Consistency of Fats: A Review[1]

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ABSTRACT

The consistency of fats can be measured with the cone penetrometer (AOCS Method Cc 16-60). Several suggestions have been made to convert readings of penetration depth into parameters such as yield value, hardness or hardness index. This may extend the usefulness of the method. Motor-driven penetrating devices yield results in terms of force/area or stress. More basic information about the rheological properties of fats can be obtained with creep measurements. This includes the viscous flow component as well as instantaneous and retarded elastic components. Such methods are more suitable for research purposes than for quality control. Characteristics and application of various methods will be reviewed.

Plastic fats are mixtures of solid fat crystals and liquid oil. The fat crystals form a three-dimensional network which imparts plasticity to the material. The consistency of fats is an important quality aspect of these products. Consistency is definitely related to the mechanical properties of fats, but there is no uniform and universally acceptable definition of this term. The International Society of Biorheology Committee on Nomenclature and Classification published tentative proposals for definition of rheological terms (1). This list gives two definitions for consistency: (a) An ill-defined and subjectively assessable characteristic of a material dependent on the complete stress-flow relation; and (b) the property by which a material resists change of shape. The first definition would imply that consistency has a number of components related to the rheology of the product. Plastic fats have complex mechanical properties and the complete stress-flow relation would have to include time-dependent characteristics. This definition also points to the fact that we make sensory judgments about consistency and, in recent years, studies of fat consistency have often combined sensory and instrumental methods of analysis. The second definition is similar to definitions of hardness. The ISB list defines hardness as "the resistance of the surface of a body to penetration". In the texture profile system, hardness is defined as the maximum force required to achieve a given deformation (2). A term which has been frequently used in connection with fat consistency is spreadability, usually defined as the force required to spread the fat with a knife. It has sometimes been stated that hardness and spreadability are different properties of a material. However, both types of measurement involve evaluation of a force required to bring about a certain deformation. There is no reason to expect any fundamental difference in these two tests.

In measuring the consistency of fats, there are several alternatives: use of a simple, rapid test for quality control purposes; use of sophisticated rheological measurements to evaluate stress-strain-time relationships; or use of sensory methods.

Simple, rapid tests have been popular in the fats industries for quality control and product improvement purposes. These tests are usually of an empirical nature but certainly bear some relationship to the subjectively assessed aspects of consistency. These methods include penetrometer tests, extrusion, wire cutting or sectility and simple compression tests. The most widely used test of this type in North America is the cone penetrometer method (AOCS Method Cc 16-60). Extruders and wire cutting devices have been used widely in parts of Europe. Such simple devices are extremely useful in industry but suffer from several shortcomings, especially the difficulty of interpretation of the results.

The more sophisticated rheological methods are useful for increasing our knowledge and understanding of the fundamental properties of plastic fats. Much has been learned in recent years through the application of such methods.

Sensory analysis has not been widely used in the examination of plastic fats. However, there is increasing interest in correlating the results of sensory methods with those obtained using instruments. This permits the "calibration" of instrumental tests with sensory responses.

Simple Test Methods

The cone penetrometer test for measuring fat consistency has been standardized (AOCS Method Cc 16-60). According to this method, the cone has an angle of 20° and is truncated: the height of this truncation is 2.27 mm or 22.7 penetrometer units (1 pu = 0.1 mm). Since the depth of penetration will be higher for a soft fat than for a hard fat, this method indicates softness rather than hardness. The official method instructs the user to read the depth of penetration in 0.1 mm units but gives no instruction relating to the different weights of cone assembly which may be used. It is not surprising, therefore, that there have been a series of proposals to convert penetration depth to a more logical unit which would be independent of cone assembly weight. It has been pointed out that the cone will sink into the fat until the stress exerted by the increasing contact surface of the cone is balanced by the hardness of the fat. This value has the dimension of a stress and several investigators have suggested to convert readings to yield value.

The following suggestions have been made for conversion of penetrometer readings.

Rebinder and Semenenko (3) investigated the relationship between cone dimensions and weight and penetration depth and concluded that a yield value can be calculated from the relationship:

$$YV = \frac{g.\cos^2\alpha.M}{\tan\alpha.p^2} \quad [1]$$

where: M = mass of penetrating assembly, α = half angle of cone, g = acceleration due to gravity, and p = penetration depth.

Haighton (4) proposed the following relationship for the conversion of penetration value to yield value:

$$C = KW/p^{1.6} \quad [2]$$

where: C = yield value, K = a constant depending on the cone angle, p = penetration depth, and W = weight of cone assembly.

A similar equation was proposed by Mottram (5) which

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took the form of:

$$S_o = Kwg/h^n \qquad [3]$$

where: S_o = yield value, K = a constant, w = weight of cone assembly, g = acceleration due to gravity, h = depth of penetration, and n = an exponent. The exponent n was suggested to be close to 2, but could vary with the nature of the test material.

Vasic and deMan (6) proposed to convert penetration values to hardness defined as force divided by area of penetration. This was calculated from:

$$H = \frac{G.10^{-3}}{h\pi \frac{\tan \alpha}{\cos \alpha}(h + \frac{2r}{\tan \alpha}) + r^2 \pi 10^{-4}} \qquad [4]$$

where: H = hardness, G = weight of cone assembly, h = depth of penetration, α = half angle of cone, and r = radius of flat tip of cone.

Recently, the International Dairy Federation (7) proposed the following relationship:

$$AYS = \frac{g\,w}{\tan^2 (\alpha/2)\, p^2} \qquad [5]$$

where: AYS = apparent yield stress, g = acceleration due to gravity, w = weight of cone assembly, p = depth of penetration, and α = cone angle.

Dixon and Parekh (8) investigated the use of the cone penetrometer for measuring the hardness of butter and found that the so-called cone stress index correlated well with sensory evaluation. The cone stress index (C_V) was calculated from:

$$C_V = \frac{C\,A^{-1.65}}{p^2} \qquad [6]$$

where: A = cone angle, C = mass of cone assembly, and p = depth of penetration.

All of these suggestions can be related to the following general equation:

$$H = C\frac{M}{p^n} \qquad [7]$$

where: H = hardness or yield value, C = a constant depending on cone geometry, M = mass of penetrating assembly, p = depth of penetration, and n = an exponent.

For the standard cone of the AOCS method, this could be simplified to:

$$H = \frac{M}{p^n} \qquad [8]$$

The use of such a simplified conversion formula has several advantages. First, the values are no longer dependent on cone assembly mass. Second, the hardness measurement indicates higher values for harder than for softer fats which makes it easier to visualize differences between different samples.

One of the problems to be solved is the value of the exponent n. When a value of 2 is used, the dimension of the hardness is g/cm^2 or stress. Rheologically, this would be more acceptable than using other values from 1-2. It has been shown (9) that there is advantage in using a value of 1 or n. A double logarithmic plot of penetration against hardness yields a straight line for both n = 1 and n = 2 (Figs. 1 and 2). When the truncation of the cone is taken into account, the relationship is not straight. This was shown by Vasic and deMan (6) (Fig. 3). Their conversion from penetration to hardness does take into account the effect of truncation. It has been suggested (9) to use the term hardness index for this purpose, especially if the value of the exponent chosen is not equal to 2. Dixon and Parekh (8) investigated test parameters for the use of the cone penetrometer and found that the cone stress index correlated well (R > 91%) with the sensory assessment of spreadability. The relationship between spreadability panel scores

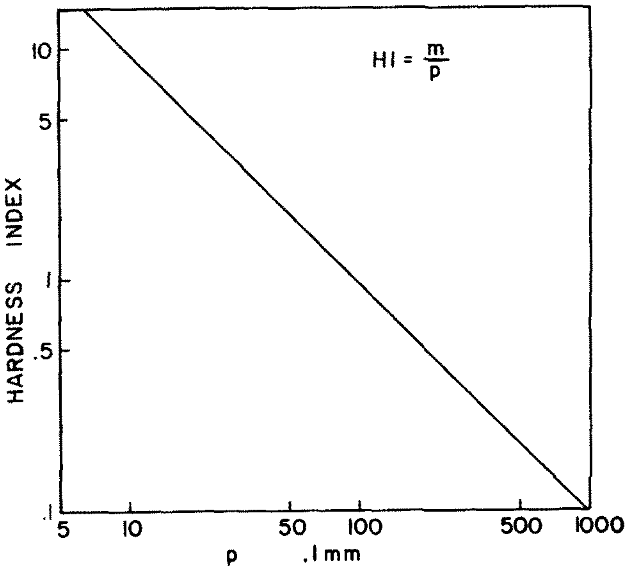

FIG. 1. Double logarithmic plot of hardness index and penetration expressed as M/P.

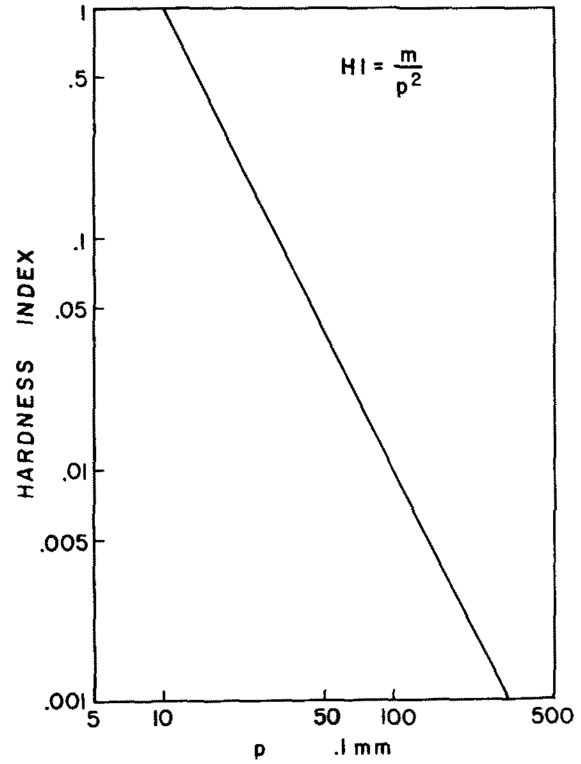

FIG. 2. Double logarithmic plot of hardness index and penetration expressed as M/P^2.

and cone stress index is shown in Figure 4. The cone penetrometer remains the instrument of choice for testing fat consistency, because of its ease and simplicity. A modification which would permit the recording of penetration depth as a function of temperature would be a useful addition to our testing capabilities.

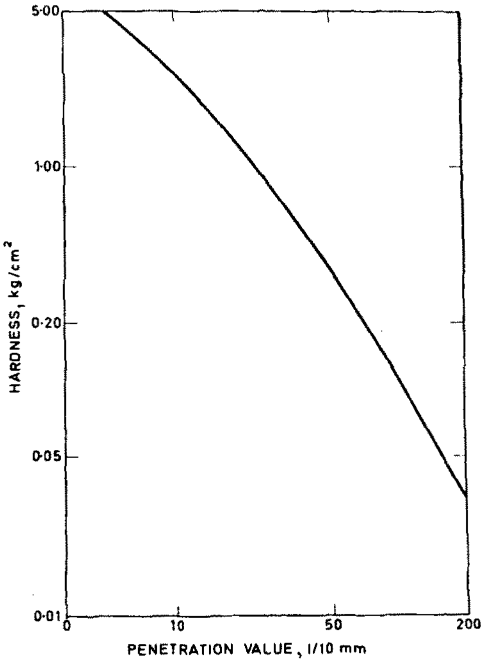

FIG. 3. Double logarithmic plot of hardness and penetration value using the formula of Vasic and deMan (6).

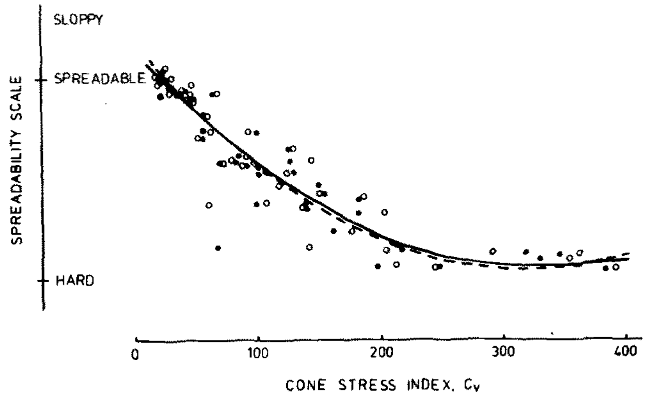

FIG. 4. Mean panel scores for spreadability vs cone stress (from ref. 8).

The only other instrument of a similar type is the micropenetrometer of Feuge and Bailey (10). This method employs a needle falling through a length of glass tubing into the fat sample. This method has not been widely used.

Next in popularity to the cone penetrometer are various penetrometers in which the penetrating body is driven into the sample by mechanical means rather than by force of gravity. One of the first uses of this technique was described by Kruisheer and denHerder (11). The penetrating body consisted of a stainless steel cylinder with a height of 10 mm and a surface area of 4 cm^2. This method has been used in several European countries for quality control purposes of butter. A similar device named the shortening consistometer was described by Clardy et al. (12). The penetrating body consisted of a metal ring with narrower internal diameter at the top than at the bottom. It was found that the use of the latter system made it difficult to determine the exact point at which the force should be recorded (13). With flat cylindrical punches, a distinct yield point was observed (Fig. 5). No significant difference in force readings was observed when speeds of 0.12 and 0.6 cm/sec were used.

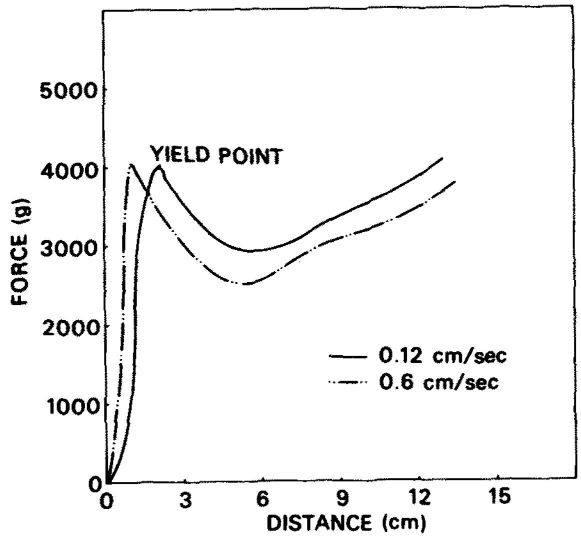

FIG. 5. Typical force-distance diagrams using flat punches in a penetrometer test.

The relationship between force and size of penetrating body was elucidated by Bourne (14). He discovered that, for many foods, penetration force can be represented by:

$$F = K_C A + K_S P + C \qquad [10]$$

where: F = penetration force, K_C = compression coefficient, K_S = shear coefficient, A = punch area, P = punch perimeter, and C = constant. This explained the nonlinear change in force registered when the size of the punches was changed. With fats, it was subsequently shown by Kamel and deMan (13) that shear is not involved in penetration testing of fats. The force registered when using punches of different size is directly proportional to the area of the punch.

A study of the spreadability of butter and margarine was made by deMan et al. (15), using a motor driven penetrometer for measuring hardness and a sensory panel for spreadability scores. A comparison was made of the consistency of margarines and butter at temperatures ranging from 5-25C.

Tanaka et al. (16) used a constant speed penetrometer technique with a 20° cone as the penetrating body. Force-time recordings on soft margarine performed at different speeds are shown in Figure 6. Penetration stress was calculated from the following relationship:

$$F'/A' = F \cos(\theta/2) \cot(\theta/2)/\pi h^2 \qquad [11]$$

where: F'/A' = penetration stress, F = vertical force applied to cone, and h = depth of penetration. At any depth of penetration, the stress on the cone is equal to the sum of both plastic and viscous deformations:

$$F'/A' = \eta_{app}\,(dh/dt) + F \cot(\theta/2) \cos(\theta/2)\pi h^2 \quad [12]$$

When penetration stress was plotted against penetration speed (Fig. 7), a straight line was obtained. The slope of the line represents the value of apparent viscosity and the intercept with the penetration stress axis equals the yield value.

One of the major advantages of penetrometer measurements is that virtually no sample preparation is necessary. Often the tests can be conducted on the product in retail packages. Other tests such as extruders require fairly elaborate techniques for filling the samples into the test units. This increases the possibility of undesirable work softening effects and temperature fluctuations.

The most widely used extruder instrument is the FIRA-NIRD extruder (17). Johansson and Joost (18) used this instrument and compared the results with those obtained with a penetrometer. They concluded that different properties were measured by these instruments and the results were not well correlated. Several other investigators, e.g., Hoffer and Sobeck-Skal (19), have found the instrument useful in evaluating consistency.

Other uses for extrusion type instruments were described by Vasic and deMan (20) who used an extrusion modification of the Kramer Shear Press and by Scheer and Witnauer (21) who used a capillary extrusion rheometer to determine the flow properties of lard.

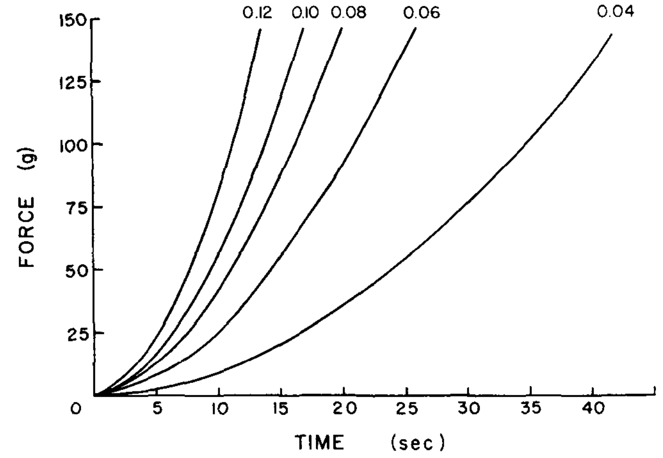

FIG. 6. Force-time recordings for constant speed cone penetrometer tests of soft margarines, speed indicated on curves in cm/sec (from ref. 16).

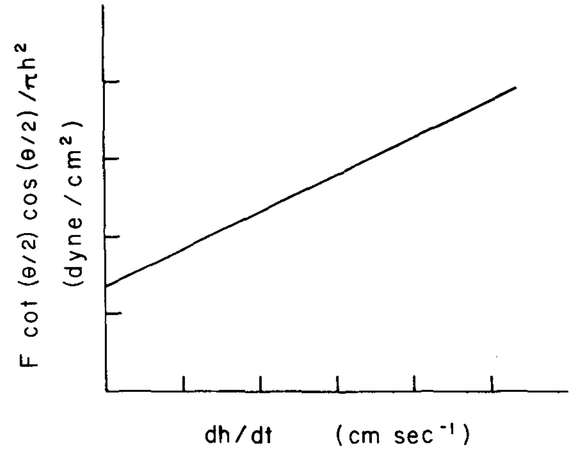

FIG. 7. Plot of penetration speed vs penetration stress in a constant speed cone penetrometer test. (from ref. 16).

Sophisticated Rheological Measurements

The simple tests described above mostly relate to a single rheological property, hardness or yield value. There is no doubt that information from these tests correlate with consumer evaluations of consistency. However, in a rheological sense, fats exhibit plastic, viscous and elastic properties and these can only be measured with more sophisticated equipment. In the constant speed cone penetrometer studies of Tanaka et al. (16), it was assumed that plastic fats behave according to the model of Figure 8. This consists of a dashpot and a friction element in parallel representing viscous and plastic components, respectively.

On the basis of rheological measurements made with the Weissenberg Rheogoniometer, Elliott and Ganz (22) proposed a model for the rheological behavior of fats (Fig. 9)

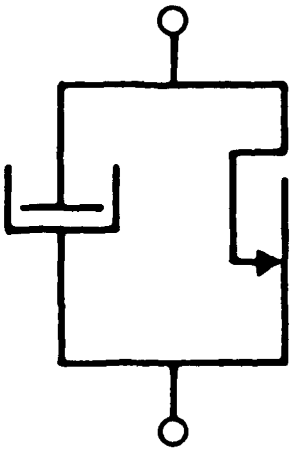

FIG. 8. Rheological model for plastic fats proposed by Tanaka et al. (16).

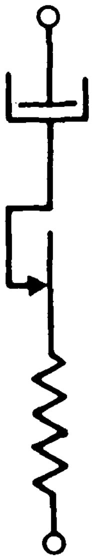

FIG. 9. Rheological model for plastic fats proposed by Elliott and Ganz (22).

which includes a viscous, a plastic and an elastic element placed in series. A sinusoidal strain was applied to butter and it was observed that the resulting stress curve was no longer sinusoidal but appeared almost as a square wave (Fig. 10). The shape of this wave is related to the yield stress $\sigma_{o,r}$, and indicates that the applied shear has caused structural breakdown which is not recovered within the time of the experiment. Surprisingly, no mention is made in this study of the temperature at which this experiment was performed, since it can be expected that this factor has a profound effect on the rheological behavior.

A more complex rheological model for butter was proposed by Diener and Heldman (23). This model (Fig. 11) includes a plastic and a viscous element in parallel, coupled in series with a viscous element in parallel with a combination of a viscous and an elastic element. These elements were suggested to be associated with various structural components as shown in Figure 11.

Shama and Sherman (24) used creep compliance analysis to study the rheological properties of margarine. A parallel plate viscoelastometer was used in this investigation. Analysis of the creep compliance curves resulted in the construction of the 10-element mechanical model of Figure 12. From this type of analysis, three rheological parameters were derived: instantaneous elasticity, retarded elasticity and viscous flow. Creep testing is a convenient was of analyzing the viscoelastic properties of fats. A typical creep analysis recording obtained in our laboratory is presented in Figure 13. The curve shows the instantaneous deformation at time 0, followed by a gradually increasing deformation until at time = t the load is removed. At this time, there is an instantaneous recovery which is assigned to the instantaneous elasticity, I. Subsequently, there is a time-dependent elastic recovery which is assigned to the retarded elasticity, R. The permanent deformation P is associated with the viscous component. The rheological behavior of fats in this

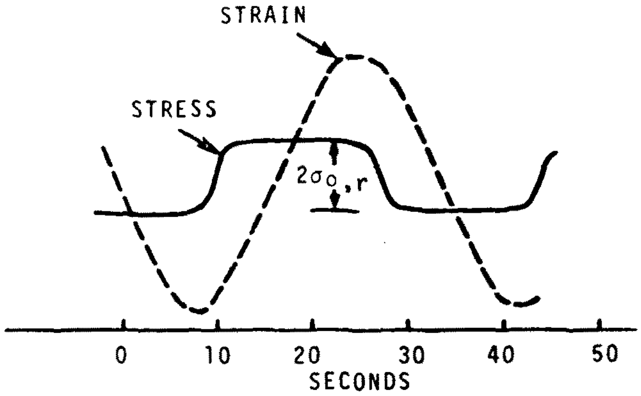

FIG. 10. Dynamic measurements on butter (frequency 3 × 10^{-2} cps, strain amplitude ± 0.66) (22).

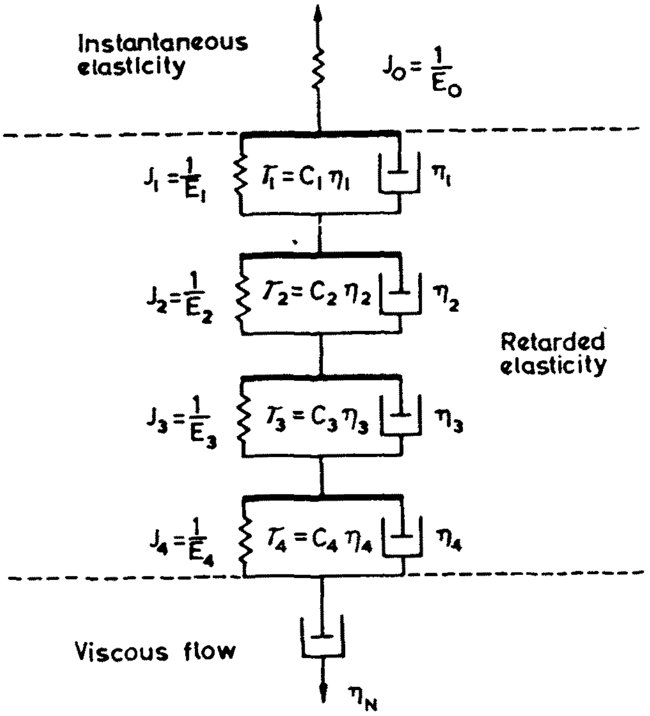

FIG. 12. Ten-element rheological model proposed for margarine by Shama and Sherman (24).

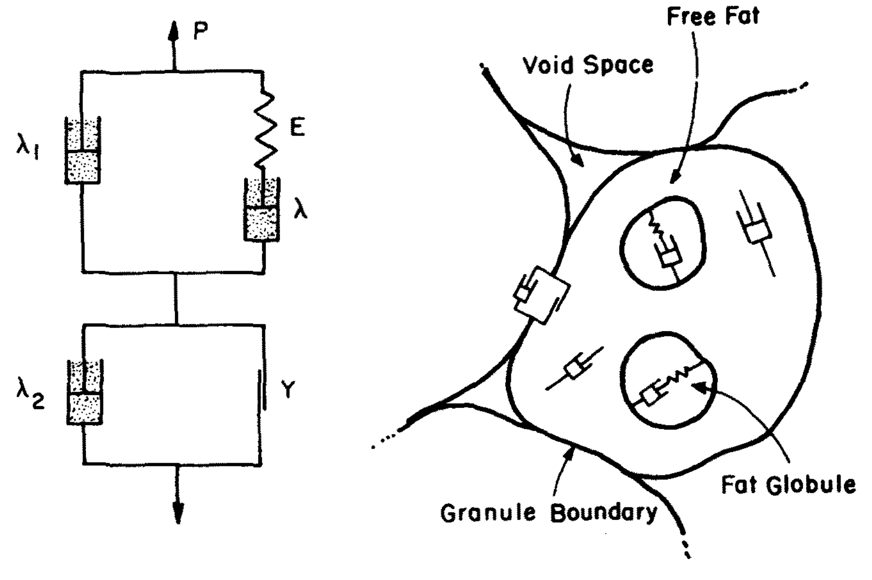

FIG. 11. Rheological model proposed for butter (left) and relation of model elements to structural components (right) (23).

type of test appears to differ from that usually associated with viscoelastic materials. Mohsenin (25) suggest a creep curve of a viscoelastic material to have the shape shown in Figure 14. In this type of curve the initial deformation is equal to the instantaneous elasticity. With fats, this appears not to be the case and the initial deformation is larger, probably consisting of the instantaneous elastic component as well as a large part of the permanent deformation.

Some typical results of creep analysis of butter and margarine are presented in Table I. There is a definite effect of temperature, indicated by the fact that the elastic components become more important at lower temperature. This is not surprising, since at lower temperature the crystal network becomes stronger. This type of analysis should be useful in explaining the rheological behavior of fat products at different temperatures. It is not clear what role, if any, the elastic components play in the sensory evaluation of fat consistency. Further studies are needed to elucidate this relationship so that these rheological measurements will be of practical assistance in formulating fat products.

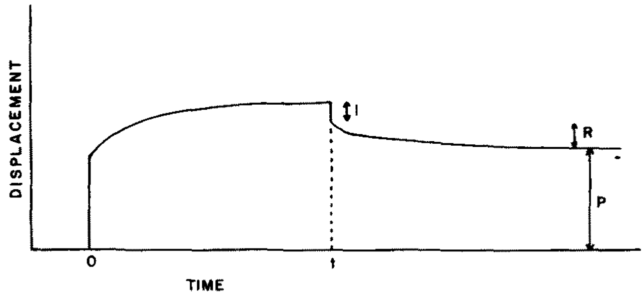

FIG. 13. Creep test record obtained on margarine.

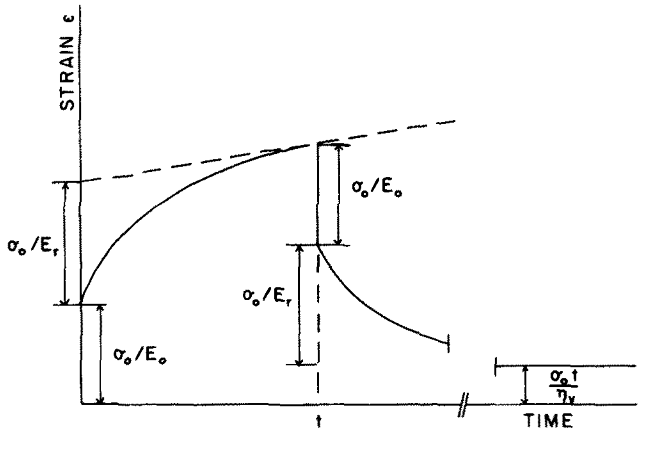

FIG. 14. Creep curve of viscoelastic material according to Mohsenin (25).

TABLE I

Viscoelastic Parameters of Fats Obtained by Creep Analysis

Product	Temp (C)	Instantaneous elasticity (Pa)	Retarded elasticity (Pa)	Viscous flow (Pa.sec)
Butter	5	4.2×10^{-1}	1.9×10^{-1}	45.22
Butter	10	5.7×10^{-2}	3.9×10^{-2}	13.99
Margarine	5	5.1×10^{-2}	3.8×10^{-2}	6.19
Margarine	10	4.1×10^{-2}	1.3×10^{-2}	5.62

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