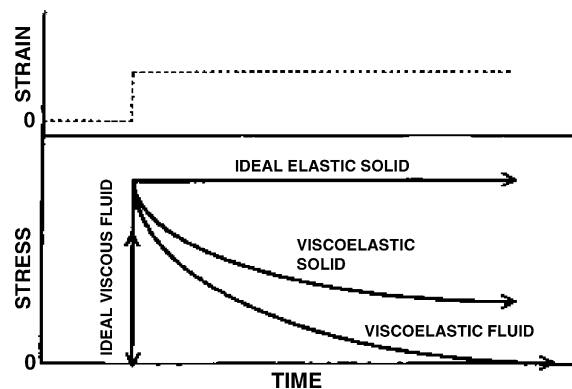


Fig. 3. Concepts of stress relaxation testing.

sample damage. Deformation or strain is maintained constant throughout the test while the stress is monitored as a function of time. For viscoelastic materials, this stress will decay to an asymptotic value. The equation for stress as a function of time is usually expressed as:

$$\sigma(t) = \sigma_e + (\sigma_0 - \sigma_e) \exp\left(\frac{-t}{\tau}\right), \quad (1)$$

where σ is the stress at the time t , σ_e is the equilibrium stress and τ is the relaxation time.

With a modified Maxwell model (Eq. (1)) the material can be described by three constant factors: initial modulus (σ_0), which is the first reading at maximum strain; equilibrium modulus (σ_e); and relaxation time (τ). The relaxation time constant is the time it takes for the stress to decay to $1/e$ or 36.8% of its initial value. Since $1/e = 0.368$, the relaxation time is found by determining the time corresponding to $\sigma = \sigma_e + (\sigma_0 - \sigma_e) \cdot 0.368$ (Nielsen, 1998).

2.3.3. Yield stress determination

Yield stress is another important rheological parameter for predicting the product's processing and/or end-use performance. The stress level required to initiate flow is usually referred to as yield stress and is related to the level of internal structure in the material, which must be destroyed before flow can occur. Quantifying yield stress, however, must be done carefully because the value obtained depends on the analytical technique used. Controlled stress rheology provides a more sensitive measure of apparent yield stress than controlled rate rheology because the variable of primary interest can be more carefully controlled. That is, in the controlled stress approach, it is possible to gradually increase the stress applied to the material; and detect the point at which movement (yield) first occurs (Semancik, TA Instruments, unpublished).

Harte, Clark, and Barbosa-Cánovas (submitted) reported that the determination of the yield stress offers the potential for manufacture of yogurt with targeted

firmness and viscosity properties as identified by consumer panels. Since yogurt is a non-Newtonian highly structured material and its characterization through the measurement of fundamental rheological properties is not an easy task, empirical or imitative methods, such as penetrometry tests, TPA, and Posthumus funnel, have been preferred in characterizing the textural properties of yogurt (Benezech & Maingonnat, 1994; Fiszman & Salvador, 1999; Hellinga, Somsen, & Koenaads, 1986; Skriver, Holstborg, & Qvist, 1999). However, the yield stress provided better detection of differences in firmness, thus requiring fewer samples, and was also considered a good predictor of the sensory firmness perceived by panelists (Fig. 4). Moreover, using the vane method, measurements are done in situ and, thus, there is no damage associated with sample handling; then the empirical apparent stress, after shearing, exhibits high correlation with the sensory viscosity perceived by panelists. It was also showed in assessing the firmness of yogurt that using yield stress required less time than required to run the samples, and no costs were associated with training and managing large panel groups to achieve adequate sensitivity (Harte et al., submitted).

On the other hand, a creep experiment can be used to compare and predict material behavior; here the stress is applied to the material and strain is monitored with time to establish an equilibrium yield stress. By running a series of creep experiments at different stress levels and plotting viscosity versus stress, the apparent yield stress is represented by the point of abrupt change in viscosity (Fig. 5). The viscosity drop for the salad dressing was not as sharp as for other products. This suggests that the structure resisting flow may be weaker and that the structure breakdown/formation process may follow significantly different kinetics than the other products

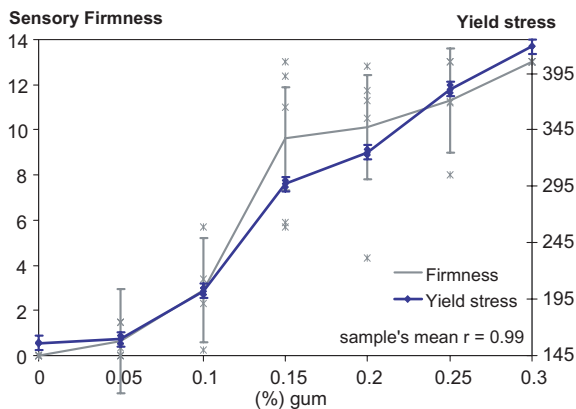


Fig. 4. Sensory firmness and yield stress of yogurts having selected gum concentration. Bars are 95% confidence intervals for the mean. Stars are individual panelist determinations and diamonds are yield stress replications.

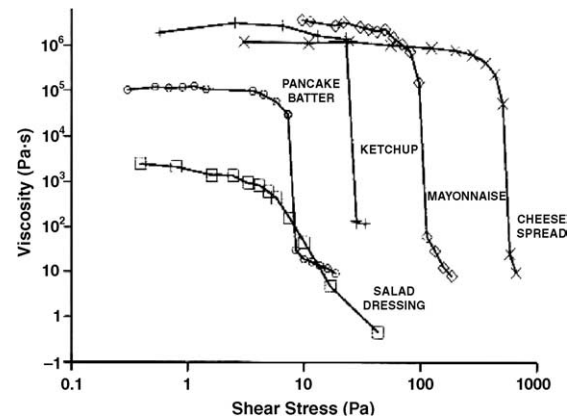


Fig. 5. The equilibrium yield stress through a creep experiments in a variety of food products.

(ketchup, mayonnaise, cheese spread and pancake batter) (Semancik, TA Instruments, unpublished).

2.3.4. Rheological characterization of time dependent fluids

One of the fundamental parameters, which characterize flow behavior of liquid and semi-liquid foods, is viscosity, which is an intrinsic parameter and a measure of a fluid's resistance to motion (flow) when a shearing stress is applied. The flow behavior of these foods under applied stresses classifies them as Newtonian or non-Newtonian, classification that is based on their stress-strain relationship. The flow behavior of a material during processing may vary significantly because the consistency and composition of the material could be drastically altered due to mixing, heating, cooling, compounding, aeration, homogenization, crystallization, etc. (Bhattacharya, 1997).

The majority of the foods do not show Newtonian flow behavior. For non-Newtonian liquid the viscosity is a function of the rate of shear, meaning that for an applied rate of shear the corresponding shear stress remains constant provided the rate of shear has not changed, however, this is not true for many fluids particularly for multiphase mixtures. The measured shear stress viscosity may increase or decrease with time even through the shear rate is maintained constant. In such as case the fluid is called a time dependent fluid (Bhattacharya, 1997). Time independent deviation from ideal Newtonian behavior will cause the relationship between shear stress and shear rate to be nonlinear. When the material exhibit a diminish of viscosity as shear rate increase it is called shear thinning or pseudoplastic, however if the viscosity increase with shear rate and is called shear thickening or dilatant. Pseudoplasticity and dilatancy are time independent properties (Daubert & Foegeding, 2003).

Time dependent flow behavior can be investigated as a function of time throughout tests where both the

degree of shear load and the measuring temperature are preset as constant values. Foods such as suspensions, emulsions and foams are time dependent fluids and show thixotropy and rheopexy behavior. Thixotropic behavior means the reduction in structural strength during the shear load phase and the more or less rapid, but complete structural regeneration during the subsequent rest phase (Mezger, 2002). Moreover, the existence of thixotropy means that the flow history is important in the prediction of viscosity in processes such as mixing, flow through pipes, centrifugation etc. where viscosity continues to change for a long time. On the contrary, rheopectic behavior means an increase in the structural strength during the load phase and a more or less rapid but complete decomposition of the increased structural strength during the subsequent period of rest. In other words, when the viscosity of a fluid slowly increases with time at a constant shear stress or shear rate, the recovery of the original viscosity is achieved over a period of time after the cessation of the applied stress (Bhattacharya, 1997; Steffe, 1996).

3. Rheology of emulsions

Emulsions are dispersions of one liquid phase in the form of fine droplets in another immiscible liquid phase. The immiscible phases are usually oil and water, so emulsions can be broadly classified as oil-in-water or water-in-oil emulsions, depending on the dispersed phase. Some typical food emulsions are mild cream, ice cream, butter, margarine, salad dressing, and meat emulsions (Barbosa-Cánovas et al., 1996).

Rheological properties of mayonnaise have been studied using different rheological techniques: steady shear rate-shear stress, time dependent shear rate-shear stress, stress growth and decay at a constant shear rate, dynamic viscoelastic behavior, and creep-compliance viscoelastic behavior (Rao, 1999). Mayonnaise is an emulsion of vegetable oil-in-water, where the oil droplets are stabilized by lipoprotein from egg yolk. Food product developers generally have problems related to physical properties of new products and their behavior under different conditions. A similar situation can be observed in margarine spreads where rheological behavior is influenced by the need to be easily deformable at low temperature, since they are a combination of seed and/or vegetable oils, whey, water and various additives, including dispersants and flavoring.

For example, in the case of replacing traditional mayonnaise with a low calorie version, it is important to consider that low calorie mayonnaise needs an added artificial dispersant to prevent destabilization. Furthermore, in applying a stress sweep analysis, where the material is subjected to a sinusoidal stress and the strain response is measured, it is possible to identify the linear

viscoelastic region (LVR) (Fig. 6) (Bohlin Instruments, unpublished). As stress is increased, the material will become non-linear and the extent of this linear region will give indication of the type of structure in the material. Generally, coagulated and strongly flocculated dispersions have relatively short linear regions; while weakly flocculated and stable dispersions have longer linear regions. Light mayonnaise has a slightly longer LVR than traditional mayonnaise because it has higher water content and artificial dispersant/stabilizers. Moreover, when a G^* is determined within the LVR, traditional mayonnaise gives a higher G^* value than low calorie mayonnaise, indicating a more stable structure that allows a high degree of stability. In contrast, traditional mayonnaise can show phase separation during storage and destabilization during shear (Bohlin Instruments, unpublished).

Structure stability can also be observed through yield stress analysis (Fig. 7) (Bohlin Instruments, unpublished). Materials with structure can absorb the stress being applied until the structure starts to breakdown. The result is an increase in viscosity as the structure is maintained, followed by a rapid decrease in viscosity as the structure collapses. Comparing the yield stress of traditional mayonnaise and light mayonnaise, a higher

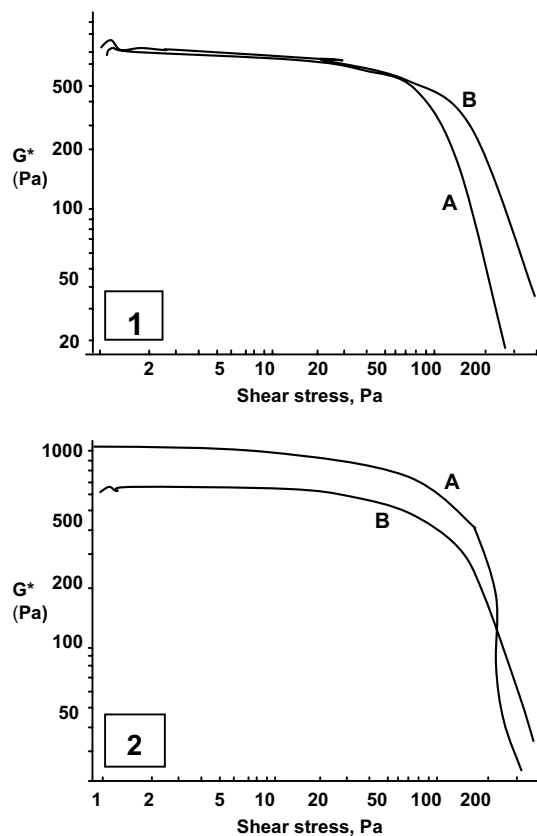


Fig. 6. Stress sweep experiments on mayonnaise: (1A) traditional mayonnaise, (1B) low calorie mayonnaise, (2A) low calorie mayonnaise and (2B) supermarket brand.

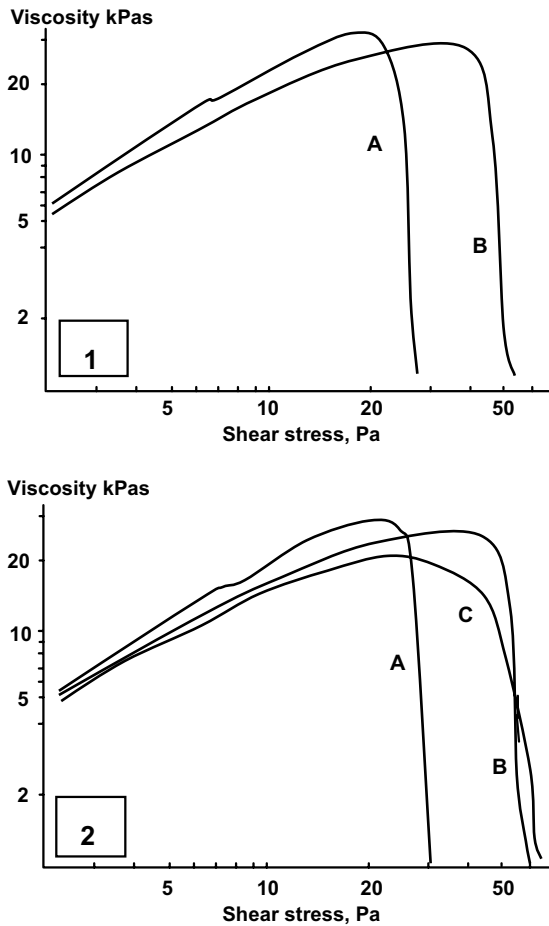


Fig. 7. Yield stress experiments on mayonnaise: (1A) traditional mayonnaise, (1B) low calorie mayonnaise, (2A) traditional mayonnaise, (2B) low calorie mayonnaise and (2C) supermarket brand.

value is observed in light mayonnaise suggesting that traditional mayonnaise can be pumped easier than light mayonnaise (Bohlin Instruments, unpublished). However, in both samples, onset of the flow of mayonnaise causes a dramatic decrease in viscosity, which indicates a uniformity of the microstructure. On the other hand, non-uniformity in the emulsion could likely result in non-uniform flow during pumping, which is an important issue because some of the mayonnaise will remain resident in the pipeline for long periods of time (Bohlin Instruments, unpublished). Moreover, Ma and Barbosa-Cánovas (1995a) showed that the slip phenomenon in mayonnaise during shear measurements, which is due to the non-homogeneous stress field and/or direct fluid-geometry surface interactions, could be corrected with measured apparent shear rate using a simple model, which is based on the assumption that slip velocity is a function of stress only.

Salad dressings are another example of emulsions (oil-water emulsion) that have been studied from a rheological point of view. Wendin and Hall (2001) used a yield stress and creep and recovery analysis to evaluate

the effects of fat content, thickener, and emulsifier in salad dressing. They found that fat content was the most influencing parameter, thus samples with high contents of fat and thickener had the highest yield stress values, and fat content alone had the highest impact on creep recovery values. Moreover, viscosity increased as fat and thickener contents increased.

4. Rheological measurements: equipment

The rheometer, or viscometer, which measures the rheological properties of fluids by the resistance to flow under a known force or the produced stress by a known amount of flow, is an essential tool in food rheological studies. Capillary viscometers, falling-ball viscometers, rotational and oscillatory rheometers, among others, are used to perform rheological measurements (Fig. 8). Working conditions usually considered for sample are: (a) steady flow, (b) laminar flow, and (c) uniform temperature (Barringer & Ratanatriwong, 2003). On the other hand, equipment specifications should at least consider: minimum and maximum torque, maximum and minimum angular velocity, air bearing (porous carbon or jet bearings), auto gap set, gap resolution, normal force range, temperature control, and software.

Commercial rheometers can be divided into analytical and empirical rheometers, given the actual viscosity, the first and second used for quality control where precise data may not be needed, although data should correlate to sensory results or processing characteristics

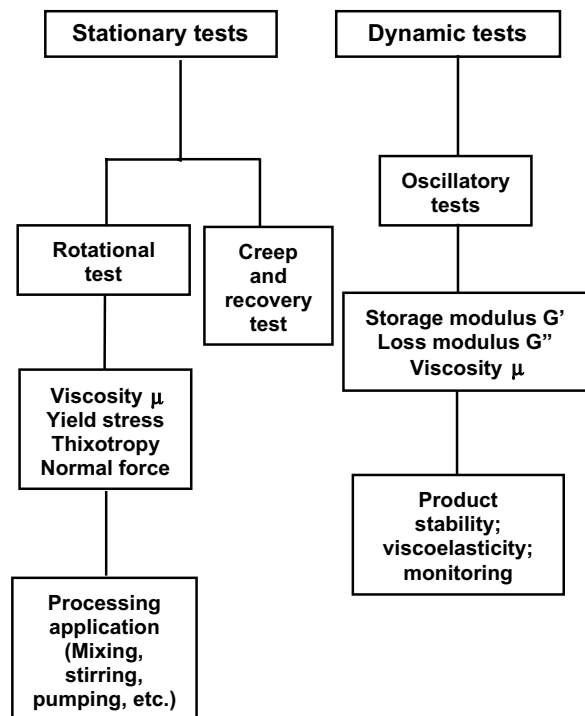


Fig. 8. Rheological tests used in food characterization.

(Barringer & Ratanatriwong, 2003). Paar Physica (Physica USA, Spring, TX, USA), TA Instruments (New Castle, DE, USA), Bohlin (Bohlin Instruments, Inc., East Brunswick, NJ, USA), Haake (Haake, Inc., Para-

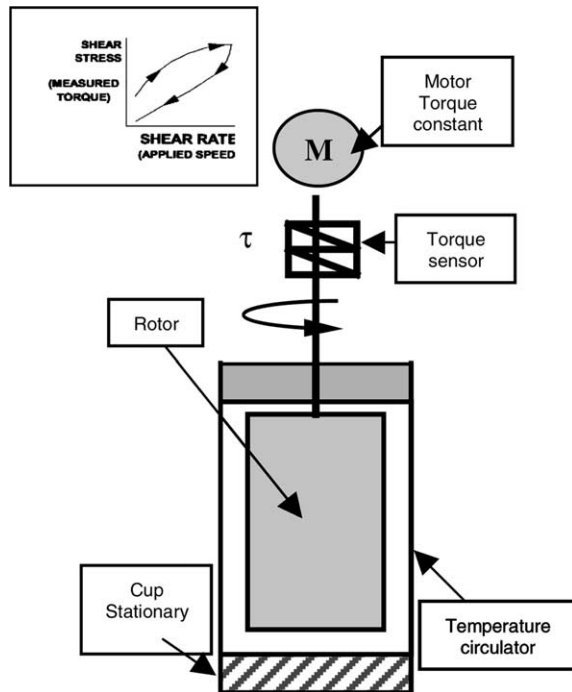


Fig. 9. Controlled rate rheometer with Searle operation mode.

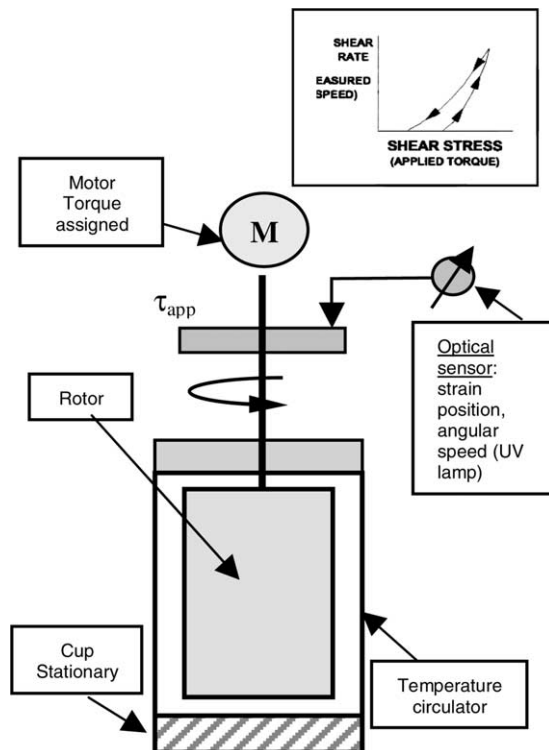


Fig. 10. Controlled stress rheometer with Searle operation mode.

mus, NJ, USA), Brookfield (Middleboro, MA, USA), and Reologica (Reologica Instruments, Inc., Borden-town, NJ, USA), among others, are the main providers of rheology instrumentation in the food industry. Lately they have been releasing different types of equipment to cover all the needs of the food industry.

The two common approaches used in rotational rheometers are controlled rate and controlled stress. In the controlled rate approach, the material being studied is placed between two plates. One of the plates is rotated at a fixed speed and the torsional force produced at the other plate is measured. Hence, speed (strain rate) is the independent variable and torque (stress) is the dependent variable (Fig. 9). In the controlled stress approach, the situation is reversed. A torque (stress) is applied to one plate and the displacement or rotational speed (strain rate) of that same plate is measured (Semancik, TA Instruments, unpublished) (Fig. 10).

5. Device measuring systems

Most of the commercial rheometers employ similar measuring geometries (cone-plate, parallel plate, concentric cylinder, etc.) and have comparable measuring ranges. However, the design varies from one rheometer to the next (Ma & Barbosa-Cánovas, 1995b). The different measuring systems available to perform tests using rotational, creep, relaxation and oscillatory follows.

Rotational rheometers have typical interchangeable measuring geometries: concentric cylinder, cone and plate, and parallel plate. In the concentric cylinder, the fluid is sheared in the gap between inner and outer cylinders where either the inner (Couette) or outer (Searle) cylinder rotates (Barringer & Ratanatriwong, 2003). The Searle and Couette mode are the main operating modes of this device. Almost all rheometers work under the Searle mode, where the bob is driven and the cup is motionless (Figs. 9 and 10). However, Taylor vortices can occur with low-viscosity liquids when flowing at high speeds. In contrast, the Couette mode, where the cup is driven and the bob is in a passive sensor, avoids this problem (Barringer & Ratanatriwong, 2003).

A double-gap measuring systems is also available for low-viscosity liquid where a large shear area is provided to achieve a sufficiently high torque value. Its shear area includes both the inner and the outer surfaces, making possible its temperature control (Mezger, 2002). On the other hand, cone and plate geometry, which consists of a bob with a conical surface and a fixed plate with a flat surface, torque is measured as a consequence of the drag of fluid on the cone. According to the ISO standard, using an angle between the cone and plate of $\alpha = 0.5\text{--}3^\circ$ is recommended (Mezger, 2002; Steffe, 1996). Moreover, cone and plate geometry can only be

used for samples containing particles $\leq \alpha/10$, otherwise there is not enough free volume available between the particles, and this would influence the deformation or flow behavior (Barbosa-Cánovas et al., 1996; Mezger, 2002). Advantages are: (a) the shear rate value is constant throughout the entire gap of the geometry due to its small angle, (b) the end effects are negligible, and (c) high shear rate measurement can be made without having to compensate for the heating effect since a thin layer of the fluid is in contact with a temperature controlled metal plate (Barringer & Ratanatriwong, 2003). Furthermore, the plate and plate measuring system consists of two flat plates where one plate is rotating or oscillating while the other is fixed. They can be used when tests need to be run at relatively low shear rates, which is good for oscillatory testing and coarse dispersions. These sensor systems facilitate filling the shearing gap with samples having strong yield values, inasmuch as they do not require a significant radial squeeze flow to reach the final gap size between plates prior to actual test (Schramm, 1994). The flexible gap between plates makes it applicable for highly viscous suspensions or particulate foods as well as three-dimensional structures, soft solids as pre-formed disks, or hardening materials. Moreover, cleaning is very easy after the test and wall slippage can be avoided by sandblasting, serrating, or profiling surface. But the distribution of shear is not uniform because shear stress is a function of radius, which makes calculations more complicated. However, when measuring low-viscosity liquids at high shear rates, there are secondary flow effects that can occur. This can lead to turbulence, causing an increase in flow resistance (Barringer & Ratanatriwong, 2003).

6. Final remarks

There are several tests for rheologically characterizing food, but it is well accepted that no single test could adequately provide all the information necessary to obtain a complete rheological description. Therefore, a careful selection among various tests is always recommended. The selection of such tests will depend on the type of food, the application, and the availability of suitable instrumentation.

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