Instrumental methods for evaluating food texture

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Introduction

Food texture has been defined in so many different ways that it would be useful at the outset to indicate the context in which the phrase will be used here. An acceptable definition must cover instrumental and sensory (visual, touch, oral) evaluations of texture, and also the interrelationship between the two methods of evaluation. In order to meet these requirements a definition which resembles that introduced by Szczesniak (1963) is proposed, namely texture is the composite of those properties which arise from the structural elements of the food and the manner in which it registers with the physiological senses (Sherman, 1970). This definition indicates that texture is not a single measurable property but a composite of many properties.

Before deciding which instrumental method to select for evaluating food texture the following points should be considered.

(a) Are data required about the static structure of the food, i.e. employing test conditions which produce only slight structural alteration?

(b) Are data required about the way in which the food will behave under practical usage conditions, i.e. employing more drastic test conditions than under (a)?

(c) Would it suffice to use an empirical method which vaguely simulates the mechanical action associated with product usage?

Tests which provide quantitative information about food texture are usually time-consuming and require rather sophisticated equipment. Consequently, they have not been used extensively and the emphasis has been on the application of semi-quantitative or empirical tests. The latter type of test, however, is useful only for repetitive routine testing where differences between samples need to be recognized but not identified.

The present discussion will be restricted to some of the quantitative and semi-quantitative methods which have been used to study the static structure, and performance in usage, of foods. These are listed in Tables 1 and 2 along with references to the more recent publications which provide data on the foods to which they have been applied.

Quantitative methods for studying the static structure of foods

Test methods may involve the application of stress or strain on a continuous-time basis, or intermittently as in dynamic testing. Four methods (Table 1) which depend upon the application of a constant low shear stress will be described. In all four test methods the strain is measured at different times after the application of the shear stress and by analysis of the curve which is obtained (by plotting

Table 1. *Creep compliance–time studies with foods*

Technique	Applications	Reference
Parallel plate viscoelastometer	Heat-coagulated fish paste	Kishimoto & Maekawa (1962)
	Frozen ice cream	Shaw (1963)
		Shama & Sherman (1966, 1968)
	Cake	Shama & Sherman (1968)
	Margarine, butter	Shama & Sherman (1970)
Compression between parallel plates	Fruit, vegetables	Somers (1965), Mohsenin & Göhlich (1962); Mohsenin *et al.* (1963)
	Bread	Cornford *et al.* (1964)
	Margarine, butter	Sone (1961), Sone *et al.* (1962)
Extension	Noodles	Shimizu *et al.* (1958)
	Hydrocolloid gels	Ward & Cobbett (1968)
	Meat	Bendall (1951), Bendall & Davey (1957)
	Dough	Glucklich & Shelef (1962a, b), Shelef & Bousso (1964)
Coaxial cylinder viscometer	Melted ice cream	Whitehead & Sherman (1967)
	Cream	Prentice (1968), Prentice & Chapman (1969)

strain against time) the texture of the sample can be defined as the sum of several physical measurements.

Many food materials are viscoelastic, so that they exhibit some of the properties of both solids and liquids when subjected to a shear stress. Provided a linear viscoelastic response is observed, i.e. the stress increases linearly with shear, the following method of analysis can be applied.

Theory of creep compliance–time studies

The shear stress can be applied in simple shear, in compression, or in extension, but in all three cases a plot of the ratio of strain:shear stress, which is known as the creep compliance, against time gives a curve with the general form shown in Fig. 1. It can be subdivided into three characteristic regions.

(1) A region of instantaneous elastic compliance (AB) in which linkages between the basic units of the microstructure are stretched elastically. If the shear stress were removed at B then the sample would recover its original structure and dimensions. The instantaneous elastic compliance J_0 is given by

$$J_0 = \frac{\epsilon_0(t)}{p} = \frac{1}{E_0}, \tag{1}$$

where $\epsilon_0(t)$ is the instantaneous strain at small values of the time t, p is the shear stress, and E_0 is the instantaneous elastic modulus.

(2) A region of retarded elastic compliance (BC) in which the rate of strain decreases gradually owing to rupture of linkages. At the lower end of the time-scale associated with this region, few linkages remain permanently broken, but at the higher end, the number of linkages which do not reform is much larger. Normally, all linkages in a sample do not have identical strength; instead, there is a spectrum of strengths with the weaker linkages breaking after shorter times than the stronger linkages.
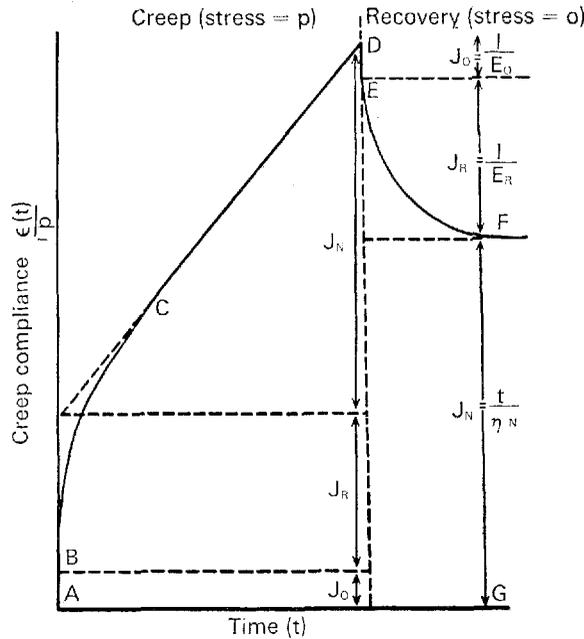
Fig. 1.   Model creep curve.

This region is characterized by a retarded elastic compliance J_R, where

$$J_R = \frac{\epsilon_R(t)}{p} = J_m[1 - \exp(-t/\tau_m)] = J_m[1 - \exp(-t/\eta_m J_m)] \tag{2}$$

and $\epsilon_R(t)$ is the strain at any time t in the retarded elastic region, J_m is the mean compliance of all the linkages undergoing rupture and redevelopment, τ_m is the mean retardation time, J_m $(=1/E_m)$ is the mean retarded elastic compliance, and η_m is the mean viscosity in this region. When greater detail is sought about the compliances associated with this region, equation (2) is replaced by

$$J_R = \frac{\epsilon_R(t)}{p} = \sum_i J_i[1 - \exp(-t/\tau_i)] = \sum_i J_i[1 - \exp(-t/J_i\eta_i)], \tag{3}$$

where J_i $(=1/E_i)$, so that there is now a spectrum of retarded elastic compliances J_1, J_2, J_3, $---$ J_i and associated viscosities η_1, η_2, η_3, $---$ η_i.

(3) A region of Newtonian compliance (CD) in which the rate of strain is constant. Once the linkages have ruptured, and are unable to reform during the time-span of the test, the micro-units are able to move past one another. The slope of CD gives the Newtonian viscosity η_N.

The Newtonian compliance J_N is given by

$$J_N = \frac{\epsilon_N(t)}{p} = \frac{t}{\eta_N}, \tag{4}$$

where $\epsilon_N(t)$ is the strain at any time t in the Newtonian region.

If the stress is removed at D then the strain decreases in two stages, initially an instantaneous elastic decrease (DE) and this is followed by a retarded elastic decrease (EF). Since part of the micro-structure was destroyed in the region CD, when stress was applied, recovery is never complete. The distance FG is proportional to the amount of structure which has been destroyed.

The creep compliance–time curve ABCD is represented by the sum of equations (1), (2) or (3), and (4),

$$J_t = J_0 + J_R + J_N = J_0 + \sum_i J_i[1 - \exp(-t/\tau_i)] + \frac{t}{\eta_N}. \tag{5}$$

This also constitutes a definition of the texture of the sample at a specified shear stress condition, since any method for assessing texture involves the response of the sample to the application of a mechanical force.

Both the compliance J_0 and η_N are calculated direct from the creep compliance–time curve (Fig. 1). Analysis of the retarded elastic compliance region and identification of the constituent elastic moduli and viscosities involve a more complex graphical procedure (Inokuchi, 1955).

In equation (3) let

$$\sum_i J_i - \frac{\epsilon_R(t)}{p} = Q; \tag{6}$$

then

$$\sum_i J_i \exp(-t/\tau_i) = Q, \tag{7}$$

so that Q is the distance at any time t between the extrapolated linear part (CD) and the retarded elastic region of the creep compliance–time curve (Fig. 1). If $\log_e Q$ is plotted against t (Fig. 2a) a straight line should be obtained at large values of t. By extrapolating this linear region back to zero time, J_1 is derived as an intercept on the $\log_e Q$ axis, and τ_1, the first retardation time, is calculated from the slope of the extrapolated line. The values of J_1 and τ_1 are now introduced into equation (3), and if it does not give a plot which satisfactorily reproduces the retarded elastic region of the creep compliance–time curve then a second plot has to be made of $\log_e [Q - J_1 \exp(-t/\tau_1)]$ against t. This plot is also linear at large values of t provided $\tau_1 > \tau_2$, and J_2 and τ_2 are derived in the same way as J_1 and τ_1. With the example quoted in Fig. 2b the whole of the second plot can be approximated by a straight line so that the analysis is complete at this stage. When the calculated and experimental plots do not coincide at this stage it is necessary to make further plots of $\log_e [Q - J_1 \exp(-t/\tau_2) - J_2 \exp(-t/\tau_2)]$ versus t, etc.

Experimental techniques for studying creep compliance–time behaviour

Parallel plate viscoelastometer. This method is applicable to solid and semi-solid foods which can be cut into rectangular slabs. Samples (S and S_1 in Fig. 3) of cross-sectional area A_r and thickness h are placed on either side of a thin, ribbed, metal plate
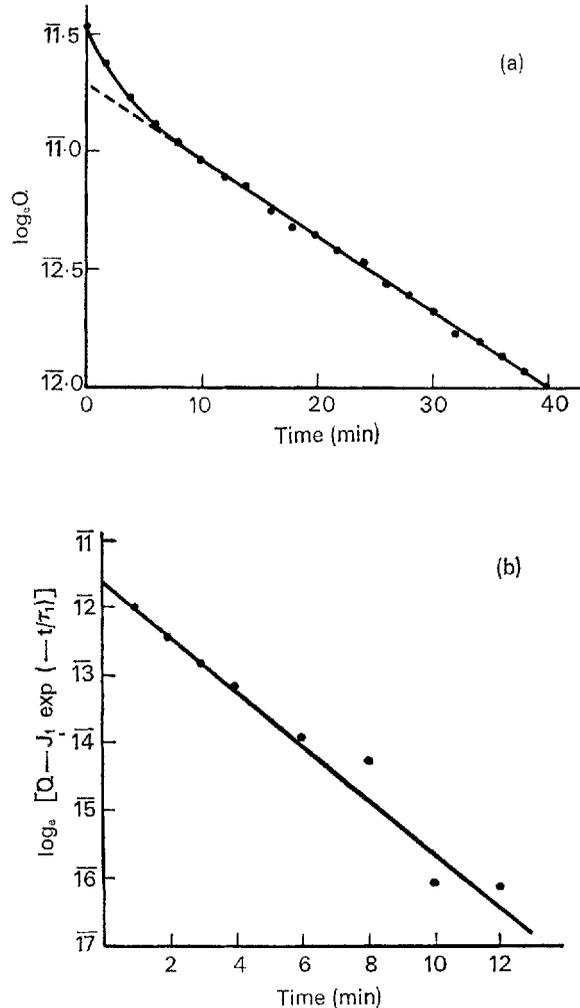
Fig. 2.   a, plot of $\log_e Q$ v. time; b, plot of $\log_e [Q - J_1 \exp (-t/\tau_1)]$.

D so as to form a sandwich, and this conformation is introduced into the visco-elastometer between the fixed, lower, ribbed plate A and the mobile, upper, ribbed plate B. Plate B is then lowered gently by means of a screw device until it just makes contact with the upper surface of sample S_1. A weight (mg) is placed on the balance-pan W, which is connected to plate D by a cord which passes over two low-friction pulleys P and P_1, and this imposes a shear stress on samples S_1 and S_2. The resultant strain is determined from the movement (c) of plate D, which can be followed by means of a travelling microscope focused on a knife edge (e.g. a thin piece of razor-blade) (K) screwed into the rear of plate D, or by more sensitive instrumentation incorporating a differential inductance displacement transducer with a transducer meter and a T–Y recorder. The transducer is mounted on the frame of the visco-elastometer and its free armature is screwed into a hole at the rear end of plate D.
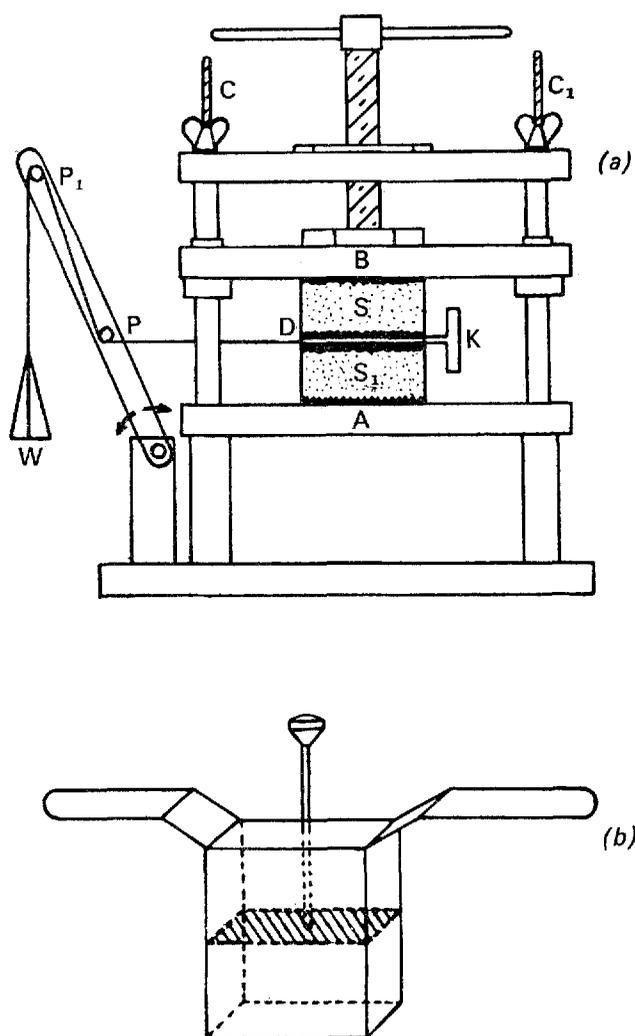
Fig. 3.   Parallel plate viscoelastometer. a, creep apparatus, A, B, D, ribbed plates; C, C_1, constant compression device; S, S_1, samples; P, P_1, pulleys (low friction); W, weight-pan; K, knife-edge; b, sample cutting device.

Shear stress (p) is calculated as $mg/2A_r$, and shear strain ϵ (t) as c/h. The greater sensitivity offered by electronic recording equipment allows one to work at lower shear stresses. This means that damage to sample structure during the test is minimized and, also, that the response of the sample is more likely to be linear viscoelastic. At higher shear stresses many foods exhibit non-linear viscoelasticity, and in this region the method of analysis is much more complex and equations (1)–(5) cannot be applied.

Compression between parallel plates. A sample of cylindrical shape is placed on a solid metal block, which is screwed into the base of a heavy metal stand, and a load (mg) is applied via a metal plate connected by a vertical rod to a platform on to

which slotted weights are gently lowered by a pulley system (Fig. 4). Both the metal block and the metal plate have diameters greater than that of the sample so as to ensure that the latter is subjected to pure compressional shear. The vertical rod
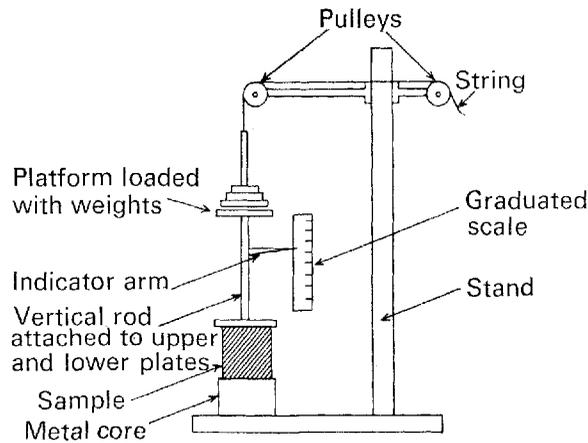

Fig. 4.   Compression between parallel plates.

support of the load platform carries a horizontal indicator arm, and the change in sample height with time is followed by focusing a travelling microscope on this indicator arm. Alternatively, the electronic recording equipment described in the previous section can be used.

The stress/unit area is given by $(mg/A) (h_a/h_b)$, where h_a and h_b are the heights of the sample before and after loading respectively. When small loads are used $h_a \approx h_b$, so that this reduces to $mg/_A$. Assuming a Poisson ratio of 0·5, $p = mg3A/$. The shear strain $\epsilon(t)$ is equal to d_n/h_a, where d_n is the deformation.

Extension testing. Extension tests apply stress in the reverse direction to compression tests. A long strip of sample is held at both ends in metal clamps (Fig. 5). One of the clamps is held stationary while the other clamp moves outwards at a constant speed so that the sample is slowly stretched. The extensometer frame
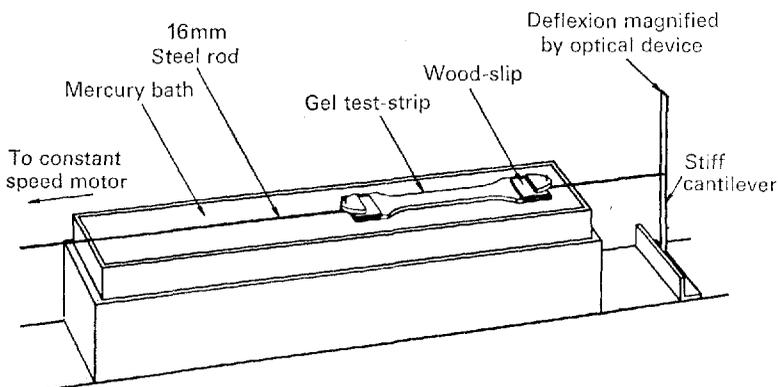

Fig. 5.   Extension testing.

usually holds the sample in a vertical plane, but in some special cases, e.g. when testing dough or gelatin gels, the frame is aligned in a horizontal plane with the sample resting on the surface of a mercury bath so that sample weight does not contribute to strain development. Strain development with time is followed either by an indicator arm and travelling microscope or with the more sensitive electronic recording equipment.

The stress is defined by $mg/3A$, as for compression, and the strain by d_n/l_a, where l_a is the original sample length.

Coaxial cylinder viscometer. Both fluid and semi-solid foods can be studied with a simple coaxial cylinder viscometer. (Fig. 6) The inner cylinder is suspended in the
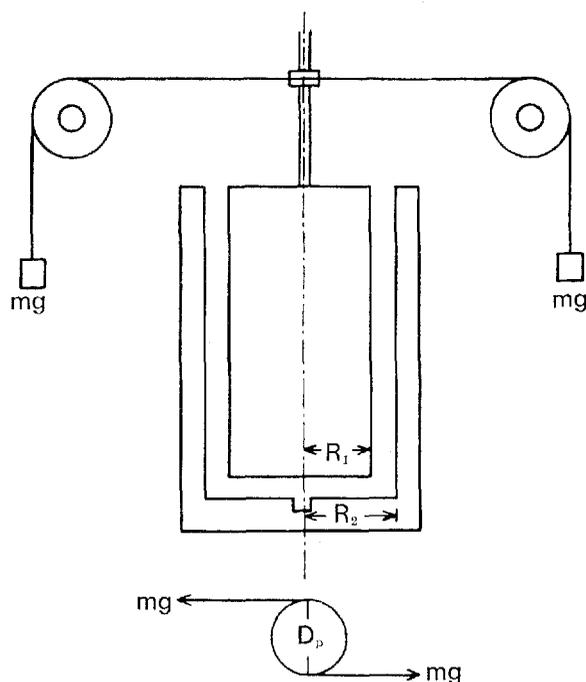

Fig. 6.   Coaxial cylinder viscometer.

middle of the outer cylinder by a thin torsion wire which is attached at its upper end to a torsion head. The surfaces of both cylinders which come into contact with the sample are preferably roughened or ribbed so as to prevent the sample from slipping along these surfaces during the test. After the sample has been introduced into the gap (4 mm width in this instance) between the two cylinders, the inner cylinder is made to rotate slowly by means of a pulley and weight arrangement, or alternatively by means of an electromagnet. The angular rotation (Ω_i) of the inner cylinder with time can be followed optically, or electronically by registering the motion of a small horizontal bar attached to the torsion wire.

The stress is given by $(mgD_p)/\pi(R_1+R_2)h$, where R_1 and R_2 are the respective radii of the inner and outer cylinders, D_p is the pulley diameter, and h is the height of the sample in the viscometer. The strain is defined as $R_1\Omega_i/(R_2-R_1)$.

Semi-quantitative test methods (Table 2)

The Instron Tester. This instrument (Instron Ltd, High Wycombe, Bucks) is capable of examining samples in compression or extension. It differs from the

Table 2. *Semi-quantitative test methods for foods*

Technique	Applications	Reference
Instron tensile tester	Potato	Somers (1965), Kulwich *et al.* (1963)
	Potato chips	Bourne *et al.* (1966)
	Apples	Bourne (1965), Somers (1965), Kulwich *et al.* (1963), Bourne *et al.* (1966), Brennan *et al.* (1970)
	Pears	Somers (1965), Bourne (1968)
	Carrots	Howard & Heinz (1970)
	Cheese, cakes	Brennan *et al.* (1970)
	Cherries	Bourne *et al.* (1966)
General Foods Corporation Texturometer	Wide range of foods	Szczesniak *et al.* (1963)
	Cake, lemon chiffon pudding, dog food, bran flakes	Friedman *et al.* (1963)
	Strawberries	Szczesniak & Smith (1969)
	Biscuits, apple, cheese, cake, toffee, fish, banana, potato, turnip, chocolate	Brennan *et al.* (1970)
Lee-Kramer shear press	Meat	Kramer *et al.* (1951), Kramer & Backinger (1959)
	Peas	Angel & Kramer (1969)
	Fruit gels	Kramer & Hawbecker (1966)
	Apple, cheese	Brennan *et al.* (1970)

instruments described previously in that the stresses applied are much larger. Basically, it comprises a heavy metal frame with a moving cross-head. By attaching special grips to the upper part of the frame and the upper side of the cross-head, extension tests can be made on sample strips using controlled rates of elongation. Alternatively, a specially designed plunger can be attached to the underside of the cross-head and compression studies can then be made on samples resting on a supported table. Load cells incorporating foil-type strain gauges measure the applied load. Manual controls allow the cross-head speed to be adjusted as required. The control console incorporates a recorder for automatic plotting of force–distance curves. Other accessories are available for cyclic application of the load, and also for computing the area under the strip chart graphs.

The published literature contains several references to specially designed accessories which have been used in conjunction with this machine to test selected products, e.g. for apples, potato chips, cherries—flat compression plates, a cylindrical compression box, needles and punches of various diameters and shapes, a plate of thirty needles, a single needle, a tube cutter, a cell of a Lee-Kramer shear press; for apple—Magness-Taylor pressure tips; for meat—stainless–steel penetrometer; for carrots—a special compression device.

General Foods Corporation Texturometer. The Texturometer (Zenken Co. Ltd, Tokyo, Japan) is stated to be 'an instrument which simulates the motions of mastication in the mouth by means of a mechanical chewing arrangement. It consists basically of a sample holder, in the form of a plate or cup, and a plunger connected to an

arm which is driven eccentrically by a 1/16 horsepower 50–60 cycle motor. A strain gauge is located on the sample plate and, in conjunction with a high-speed recorder, it registers the force–time behaviour of the sample when subjected to the action of the plunger. The motor incorporates two pairs of tooth gears so that it provides four rates of plunger action. It has been found that a speed of forty-two bites/min gave the most reproducible results. Plungers of different materials, shapes, and sizes are now available. A flat, lucite plunger (approximately 18 mm diameter and 25 mm length) is recommended for most foods, although a large, 50 mm diameter brass plunger is considered more suitable for semi-solid foods. A tooth-shaped brass plunger is claimed to give 'optimum conditions' for French-fried potatoes.

Fig. 7 shows a typical force–time curve obtained with the General Food Texturo-meter. Reading from right to left, the first peak represents the initial penetration, and the inverted peak below the horizontal (time) axis represents withdrawal of the plunger from the sample. Further penetration and withdrawal motions of the plunger provide an alternating series of both types of peak. All textural attributes, except viscosity, are evaluated from these traces. Viscosity is determined by using a rotating paddle attachment, instead of the plunger, which is immersed in a cup containing the sample. Brittle foods give force–time curves with many peaks, and brittleness is measured as the height of the first significant break in the peaks. Chewiness is calculated as the product of hardness, cohesiveness, and elasticity.
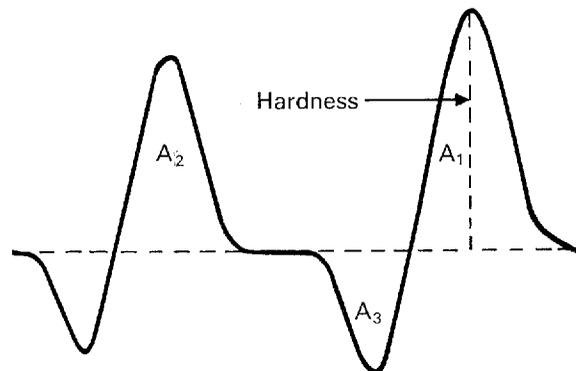

Fig. 7.   Typical trace obtained with General Foods Corporation Texturometer. Hardness = height of first peak/V input; cohesiveness = A_2/A_1; adhesiveness = A_3.

Bourne (1968) pointed out that the plunger moves through an arc of a circle, and that the area of contact between the sample and the plunger increases on the downward stroke of the latter and it decreases as the plunger rises. He suggested that more valid curves would be obtained with an Instron tester in which an inverted load cell is fitted with a flat horizontal plate for compressing the sample. Irrespective of whether this view is correct or not, analysis of data obtained with the Instron tester or the General Foods Texturometer is more complex than has been admitted. As compression or indentation of a sample proceeds, the force/unit area changes and this is not allowed for in subsequent analysis of the data. In

addition, the magnitude of any measurement used to assess texture depends not only on the force which is applied but also on the rate at which it is applied.

Lee-Kramer shear press. In the most recent form this instrument comprises a test cell, a sample-holder box, a hydraulic drive system, and a dynamometer. The test cell has ten bars which are 0·124 in (3·12 mm) thick and 0·126 in (3·20 mm) apart, and the sample box has an equivalent number of slots in its base. A sample is placed across the bars of the sample box, and the bars of the test cell are driven at a pre-selected speed, by means of a piston, through the sample. This results in sample compression and extrusion. The force acting on the sample is measured by com-pression of a proving–ring dynamometer operating within 100–5000 lb (45·4–2268 kg), and it is registered on a calibrated scale. If a recorder is linked up to the shear press, a force–time curve can be obtained. Cutting and compression cells are avail-able in addition to the shear cells.

Applications of instrumental methods for evaluating food texture

Published literature does not provide consistent evidence of statistically signifi-cant correlations between sensory evaluations of textural properties and data obtained with the Instron Tester, the General Foods Corporation Texturometer, and the Lee-Kramer shear press. This is not surprising since the mechanical action to which samples are subjected when tested with these instruments is rather complex. Recently, various foods have been tested with all three instruments (Brennan, Jowitt & Mughsi, 1970). It was found that the Texturometer gave reproducible results only with rubber; otherwise, the results were dependent on the sample dimensions, and the reproducibility decreased with increasing hardness of the samples. With some foods, instrumentally evaluated criteria (Texturometer 'hard-ness' and shear press 'maximum force') correlated with sensory evaluated criteria ('firmness' and 'crispness'), but no well-defined correlation pattern emerged for all the foods that were tested. Unpublished work by Dr A. Szczesniak and her colleagues confirms that data obtained with the Lee-Kramer shear press also depend on sample dimensions.

Quantitative test methods such as creep compliance–time studies have been used to characterize the textural properties of many foods, and to study the interrelation-ships between structure and texture. These methods do not suffer from the limita-tions of the three other instruments which have been described.

Perhaps the most important application of any test method it its ability to pro-vide data which could be used to predict consumer evaluation of textural properties. This requires a knowledge of the forces which operate when the food is consumed, so that the correct test conditions can be applied when testing the food instru-mentally. Such information is essential since the measured textural properties of most foods depend on the mechanical forces to which they are subjected during testing. Work on this problem, as it applies to the assessment of the viscosity of fluid foods, was done initially by Wood (1968), and more recently in the author's labora-tory. A similar study is now required of the correct test conditions for semi-solid

and solid foods. This latter problem is infinitely more complex since it involves the study of a much larger number of textural properties.

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Some aspects of the measurement of flavour

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The nutritional importance of those constituents of food which contribute to flavour is not due to their fulfilling a bodily requirement, but to their influence on acceptance and, therefore, consumption of food. Consequently, flavour is a factor