Imperfect squeezing flow viscosimetry for commercial refried beans

Viscosimetría de extensión biaxial imperfecta de frijoles refritos

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The imperfect squeezing flow patterns of almost intact canned fat free and vegetarian refried beans of two national brands were determined using all Teflon and grooved metal sensors. The force versus height curves were remarkably reproducible and characteristic of the products and brands irrespective of the upper plate's diameter and the sensor's finish. Both types of product had a very high degree of plasticity but those of one brand were more sensitive to the deformation rate. The consistency of the corresponding products of the two brands could be compared in terms of an apparent stress at a predetermined height (1.5 and 2.5 mm), and their yield stress in terms of an apparent residual stress, or percent force drop, after a given time (60 and 120 s). At a deformation rate of 6 mm/min the apparent stress at a height of 1.5 mm was in the order of 9–11 or 15–19 kPa for the fat free products and 14–15 versus 18–20 kPa for the vegetarian products. After 120 s of relaxation, the stress decayed to about 30 to 60% of its initial level depending on the product and brand. The residual stress level was generally higher when determined with the grooved metal sensors. The products with relatively higher stresses at a given height also showed a relatively slower relaxation pattern suggesting that consistency and apparent yield stress may be related rather than independent properties of refried beans.

Keywords: beans, viscosity, texture, rheology, yield stress

Se ha determinado el comportamiento en el flujo, en ensayos de extensión biaxial imperfecta (compresión de un fluido en un recipiente abierto), de muestras de frijoles refritos (pasta de alubias) de dos tipos comerciales (sin grasa y vegetariano) y de dos marcas comerciales, utilizando sensores de teflón y de metal estriado. Las curvas de fuerza frente a altura eran muy reproducibles y características de los productos y de las marcas, independientemente del diámetro del plato y de la superficie del sensor. Ambos productos mostraron un alto grado de plasticidad pero los de una marca eran más sensibles a la velocidad de deformación aplicada. La consistencia de los productos de las dos marcas eran comparables en términos de esfuerzo aparente a una altura determinada (1,5 y 2,5 mm) y el esfuerzo de fluencia en términos de esfuerzo residual aparente, o porcentaje de caída de fuerza, después de un tiempo dado (60 y 120 s). A una velocidad de deformación de 6 mm/min, el esfuerzo aparente a una altura de 1,5 mm fue del orden de 9–11 ó 15–19, para las muestras sin grasa y de 14–15 ó 18–20 para las de tipo vegetariano, dependiendo de la marca. Después de 120 s de relajación, el esfuerzo se redujo al 30–60% del valor inicial, dependiendo del producto y de la marca. En general, el esfuerzo residual fue mayor cuando la medida se realizó con los sensores de metal estriado. Los productos con mayores valores de esfuerzo a una altura determinada mostraron también pautas de relajación relativamente más lentas, lo que parece indicar que la consistencia y el esfuerzo de fluencia aparente no son propiedades independientes en este producto.

Palabras clave: alubias, frijoles, viscosidad, textura, reología, esfuerzo de fluencia

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INTRODUCTION

With the rise in popularity of Mexican and other 'ethnic' foods, mashed beans have become significant products of the canning industry. A major quality attribute of these products is their consistency, hence the need for a method for its objective assessment. Conventional rheological methods, such as coaxial viscosimetry (Couette, cone and plate or parallel plates) or capillary viscosimetry may not be suitable for such products, especially if they contain particulates of a size in the order of or larger than the sensors' gap, or, in the case of the capillary viscosimeter, the capillary diameter. Uncontrolled slip during the test and/or partial structural disruption during the specimen insertion into the viscosimeter's sensor can also be a problem. The consistency of such products (Bourne, 1982; Steffe and Osorio, 1987) can be assessed by empirical and semi-empirical methods but, because of the arbitrary geometry or ill defined test conditions, the results can not easily be converted into or expressed in terms of generally recognized rheological parameters. A partial solution to all these problems is what is known as squeezing flow viscosimetry (Leider, 1974; Leider and Bird, 1974; Chatraei *et al.*, 1981; Soskey and Winter, 1985) originally introduced into food rheology by Dr Edward Bagley and his group at the USDA–NRRD in Peoria, IL (Casiraghi *et al.*, 1985). This method has since been applied to several food products (Campanella and Peleg, 1987; Campanella *et al*, 1987; Huang and Kokini, 1993; Lo *et al.*, 1999; Ramirez-Wong *et al.*, 1996). It is based on squeezing a thin specimen between parallel plates of the same diameter, hence its name. Since the liquid under the plates maintains a cylindrical shape (although with a diminishing height) the test's geometry is clearly defined. Also, because the specimen is mounted when the plates are separated, structural disruption is dramatically reduced even if not totally eliminated. Thus, the problems created by the forced insertion of the specimen into the narrow gap of a conventional viscosimeter can, to a great extent, be avoided.

Since the formation of a flat cylindrical specimen of semi liquid foods can be inconvenient, it has recently been proposed that the bottom plate of the sensor be replaced by a shallow container (Figure 1). However, this substitution produces buoyancy and creates annular flow and entry effects, hence the name 'imperfect squeezing flow viscosimetry' (Lee and Peleg, 1992; Hoffner *et al.*, 1997; Lorenzo *et al.*, 1997).

As in the ideal configuration, there are two main flow regimes: frictional (Leider, 1974; Leider and Bird, 1974) and lubricated (Chatraei *et al.*, 1981; Soskey and Winter, 1985). In frictional flow, the specimen is sheared throughout and therefore the forces that develop are comparatively much higher than those generated during the plug flow that ensues when the plates are lubricated (see below).

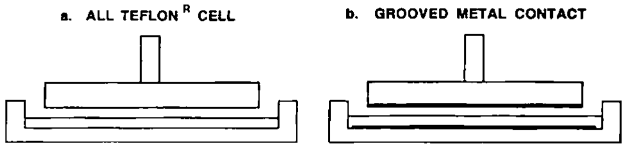

Figure 1. Schematic view of the two types of sensor used in the imperfect squeezing flow viscosimetry of commercial refried beans.

Figura 1. Esquema de los dos tipos de sensores empleados en la viscosimetría de extensión biaxial imperfecta de frijoles refritos comerciales.

The objective of this work was to evaluate the imperfect squeezing flow configuration, previously employed for the rheological evaluation of other food products, as a means of assessing the consistency of commercial refried beans.

Theoretical background

When a flat fluid specimen is compressed between two parallel plates of same radius, R, at a constant displacement rate, V, the forces that develop are a function of the fluid rheological properties, the plate radius, the displacement rate and the friction between the fluid and the plates. In the ideal case of total absence of friction the force–height relationship of a Newtonian fluid having a viscosity μ is given by:

$$F = 3\pi\mu R^2 V/H \tag{1}$$

For a pseudoplastic power law fluid having a consistency coefficient K and a flow index n, $n < 1$, the flow curve is given by:

$$F = \pi R^2 K 3^{(n+1)/2}(V/H)^n \tag{2}$$

Consequently, a plot of the force versus height relationship of Newtonian and power law fluids in logarithmic coordinates, i.e. log F versus log H, will be a straight line with a slope of -1 or $-n$, respectively.

If, however, there is sufficient friction between the specimen and the two plates such that the velocity of the fluid at the interface is zero, then the F versus H relationship for a Newtonian fluid is given by:

$$F = (3/2)\pi\mu R^4 V/H^3 \tag{3}$$

whereas for a pseudoplastic fluid the relationship is given by:

$$F = 2\pi K R^{n+3} V^n [(2n+1)/n]^n / [(n+3)H^{2n+1}] \tag{4}$$

As in the case of the lubricated configuration, the plot of this relationship for Newtonian and pseudoplastic fluids in logarithmic coordinates will be linear, but the slope will be -3 or $-(2n + 1)$, respectively.

Since the flow index of pseudoplastic fluids must be in the range $0 < n < 1$, the absolute magnitude of the slope of the frictional flow curve, when plotted in logarithmic coordinates, must be greater than one. Or conversely, if an experimental F versus H curve, plotted in logarithmic coordinates, has a slope whose absolute magnitude is smaller than one, it can safely be assumed that there is a substantial slip (Hoffner *et al.*, 1997). The situation is not as clear if the absolute magnitude of the slope is between 1 and 3 because it can imply either partial slip, pseudoplasticity or both. However, because the absolute magnitude of the forces in lubricated flow is approximately proportional to R/H or $(R/H)^n$ (where $R/H >> 1$) while in frictional flow it is proportional to $(R/H)^3$ or $(R/H)^{2n+1}$, there are big differences in the force levels. This offers a way to probe whether the flow regime is primarily governed by slip (Hoffner *et al.*, 1997). If, for example, the slip can be eliminated or drastically reduced by grooving the plates surfaces, the result would be a dramatic effect in the forces—by one or more orders of magnitude depending on the R/H ratio. No increase, or merely a modest one, would indicate that the fluid is strongly self lubricating and the slope's absolute magnitude remains below one (Hoffner *et al.*, 1997). However, there is also a theoretical possibility that the material is highly pseudoplastic, bordering ideal plasticity, i.e. $n \sim 0$, in which case the magnitude of the slope will be close to one even in the absence of slip (see below).

Yield stress

If, after an ideal squeezing flow experiment of a Newtonian liquid the crosshead is stopped, the force is expected to drop to zero instantaneously. The same is expected to happen with non-Newtonian fluids provided that they do not have elasticity or a yield stress. In an imperfect squeezing flow experiment, the force is expected to drop not to zero but to a residual level determined by the buoyancy effect. Calculation shows that for foods with a density of about 1g/cm^3, tested with a sensor of the kind used in this work (see below), the buoyancy force is in the order of 0.5 N per mm displacement (Damrau and Peleg 1997; Lorenzo *et al.*, 1997). Thus, if the residual force is in the order of, for example, 10–20 N one can assume that the specimen has a considerable yield stress. The existence of the latter also affects the geometry of the expelled liquid (Figure 2). However, since the role of the annulus effect is not easy to quantify, in such a case the apparent residual stress after a given time was used as a semi-empirical yield stress measure without correction for buoyancy (Lorenzo *et al.*, 1997). It was calculated by:

$$\sigma_{app} = F_{@t=1\text{ or }2\text{ min}} / (\pi R^2) \tag{5}$$

where $F_{@t=1\text{ or }2\text{ min}}$ is the residual force after 1 or 2 min, respectively, and R is the upper plate radius.

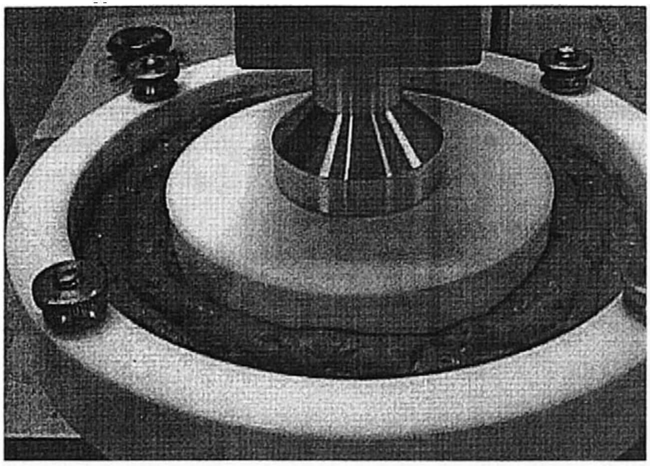

Figure 2. The appearance of a refried beans specimen after being squeezed in an all Teflon® sensor. Note the product rise pattern around the upper plate as an indication of a yield stress.

Figura 2. Aspecto de los frijoles refritos después de ser comprimidos en el sensor de teflón. Obsérvese la forma del producto alrededor del plato superior como indicador de la existencia de un umbral de fluencia.

MATERIAL AND METHODS

Samples

Cans of refried beans, regular vegetarian and fat free, of two national brands were purchased at a local supermarket and their contents tested immediately after opening. No attempt has been made to establish how representative the samples were of their respective products; therefore, the manufacturers are not identified by name.

Mechanical testing

Specimens of the refried beans were gently transferred into an all Teflon® sensor having a container 140 mm in diameter. Subsequently they were compressed by Teflon® upper plates 64 and 100 mm in diameter (Figure 1a) as described by Hoffner *et al.* (1997). In parallel tests a flat thin metal plate 120 mm in diameter was placed at the bottom of the container. This plate had a polished side and a grooved side with concentric grooves about 0.5 mm deep. The plate was placed in such a way that the polished side faced downward, to make a good contact with the cell's bottom, and the grooved side faced upward (Figure 1b). In this configuration the specimens were compressed with similarly grooved upper plates 64 and 100 mm in diameter, as described by Lorenzo *et al.* (1997). The initial height of the specimen was about 6–7 mm in all the tests.

The compression tests were performed with a TA.TX2 Texture Analyzer (Texture Technologies Corporation, Scarsdale, NY) equipped with a 25 kg load cell and interfaced with a Gateway 2000 microcomputer. The specimens were compressed to a final height of 1.5 mm at speeds of 6 and 12 mm/min. In some experiments the crosshead was stopped when the specimen height reached 1.5 mm and the decaying force was recorded for about 3 min before the crosshead was withdrawn. The raw data files were imported to and processed by the Systat 5.0 package (Systat Inc., Envanston, IL). Each test was replicated three times.

Data processing

The recorded raw data were converted into force–height relationships plotted in linear and logarithmic coordinates (see below). The linear part of this relationship was considered as representing the region of dominant squeezing flow (Hoffner *et al.*, 1997; Lorenzo *et al.*, 1997) and its slope was determined by linear regression. The initial part of the flow curves (corresponding to specimen heights down to about 4–5 mm) was considered as reflecting entry effects and therefore discarded. The slope of the linear parts was used to estimate the value of n (Equations 2 or 4) without taking into account buoyancy, secondary flows and end effects (see below). In a similar manner to the residual stress after relaxation (Equation 5) the apparent stress at a specimen height of 1.5 or 2.5 mm, $\sigma_{\mathrm{app@}H\,=\,1.5\ \mathrm{or}\ 2.5\ \mathrm{mm}}$, was calculated by:

$$\sigma_{\mathrm{app@}H\,=\,1.5\ \mathrm{or}\ 2.5\ \mathrm{mm}} = F_{@H\,=\,1.5\ \mathrm{or}\ 2.5\ \mathrm{mm}}/(\pi R^2) \qquad (6)$$

and was used as a semi-empirical consistency measure.

The force decay data were used to calculate an apparent residual stress (Equation 5). The ratios between the residual forces after 1 and 2 mins and the corresponding initial force were also recorded and served as indicators of the stress decay rate. As already stated, the apparent residual stresses without a correction for buoyancy were considered as semi-empirical measures of the specimen's yield stress (Lorenzo *et al.*, 1997).

RESULTS AND DISCUSSION

The curves of F versus H in Figures 3 and 4 are remarkably reproducible and enabled characterization of the products in terms of the various mechanical parameters listed in Tables 1 and 2. Since the tests were performed with upper plates of two diameters (64 and 100 mm), sensors with two kinds of surface finish (Teflon® and grooved metal) and, in some cases, at two crosshead speeds (6 and 12 mm/ min), the internal consistency of the various mechanical parameters could be cross checked.

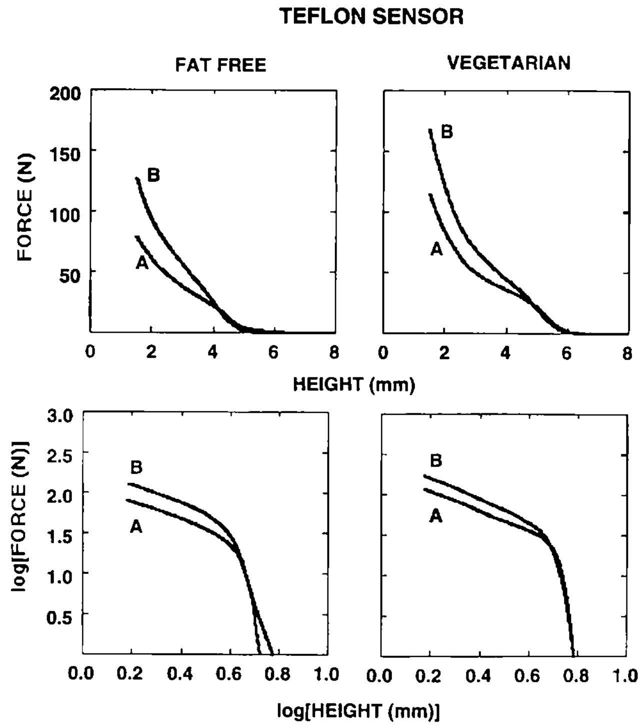

Figure 3. Typical experimental F versus H curves of refried beans obtained with an all Teflon® sensor plotted on linear and logarithmic coordinates. (Upper plate diameter 100 mm, crosshead speed 6 mm/min.)

Figura 3. Curvas experimentales típicas de F vs H de frijoles refritos, obtenidas con un sensor de teflon. (Diámetro del plato superior, 100 mm, velocidad del cabezal 6 mm/min.)

The F versus H relationship and the products' consistency

The slopes of the linear parts of the log F versus log H curves are listed in Tables 1 and 2. Typical values of the two products of manufacturer A were around 1.0, irrespective of the sensor's finish, plate diameter and crosshead speed. This suggests, but does not prove, that the two products in question are almost ideally plastic, that is that their deformability pattern is not rate sensitive at least in the reported range of deformation rates. Slip, although a possibility, did not appear a major factor because neither grooving nor speed had a considerable effect on the shapes of the curves or on the overall force levels. By contrast, the products of manufacturer B had a slope of an absolute magnitude greater than one, irrespective of the sensor's finish and diameter. According to Equation 4, this corresponds to an n value in the order of 0.1–0.25. Compared with other pseudoplastic fluids, such an n value is still very low and would imply an unusually high degree of pseudoplasticity. The ori-

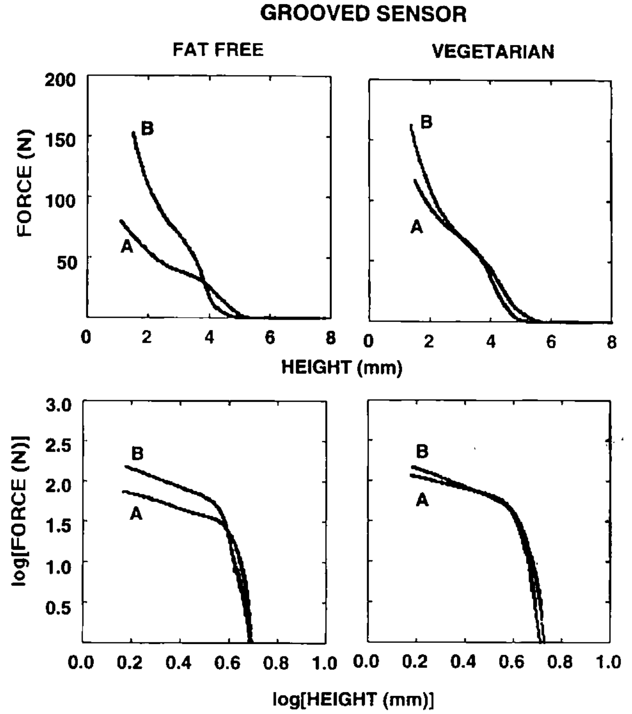

Figure 4. Typical experimental F versus H curves of refried beans obtained with a grooved metal sensor plotted on linear and logarithmic coordinates. (Upper plate diameter 100 mm, crosshead speed 6 mm/min.)

Figura 4. Curvas experimentales típicas de F versus H de frijoles refritos obtenidas con un sensor de metal estriado. (Diámetro del plato superior 100 mm, velocidad del cabezal 6 mm/min.)

gin of the apparent pseudoplasticity of the products of brand B, and the almost total plasticity of those of brand A, is unknown to the authors and may be in a different formulation and/or processing conditions. However, if the calculated magnitude of n is indeed an indicator of rate sensitivity, then the effect of the deformation rate on the stress levels generated in the products of brand B should be appreciably higher than on those of brand A. As can be seen by comparing the respective values of $\sigma_{app@1.5\,mm}$ and $\sigma_{app@2.5\,mm}$ (at 6 and 12 mm/min) in Tables 1 and 2, this was generally the case especially in the grooved sensors. The effect may also have been caused by the yield stress, the role of which in imperfect squeezing flow has still not been fully investigated.

The effect of the upper plate diameter

In principle, the larger the upper plate diameter and the wider the annulus the closer are the results to those of a perfect squeezing flow test (Damrau and Peleg, 1997). There is of course a practical limit to the sensor size, determined by physical considerations—including the difficulty of avoiding a slight tilt. It has previously been shown (Hoffner *et al.*, 1997) that increasing the upper plate diameter did indeed result in higher apparent stresses. But it was also observed that in sensors having geometries similar to those used in this work, the differences were not very large. Comparison of the apparent stresses of the refried beans at a given specimen height (1.5 and 2.5 mm) showed a similar trend. The stresses determined with the wider upper plate (100 mm) were slightly but consistently higher than those determined with the narrower plate (64 mm). However, the products' ranking through their apparent stresses remained unaffected by the sensor's geometry and finish, and by the specimen height at which the apparent stress was determined. Consequently, the apparent stress can serve as a comparative measure of the texture of refried beans, and the validity can be verified by repeating the test with a sensor of a different dimension and finish.

Table 1. Imperfect squeezing flow characteristics of refried beans. Brand A.

Tabla 1. Viscosimetría de extensión biaxial imperfecta de frijoles refritos. Marca A

Product	Sensor	Diameter (mm)	Speed (mm/min)	Slope	$\sigma_{@2.5\,mm}$ (kPa)	$\sigma_{@1.5\,mm}$ (kPa)	$\sigma_{@60\,s}$[a] (kPa)	$\sigma_{@120\,s}$[a] (kPa)
Fat free	Teflon	64	6	−1.1 ± 0.0	5.2 ± 0.5	9.2 ± 1.0	3.5 ± 0.1 (38)	2.9 ± 0.2 (31)
		64	12	−1.1 ± 0.1	5.6 ± 0.4	10.0 ± 1.1	3.4 ± 0.8 (34)	3.1 ± 0.8 (30)
		100	6	−1.0 ± 0.1	5.4 ± 0.6	9.6 ± 0.5	4.6 ± 0.2 (44)	4.2 ± 0.2 (44)
	Grooved	64	6	−1.0 ± 0.1	5.7 ± 0.3	10.0 ± 1.1	5.2 ± 0.9 (52)	4.7 ± 0.9 (47)
		64	12	−1.1 ± 0.1	10.0 ± 2.1	16.5 ± 2.7	8.3 ± 0.9 (51)	6.9 ± 1.0 (43)
		100	6	−0.9 ± 0.1	6.8 ± 0.2	10.9 ± 0.6	6.7 ± 0.6 (61)	6.4 ± 0.6 (58)
Vegetarian	Teflon	64	6	−1.0 ± 0.1	7.3 ± 0.7	13.2 ± 2.6	5.4 ± 1.5 (41)	4.6 ± 1.4 (35)
		64	12	−1.1 ± 0.1	8.7 ± 0.8	14.9 ± 1.2	5.3 ± 0.9 (36)	4.4 ± 1.0 (30)
		100	6	−1.0 ± 0.1	7.8 ± 0.4	13.4 ± 1.4	7.3 ± 0.7 (55)	6.5 ± 0.6 (49)
	Grooved	64	6	−1.0 ± 0.1	8.2 ± 1.9	13.4 ± 2.7	7.0 ± 0.9 (53)	6.0 ± 0.5 (45)
		64	12	−1.0 ± 0.1	10.0 ± 2.1	16.5 ± 2.7	8.3 ± 0.9 (51)	7.0 ± 1.0 (43)
		100	6	−0.8 ± 0.0	10.5 ± 0.4	15.2 ± 0.3	9.2 ± 0.3 (61)	8.2 ± 0.3 (54)

[a] Numbers in parentheses represent the residual force as % of the initial force.

Table 2. Imperfect squeezing flow characteristics of refried beans. Brand B.

Tabla 2. Viscosimetría de extensión biaxial imperfecta de frijoles refritos. Marca B

Product	Sensor	Diameter (mm)	Speed (mm/min)	Slope	$\sigma_{@2.5\,mm}$ (kPa)	$\sigma_{@1.5\,mm}$ (kPa)	$\sigma_{@60\,s}$ (kPa)	$\sigma_{@120\,s}$ (kPa)
Fat free	Teflon	64	6	−1.4 ± 0.0	7.4 ± 0.4	15.6 ± 1.0	7.4 ± 0.7 (47)	6.9 ± 0.6 (44)
		64	12	−1.5 ± 0.1	12.4 ± 1.2	27.0 ± 3.5	12.1 ± 1.9 (45)	11.3 ± 1.7 (41)
		100	6	−1.2 ± 0.1	8.8 ± 1.5	15.4 ± 2.3	8.6 ± 1.3 (56)	8.2 ± 1.1 (53)
	Grooved	64	6	−1.3 ± 0.1	10.0 ± 1.3	18.2 ± 3.1	10.6 ± 2.2 (58)	10.0 ± 2.3 (54)
		64	12	−1.2 ± 0.1	14.4 ± 1.5	27.0 ± 2.6	15.1 ± 1.5 (56)	14.4 ± 1.5 (53)
		100	6	−1.2 ± 0.1	10.2 ± 1.7	18.6 ± 2.1	11.4 ± 1.6 (61)	11.0 ± 1.6 (59)
Vegetarian	Teflon	64	6	−1.4 ± 0.1	8.1 ± 0.3	18.6 ± 1.5	10.1 ± 0.8 (54)	9.6 ± 0.8 (51)
		64	12	−1.4 ± 0.0	10.5 ± 0.3	21.7 ± 0.9	9.9 ± 0.3 (46)	9.5 ± 0.3 (43)
		100	6	−1.3 ± 0.1	10.9 ± 0.7	20.8 ± 0.3	11.9 ± 0.2 (57)	11.3 ± 0.3 (54)
	Grooved	64	6	−1.3 ± 0.0	10.2 ± 0.7	18.3 ± 0.3	11.2 ± 0.5 (61)	10.7 ± 0.5 (58)
		64	12	−1.3 ± 0.1	13.3 ± 1.2	25.9 ± 3.0	14.4 ± 2.7 (55)	13.8 ± 2.7 (53)
		100	6	−1.3 ± 0.1	11.2 ± 0.4	20.4 ± 0.2	13.1 ± 0.3 (64)	12.6 ± 0.3 (61)

Numbers in parentheses represent the residual force as % of the initial force.

As can be seen from Tables 1 and 2, the selection of the height is unimportant as long as it is in the region of dominant squeezing flow, i.e. where log *F* versus log *H* is linear. In principle, the smaller the height the more sensitive is the comparison. Nevertheless, the effective specimen height is limited by two major factors; the smaller the height, the larger the error caused by any uncertainty regarding the true position of the crosshead, and, as the specimen height decreases, any uncontrolled tilt of the sensor will add to this error. As shown in Tables 1 and 2, a height in the order of 1.5–2.5 mm seems to be a workable practical compromise. It was also observed that the presence of solid bean parts had little effect on the shapes of the flow curves and hence on the results of the analysis. Had these solid pieces played a major role, the *F* versus *H* curves would not have been as smooth as recorded. However, if the particles present were bigger and much harder, then the possibility that their deformability had affected the shape of the *F* versus *H* curve could not be excluded.

Relaxation parameters

The apparent stresses of the different types of refried beans after 60 and 120 s of relaxation are also listed in Tables 1 and 2. They show that all the products had a considerable 'yield stress' as judged by the magnitude of these residual stresses. The latter were certainly higher than that expected from a buoyancy effect. In general, the more viscous products, as indicated by the stress level at a given height, also had a higher larger yield stress measure irrespective of how it was determined. In other words, in the products tested, the 'deformation' and 'relaxation' parameters were interrelated. The small effect of grooving on the relaxation pattern suggests that some of the relaxation might have been associated with sliding along the sensor surfaces but this possibility was not confirmed.

The role of the yield stress in the interpretation of the results

The observed relaxation pattern (Figure 5) and the specimen appearance after the test (Figure 2) clearly establish that the four refried beans products all had a significant yield stress (at least on the time scale of the experiments). It was shown by Campanella (1987) that the existence of a yield stress creates a shear free region in the squeezed specimen, thus violating the assumption on which the non-lubricated flow equations (Equations 3 and 4) are based. Consequently, the exact physical meaning of the power law model constants (*K* and *n*) is not as clear as in merely psuedoplastic fluids. This can be a particularly serious problem when the flow rates are low and therefore the rheological response is dominated by the yield stress. A comprehensive treatment of this issue is certainly beyond the scope of this work. Suffice to say that as long as the mechanical parameters previously discussed are considered as apparent values, and are not used to calculate a model dependent on rheological constants, they are valid as textural measures and can be used legitimately for comparison. They are still preferable to the conventional empirical measures currently used to evaluate such products' texture. By contrast, the apparent stresses at a given deformation and after relaxation for a given duration are expressed in universally accepted units, and their magnitude has only a weak dependence on the geometric and other features of the sensor. Because of the small thickness of the tested specimen and its large diameter, the role of artifacts resulting from the imperfect geometry of the array is considerably reduced. Also, the test reproducibility was remarkably high as was previously observed in other products (Hoffner *et al.*, 1997; Lorenzo *et al.*, 1997). Hence, at least in principle the described analysis can be used to detect relatively small differences between products, especially if the tests are performed on a larger number of replicates than in this work. Whether such differences correspond to textural differences that can be detected sensorily is a question that requires a different kind of research. The same applies to the relationship between the described rheological parameters and perceived sensory attributes such as 'consistency', 'thickness', etc. Again, exactly how the mechanical properties of refried beans are perceived and assessed in terms of organoleptic quality is a topic that requires a different type of study.

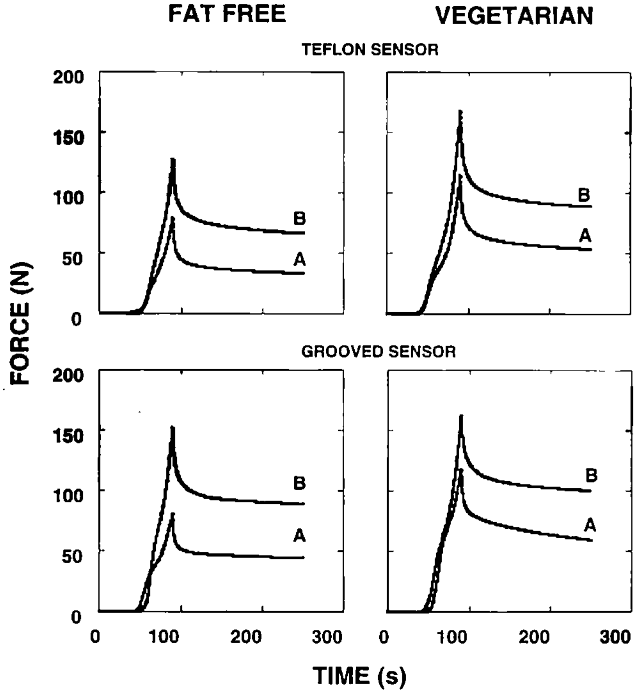

Figure 5. Typical force versus time curves (deformation and relaxation) of refried beans determined with all Teflon® and grooved metal sensors. (Upper plate diameter 100 mm, crosshead speed 6 mm/min, height 1.5 mm.)

Figura 5. Curvas típicas de furza versus tiempo (deformacion y relajación) de frijoles refritos, obtenidas con sensores de teflón y de metal estriado. (Diámetro del plato superior 100 mm, velocidad del cabezal 6 mm/min, altura 1,5 mm.)

CONCLUSIONS

Imperfect squeezing flow is a practical method to assess and compare the texture of refried beans products. Translation of the force–height relationships produced into the familiar rheological parameters (namely the flow index, consistency coefficient and yield stress) is a more difficult task than originally assumed. Nevertheless the method still provides mechanical parameters that are directly related to consistency of the refried beans, and which can be expressed in the universal units of stress. Despite the crudeness of the sensor construction and testing procedure the results were remarkably reproducible. The apparent reason is that the specimens were hardly disturbed prior to their testing—by contrast with conventional viscometric methods where the specimen is sheared uncontrollably during its insertion into the sensor's narrow gap. Also, because the useful data are obtained when the specimen is compressed to a height in the order of 1–3 mm an initial non-uniform height has hardly any effect on the results. Clearly the method is sensitive enough to distinguish between commercial refried beans products on the basis of their rheological properties and it can be used regardless of the presence of suspended bean parts. Whether the differences between the products can also be detected by humans remains to be established by sensory tests.

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