Squeezing Flow Viscosimetry of Peanut Butter

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ABSTRACT

The rheological characteristics of peanut butter were determined in two types of lubricated squeezing flow tests, one based on constant deformation rate and the other on deformation under constant stress (creep). Elongational flow was observed in both types of tests. When the flow regime was not governed by viscoelastic effects, peanut butter could be described as a power law fluid with consistency on the order of 70–200 KPa and flow index of 0.5–0.7.

INTRODUCTION

THE RHEOLOGICAL CHARACTERISTICS of viscous semi-liquid foods are usually determined in shear flow using a coaxial viscosimeter and less frequently by a cone and plate viscosimeter. One of the prerequisites for such determinations is that the sample is indeed sheared and that there is no slip between the instrument surfaces and the tested fluid. This condition is satisfied in most semi-liquid foods but there is a notable group of foods for which the "no slip" assumption cannot be taken for granted. This group consists of highly viscous materials which contain a considerable amount of fat (e.g., melted cheeses, peanut butter). These materials can be considered as self-lubricating and, therefore, their flow pattern in a coaxial (or capillary) rheometer is either a distorted shear flow or plug flow. A way to avoid the problems that are associated with self-lubrication is to use squeezing flow viscosimetry with lubricated plates. In such tests the existence of lubrication and slip is not only acknowledged but also incorporated in the calculation of the results.

The objectives of this work were to test the applicability of lubricated squeezing flow viscosimetry to peanut butter and to determine its rheological properties using this method.

THEORY

Squeezing flow viscosimetry

Squeezing flow viscosimetry is based on compression of a fluid specimen between two parallel plates. There are four types of test arrays which offer both technical simplicity and a convenient rheological interpretation of the results. The four arrays are schematically described in Fig. 1. They can be classified as those based on constant area or constant volume, or alternatively, those based on constant load or constant rate of deformation. The mathematical aspects of squeezing flow, with and without lubrication, have been discussed extensively in the rheological and polymer literature (e.g., Oka, 1960; Leider, 1974; Leider and Bird, 1974; McClelland and Finlayson, 1983; Chatraei et al., 1981).

Consequently, there are a few published equations relating force-time or deformation-time relationships to the flow characteristics of different types of fluids, i.e., Newtonian, power law. These expressions can be used to calculate the rheological constants of such fluids from experimentally determined relationships. The existence of theoretical solutions to squeezing flow problems by themselves, however, is not a guarantee for meaningful interpretation of such tests. The reason is that instrumental or procedural artifacts can, at least theoretically, affect the magnitude of the calculated rheological constants, while the general character of the underlying mathematical relationships remains unchanged. Methodologically, therefore, it is imperative to determine the rheological constants either by two different kinds of tests and/or by the same kind of test performed under different conditions (e.g., different specimen height, load range and deformation rate). This approach was followed in this work, and the tests selected were the constant area array with constant load (stress) and constant deformation (displacement) rate (Fig. 1).

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Mathematical relationships in squeezing flow

Lubricated squeezing flow of a specimen with a constant area is governed by the equation (Leider and Bird, 1974; Chatraei et al., 1981)

$$F(t) = 2\pi \int_o^R (T_{zz} - P_o) r\,dr \quad (1)$$

where F(t) is the force, T_{zz} is the normal component of the stress tensor, P_o the atmospheric pressure, R is the specimen's radius and r is the distance from the center. For Newtonian fluid, Eq. (1) results in the relationship (Bird et al., 1977; Chatraei et al., 1981)

$$F(t) = \frac{3\pi R^2 \mu}{H(t)} \left(- \frac{dH(t)}{dt} \right) \quad (2)$$

where μ is the Newtonian viscosity and H(t) is the momentary height of the specimen. For a power law fluid, i.e., obeying the equation (Showalter, 1978)

$$\tau = -K \left(\frac{1}{2} \dot{\gamma} : \dot{\gamma} \right)^{\frac{n-1}{2}} \dot{\gamma} \quad (3)$$

where τ is the stress tensor, $\dot{\gamma}$ the strain rate tensor, $\dot{\gamma} : \dot{\gamma}$ is the scalar (double) product of the shear rate tensor, and K and n constants (also known as the consistency and flow index, respectively). Eq. (1) yields, upon integration, the following relationship between the normal component of the stress tensor (T_{zz}) and the true strain rate (dH/Hdt)

$$T_{zz} - P_o = 3^{\frac{n+1}{2}} K \left(- \frac{dH(t)}{H(t)dt} \right)^n \quad (4)$$

which in turn gives the following:

For flow under constant deformation rate (i.e., $-\frac{dH(t)}{dt} = \text{const} = V$)

$$F(t) = \frac{3^{\frac{n+1}{2}} \pi R^2 K V^n}{[H(t)]^n} \quad (5)$$

or

$$\ln F(t) = C + S_1 \ln \left(\frac{1}{H(t)} \right) \quad (6)$$

where

$$C = \ln \left[3^{\frac{n+1}{2}} \pi R^2 K V^n \right] \quad (7)$$

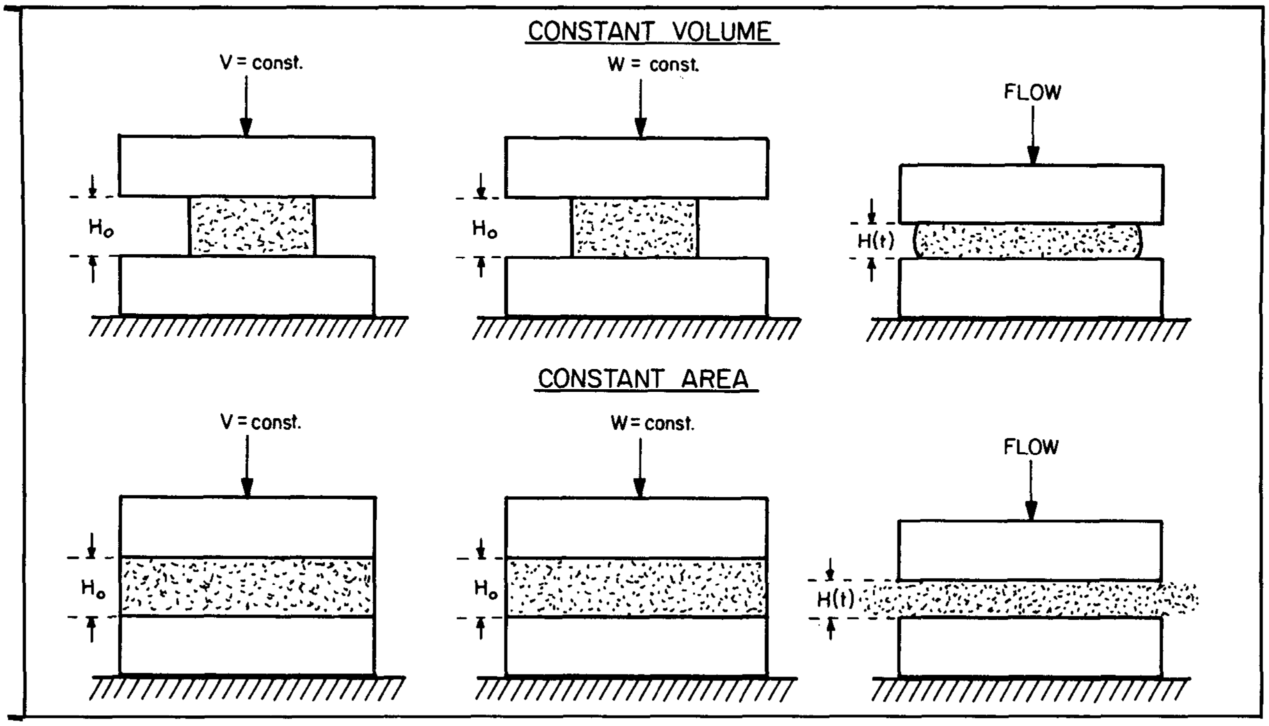

Fig. 1—Schematic view of the different arrays of squeezing flow rheometry. V is a constant deformation (displacement) rate and W, a constant load (weight). H_o, the initial specimen height, H(t), the specimen height after time t.

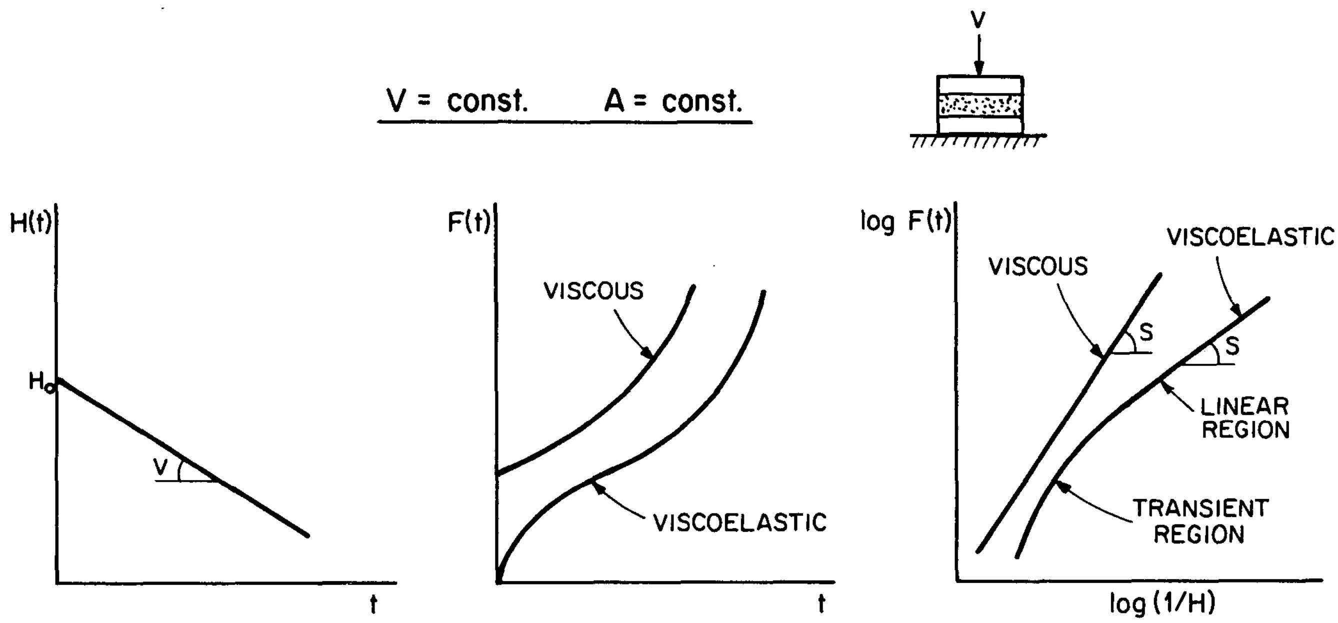

Fig. 2—Schematic view of the data retrieval procedure from a squeezing flow experiment performed with constant deformation rate (V) and constant specimen area (A). (H is the specimen momentary height, H_o the initial height, F the momentary force, t the time, and S the slope of the lower region).

and $S_1 = n$ if the relationship is indeed linear (see Fig. 2). The values of K and n, therefore, can be calculated either by linear regression of the data presented in the form of Eq. (6) or by nonlinear regression of the data presented in the form of Eq. (5).

For flow under constant load (constant stress), i.e., F(t) = const = W (see Fig. 3).

$$\ln \frac{H(t)}{H_o} = -S_2 t \tag{8}$$

where

$$S_2 = \left(\frac{W}{3^{\frac{n+1}{2}} \pi R^2 K} \right)^{1/n} \tag{9}$$

and H_o the specimen's initial height.

Recording force time relationships under constant deformation rate or height decreases under constant force enables the calculation of the constants K and n from the fit of Eq. (6) and (8) to experimental data in regions where viscoelastic effects vanish or can be neglected. It should be noted that since Eq. (9) contains both constants as part of the slope, their magnitude can only be calculated from repeated experiments with at least two different loads (W).

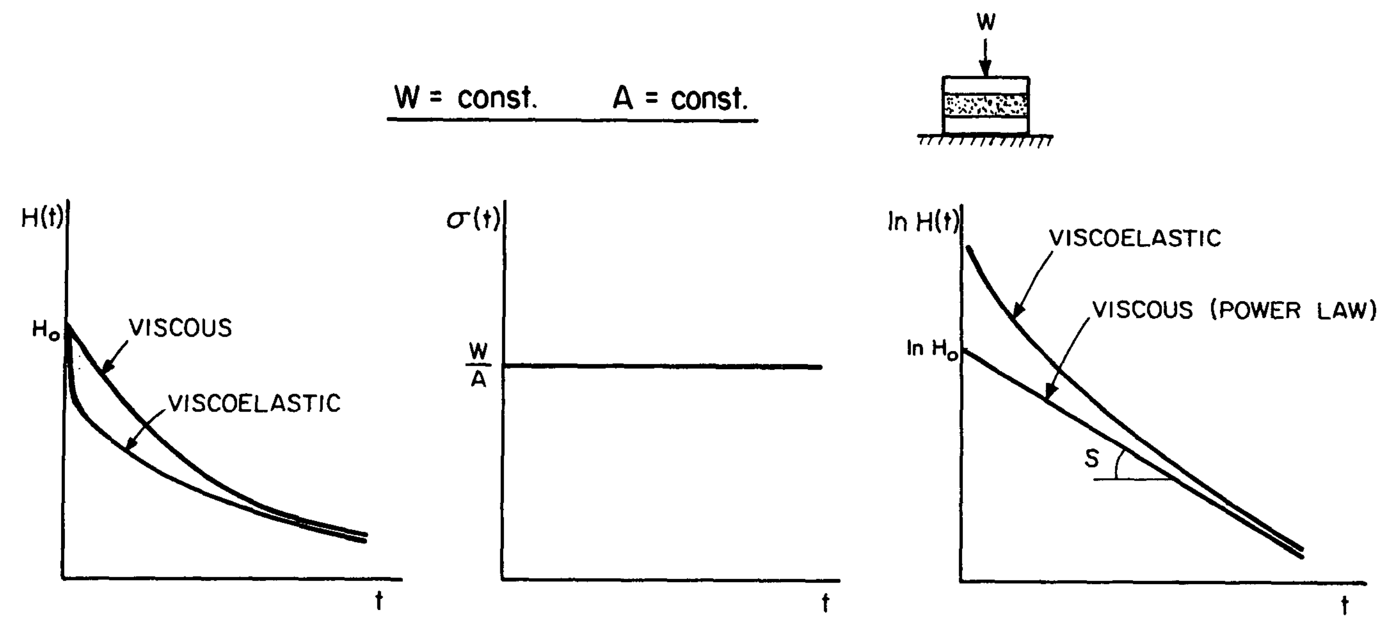

Fig. 3—Schematic view of the data retrieval procedure from a squeezing flow experiment (creep) performed with a constant load (W) and constant specimen area (A). (H is the specimen momentary height, H_o the initial height, σ(t) is the stress, t is the time, and S the slope of the linear region).

MATERIALS & METHODS

JARS OF PEANUT BUTTER of a national brand and of a supermarket chain were purchased at a local supermarket. They were left to equilibrate at laboratory ambient temperature and were tested at about 22–24°C. Samples of the peanut butter were placed between two parallel lubricated plastic platens with known diameter in the form shown schematically in Fig. 1 (constant area). The initial thickness (height) of each sample was monitored. Prior to testing the samples were allowed to rest for a few minutes to relieve the shear effects produced during the sample preparation.

Part of the samples were subjected to uniaxial deformation at various constant deformation (displacement rates using an Instron Testing Machine model TM.) Another part was subjected to uniaxial creep deformation under various constant loads using the creep tester recently described in detail by Purkayastha et al. (1985). The recorded force-time and thickness-time relationships in the two tests were digitized, replotted and fitted by Eq. (5) or (6) and (8) (Fig. 2 and 3). The constants of these equations were used to calculate the rheological constants K and n using Eq. (7) and (9).

RESULTS & DISCUSSION

THE APPEARANCE of peanut butter specimens in lubricated squeezing flow is demonstrated in Fig. 4. The figure clearly demonstrates that the flow pattern is that of elongational flow. This is evident from the flat boundary of the expelled material and the fact that the specimen retained its cylindrical shape. Shear flow would have resulted in bulging of the edge and "barreling" of the specimen shape. It should be mentioned that a similar pattern was also observed when the platens were not lubricated indicating that, at least with the platens used, peanut butter can provide enough self-lubrication to induce elongational flow. The same behavior was observed in the creep experiments, again demonstrating that self-lubrication governed the flow regime.

Calculation of the rheological constants

The experimental force-time (Fig. 5) and height-time (Fig. 6) relationships showed transient regions that were most probably produced by viscoelastic effects. Upon transformation to logarithmic relationships, however, the curves, as could be expected, had considerable linear portions that enabled calculation of the power law model constants. It is perhaps worth metioning that in the deformation tests, viscoelastic effects are evident from the start (i.e., the force deformation (time) curve starts from the original and not from a non-zero value as in the case of true liquids. Their role becomes dominant as the specimen becomes shorter as the result of the progressively increasing true strain rate). In creep, in contrast, viscoelastic effects are only manifested in the initial stage (i.e., exhibiting an "instantaneous" like compliance) and they rapidly dissipate subsequently, as the flow proceeds at an ever decreasing rate.

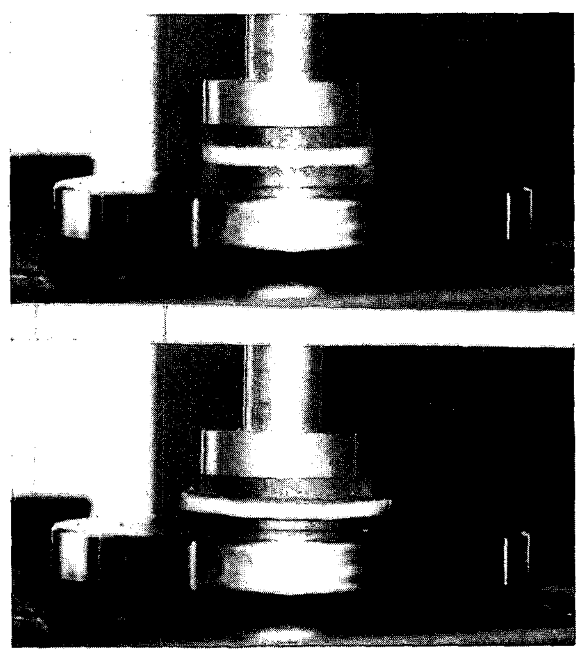

Fig. 4—The appearance of a peanut butter specimen before (top) and during lubricated squeezing flow experiments (bottom). Note the flat appearance of the deformed specimen boundary indicating elongational flow pattern.

Calculated values of the rheological characteristics of two commercial peanut butter brands are presented in Table 1. As could be expected, the table shows that peanut butter can be described as a power law fluid with a flow index on the order 0.5–0.7. It is about ten times higher than previously published

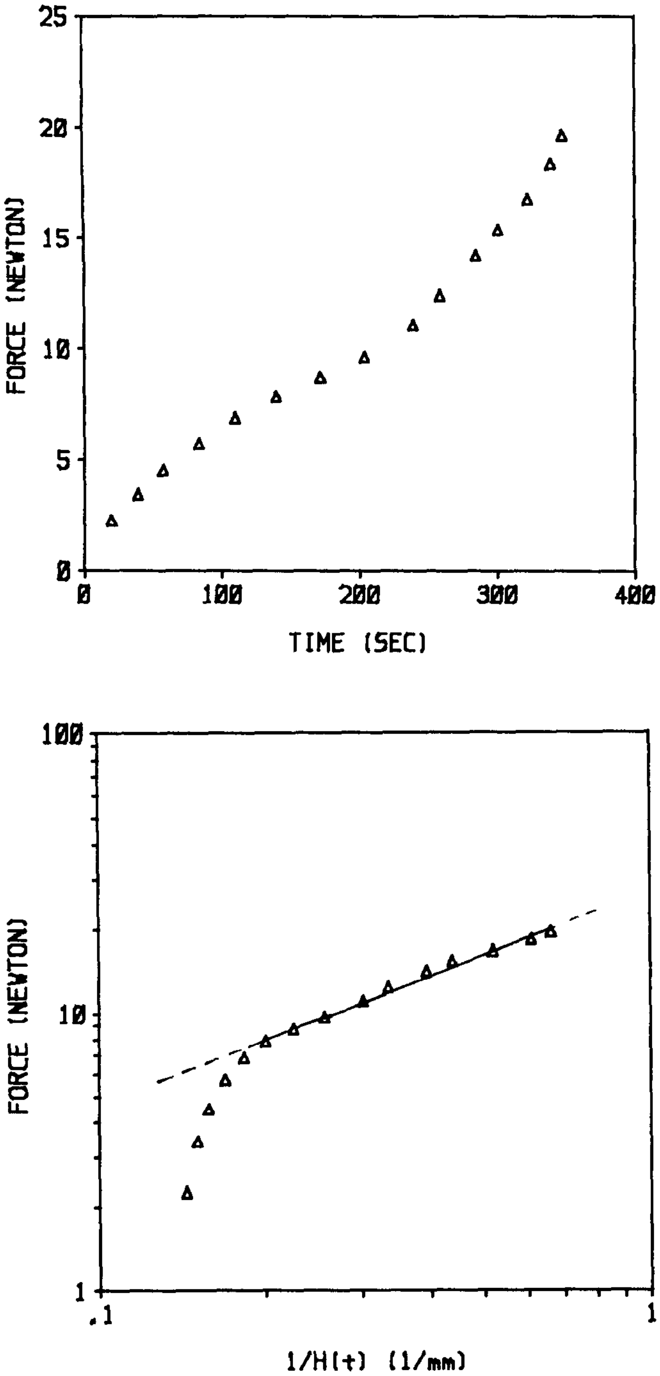

Fig. 5—Typical force-time and log F vs log 1/H(t) curves of peanut butter deformed at a constant deformation rate. Compare to Fig. 2. H(t) is the specimen height after time (t).

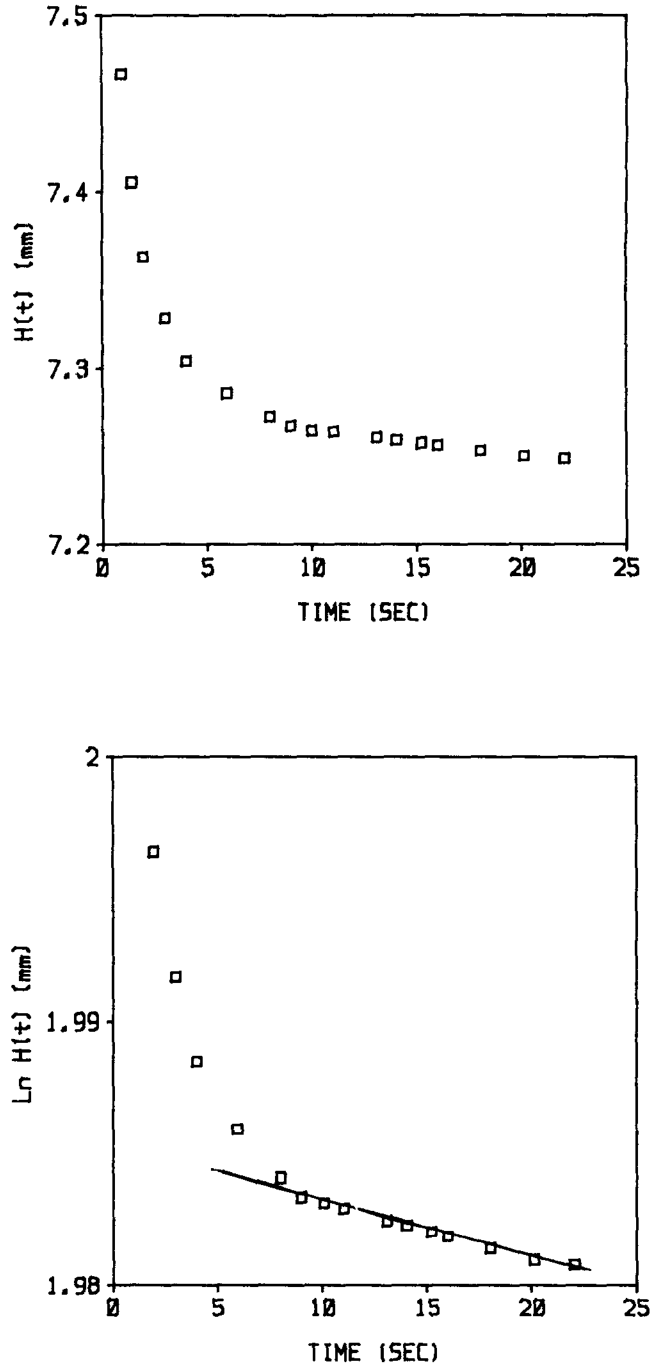

Fig. 6—Typical height-time and log H(t) vs time of peanut butter deformed under constant load (stress). Compare to Fig. 3. H(t) is the specimen height after time t.

values based on shear flow under much higher deformation rates (Dickie and Kokini, 1982). The highly viscous character of peanut butter is expressed by the magnitude of the "consistency" parameter K which had values on the order of 70–90 KPa for one brand and 140-200 KPa for another. These levels are in general agreement with the values published by Sharma and Sherman (1973). The scatter of the results was in the range of less than 10% for the values of n and on the order of up to 30% for the values of K. This scatter was probably the result of the crude manner in which the specimens were prepared and also some history related effects. Since peanut butter did show viscoelastic behavior (Fig. 5 and 6) and since the existence of rheological memory cannot be ruled out, at least part of the scatter can be related to differences in the stress history of the specimens before and during the tests. These effects were probably also responsible for the slight discrepancy between the results obtained in constant deformation rate and in tests performed with a constant load. Despite these, however, the difference between the rheological behavior of the two peanut butter brands was clearly evident, irrespective of the test employed or the conditions under which the test had been performed.

Role of yield stress

Although the reality of the yield stress has recently been challenged (Barnes and Walters, 1985), the concept itself is still useful in many practical applications. Under the conditions of the reported tests, however, the yield stress does not come into play. This is because elongational flow is either induced

Table 1—Rheological constants of peanut butter determined under different conditions in lubricated squeezing flow tests[a]

	Constant deformation rate				Constant load (Stress)				
Product	V (cm min^{-1})	H_o (mm)	K (kPa·S^n)	n (−)	$W/\pi R^2$ (kPa)	H_o (mm)	K (kPa·S^n)	n (−)	Strain rate[b] $\times 10^{-4}$ (sec^{-1})
National brand	0.05	6.9	57	0.53	2.9	14.6	99	0.49	1.4
	0.05	6.4	82	0.64	3.8	12.2			2.4
	0.10	6.5	82	0.72	6.1	11.3	85	0.47	6.5
	0.10	7.5	76	0.67	8.2	12.0			12.4
	mean:		74	0.64	mean:		92	0.48	
Supermarket chainbrand	0.05	6.4	132	0.64	1.8	9.9	205	0.58	0.63
	0.05	6.0	190	0.69	2.8	9.5			1.36
	0.1	7.1	130	0.70	4	10.9	202	0.58	2.5
	0.1	8.1	124	0.69	5	8.9			3.8
	mean:		144	0.68	mean:		203	0.58	

[a] *V is the deformation rate, H_o the initial specimen height, W the imposed load and R the specimen radius. The consistency K and the flow index n were calculated using Eq.* (5) to (9) employing the procedure described in the text.
[b] The strain rate where log H vs t was a straight line (see Fig. 6).

irrespective of its hypothetical existence (in constant deformation rate experiments) or because the measurements are taken under stresses that exceed its magnitude (in the constant stress experiments). Yield stress, however, can be determined in unlubricated squeezing flow experiments and a procedure for such determination is described elsewhere (Campanella and Peleg, 1987).

Comparison between constant deformation rate and constant stress experiment

The amount of data collected in this study, including additional experiments whose results are not reported in Table 1, and the strong possibility that the specimen history can influence the results, does not allow for a clear cut preference of either test as more meaningful rheologically. Both seemed to be on equal footing and provided a consistent picture with respect to differences between the peanut butter brands. As far as convenience was concerned, the constant deformation tests seemed to be by far the superior. The main reason was that only one curve was required for the determination of the constants K and n. The trial and error needed to select the appropriate load for the constant stress experiments were also avoided and the tests themselves were of much shorter duration. The snag is, of course, the equipment cost. While Universal testing machines are rather expensive, the "creep" experiments can be performed with self-assembled equipment at about a tenth of the cost. Since, however, Universal testing machines are becoming almost a standard item in food research laboratories, the cost becomes a lesser issue. In any case, the cost of such machines is by far less than that of sophisticated rheometers which would otherwise be required for the analysis of materials such as peanut butter.

Other implications

As previously proposed by Sharma and Sherman (1973), the sensation of peanut butter consistency in the mouth is not necessarily based on shear flow. If this is indeed the case, and we believe it is, then rheological parameters obtained by lubricated squeezing flow experiments are more pertinent to those obtained in shear. This may also be the case with respect to peanut butter "spreadability," a factor of prime concern to its manufacturer. Although the force required to spread peanut butter does involve shear, it has a significant component that results from squeezing. The reported experiments were certainly not intended to simulate spreading nor the events that occur in the mouth. Therefore, the reported values of K and n need not be directly related to the textural perception of peanut butter. However, if the stimulus for assessing the consistency of peanut butter sensorily is its resistence to deformation and flow, then it seems that the magnitude of this resistance is far greater than what could be assumed on the basis of shear flow data obtained by a more conventional type of rheometer.

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