J. Fac. Appl. Biol. Sci.,
Hiroshima Univ. (1983), 22: 43～54

A Laboratory Assembled Simple Apparatus for Objective Measurements of Mechanical Parameters of Foods

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Received: March 12, 1983.
(Fig. 1–4; Table 1–2)

INTRODUCTION

For the establishment of objective measurements of the physical parameters of food, pioneering work has been done twenty years ago, so that it is possible to designate in a clear-cut way the basic definitions of the textural parameters involved. This thorough analysis resulted in the significant elimination of a vast series of unnecessary terms and in the acceptance of five independent mechanical parameters and three dependent ones. This work led to the design of the popular General Foods Texturometer[1–5]. Even more famous is the Texture Profile Analysis technique which has had considerable influence in the advance of texture test techniques. However, before the appearance of this instrument, there did exist in fact others, although this one has been concentrated on specific physical parameters: the shear press and the tenderometers for the measurement of tenderness by recording the force necessary to shear test materials; the gelometers to measure the firmness and the strength of gels; the consistometers and the viscometers for the measurement of the resistance of the test material to flow under application of force; the compressimeters for the determination of the hardness by measuring resistance to applied force, just to name but a few examples.

Another turning point in the study of food texture was when in 1966 Borne began using the Universal testing machine[6–8] for food materials, which then exclusively restricted to the testing of textiles, paper, plastics and rubber. This istrument is now accepted as the standard means for the study of the textural parameters of foods. It is recognised as the one which gives a complete picture of all the textural properties. Moreover, some recognise the Universal Testing Machine even as the principal instrument for performing texture profile analysis too[9–19].

Both the General Food Texturometer and the Universal Tesing Machine have become quite specialised tools and expensive. Furthermore, acceptable substitutes such as the Rheometer[20] and Dynagraph[21,22] populary used in Japan are expensive too. This is the reason why we undertook to assemble a simple, unexpensive yet reliable apparatus possessing some value in practical applications when the textural quality of the food can be related to the measured property and which can also be modified at the Laboratory level for to widening its versatility at minimal costs to the investigator.

DESCRIPTION OF THE APPARATUS

A simplied representation of the apparatus is shown in Fig. 1. The main body of the instrument consists of three sub-parts of significance. The electric synchronous motor is the leading part for it is this component that makes the articulation of the whole appratus possible. A synchronous motor has been used here because this is the most reliable and simple way to obtain constant deformation speeds. The motor drives a screw that carries a system of pulleys which in turn are connected to an other pulley attached to a screw carrying the deforming member. In over all the arrangement takes a V-shape form. The system of pulleys at the apex of the V-shape allow the manipulation (selection) of the speed of deformation. Setting up the arrangement so that the speed variation pulleys are on a different screw, not only eliminates unnecessary congestion at the screw carrying the deformation member, but also creates two advantageous mechanical relations namely: the mechanical advantage between the pulley at the motor and the set of pulleys at the apex of the V-shape and the mechanical advantage between the latter and the pulley at the screw carrying the deformation member. So far three speeds are possible with possibility for more if necessary. The lowest speed has been selected in such a way that it is not too low to allow stress relaxation place in the samples during the compression experiments.

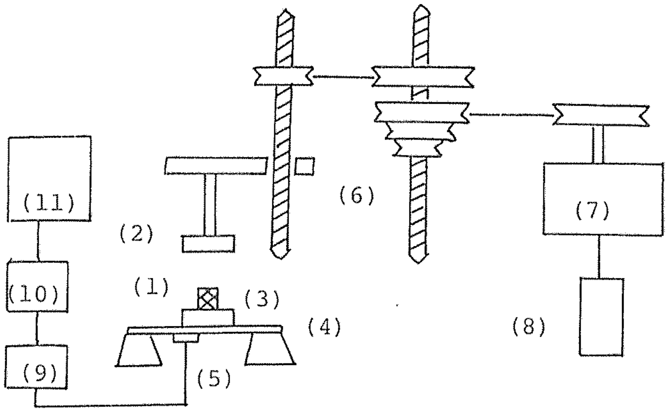

Fig. 1 Experimental apparatuses of compression testing machine used for determination of rheological parameters
(1) sample, (2) upper crosshead plate, (3) lower sample support plate, (4) metal spring plate, (5) strain gauge, (6) pulley system, (7) cynchronous motor, (8) crosshead direction changing switch, (9) Wheastone bridge, (10) strain smplifire, (11) voltage recorder

The deforming member is the part that directly applies the force that deforms the sample. This part is attached to a single screw whose rotation may lower or raise the member. As this priliminary experiments deal mainly with the application of constant stress, a flat plate made of acrylic resin was attached. The size of the plate is slightly larger than the size of the samples. The third part of the apparatus consits of a transducer, by measn of which the mechanical forces experienced during the sample compression are translated into an electric signal. The transducer has been fabricated from a plate of copper alloy to which a pair of sensitive strain gauges, one on either side have been attached. On the same plate the sample position has been made by fixing it in close contact with an acrylic seat. During the experiments, the slippage of the sample was a major drawback but this was easily overcome by making a crisscrossed surface on the acrylic seat thus providing a firm attachment. The pair of strain gauges are then connected to a Wheatstone bridge head, the output of which is fed into an amplifier and finally the output of the latter becomes the input of the recorder, the last two components being common components in this type of food texture measuring methods. The recorder traces a force deformation curve.

PREPARATION OF SAMPLE MATERIAL

The preparation of the sample material for this type of analysis has been reported repeatedely, and the most widely used technique as so far has been the use of a cock borer to scoop cylindrical smaples from the test material. While this could stay on as the most satisfactory way for materials such as fruits from which uniform and representative specimens are possible, the method suggested here might be considered a satisfactory one for food gels too. The desired amount of agar powder was dissolved in 100 ml water by heating the suspension in a bath of 100° C, under reflux conditions, for 30 minutes. The hot solution was quickly poured into an acrylic tube of a fixed diameter whose inside had been lined with a cellophane membrane of nearly the same diameter, the membrane was closed at one end to keep the solution. Agar was used as the experimental material because this stuff serves very well as a food model that yields an isotropic and homogenous material by simply cooling a molten solution. Now the whole arrangement was cooled of by submersion in a waterbath of 20° C during one hour. At the end of this period, the solodified agar gel cylinder was taken out of the tube by means of the membrane and that then was torn away. In this manner, it was possible to obtain samples without application of excessive force as would have been the case if the sample had to be recovered from a cock borer.

The use of the acrylic tubing was required because if the membrane were to be used on its own, the resulting cylinder could not keep its uniformity due to deformation of the membrane by the hot agar solution. The cylinders obtained were trimmed into 10 mm lenght by a pair of blades mounted in parallel.

The boiling under reflux of the agar served not only to prepare the molten solution but also had the beneficial effect of expelling the air from the original material and this resulted in a sample free of any recognisable air spaces.

EXPERIMENTAL

The initial step in this experiment was to calibrate the apparatus such that the profile curves obtained could be interpreted in terms of force time curves. This calibration was done by means of a mercury of various amounts which was poured into a tube of the same area contact as the sample. From the amount of mercury taken and the responce from the recorder, a force-height calibration curve was obtained. Discs of diameter 27 mm and length 10 mm were cut out of the cast cylinder and subjected to uniaixl compression at different speeds.

RHEOLOGICAL PROPERTIES

1. True stress and strain

Force-deformation curves have been transformed into "true" stress-strain curves by taking into account the cross-sectional area expansion and change in specimen length during compression[18,23–26].

The cross-sectional area of the specimen is considerably expanded and therefore cannot be approximated by the original area. For an incompressible material and with the assumption that the specimen retains its shape during deformation[26]:

$$A_t = A_0 \,[L_0 / (L_0 - \Delta L)] \tag{1}$$

where, A_r (cm^2) is the actual cross-sectional area, A_0 (cm^2) and L_0 (cm) are the original cross-sectional area and height of the underformed specimen, and ΔL (cm) is the absolute deformation length. The true stress is defined as:

$$P_t = F / A_t \tag{2}$$

where, P_t (dyn/cm^2) is the true stress and F(dyn) is the compressing force on the specimen.

The true compressive strain under these condition is[26];

$$\varepsilon_t = \ln\, [L_0 / (L_0 - \Delta L)] \tag{3}$$

where, ε_t = (–) is the true strain.

For a small deformation range the stress and strain can be approximated based on the original cross-sectional area and height as follows:

$$P_0 = F / A_0 \tag{4}$$

$$\varepsilon_0 = \Delta L / L_0 \tag{5}$$

where, P_0 (dyn/cm^2) and ε_0 (–) are the stress and strain based on the original sectional area and height, respectively. These stress and strain were used on the stress-strain data under compression of agar gels at a constant deformation rate by Omura et al[21].

2. Simple physical parameters

Breaking energy per unit volume for the force-deformation data is [19], [21]:

$$E_{tf} = \int_0^{\varepsilon_{tf}} P_t \, d\varepsilon_t \tag{6}$$

$$E_{0f} = \int_0^{\varepsilon_{0f}} P_0 \, d\varepsilon_0 \tag{7}$$

where, E_{tf} and E_{OF} (erg/cm^3) are the true breaking energy and the one based on the original cross-sectional area and height of the specimen.

The well defined term elastisity modulus should be avoided[27] in the case of non-linear stress-strain behaviour or where the upper limited of the elastic region is unknown. In this paper the modulus will be refered to as an approximated value. Young's modulus for elastic deformation is:

$$k_{tf} = P_{tf} / \varepsilon_{tf} \quad (8)$$

$$k_{of} = P_{of} / \varepsilon_{of} \quad (9)$$

where, P_{tf} (dyn/cm^2), , ε_{tf} (–) and k_{tf} (dyn/cm^2) are the true breaking compressive stress, strain and Young's modulus. P_{of} (dyn/cm^2), ε_{of} (–) and k_{of} (dyn/cm^2) are the ones based on the original cross-sectional area and height.

The parameters were calculated by using the digital computer of the Computation Center in Hiroshima Univ., HITAC M-180.

RESULTS AND DISCUSSION

1. Basic test of apparatus

For the basic test of the machanical testing machine made by us, the force-compression tests on cylindarical samples of homogeneous agar gels are studied. Compression testing of solid foods is now a well-established method for the evaluation of the physical properties such as strength, rigidity, toughness[12].

The force-compression data were recorded with a voltage recorder. This recorder was used at the full scales of 0.5 or 1.0 volt. The relationships between the forces and the recording scales were obtained by using cylindrical bottles of mercury and iron blocks whose weight was measured by a balance. The relation was linear in our testing region.

$$F = a \cdot h \quad (10)$$

where, h(cm) is the recording chart height, and a is a constant.

The compressing time was obtained by using the recording chart length and the writing speed.

$$t = x / v_r \quad (11)$$

where, t(sec) is the compressing time, v_r(cm/sec) is the recording speed and x(cm) is the recording chart length.

The compressing length by the crosshead was obtained as follows:

$$\Delta L_1 = v_h \cdot t \quad (12)$$

where, ΔL_1 (cm) is the compressing length by the crosshead, v_h (cm/sec) is the crosshead speed and t(sec) is the compressing time.

The sample lower support plate on the metal plate with a strain gauge was influenced with the weighing force. The relationships between the influencing length and the force were obtained by using a telescope. The relation was obtained as follows:

$$\Delta L_2 = b \cdot F \tag{13}$$

where, ΔL_2 (cm) is the influenceing length of sample lower support plate and b is a constant.

Then, the absolute deformation is obtained as follows:

$$\Delta L = \Delta L_1 - \Delta L_2 \tag{14}$$

where, ΔL (cm) is the absolute deformation length of the samples. The value of ΔL_2 was smaller than that of ΔL_1, in fact less than 10%.

The cynchronous motor and the pulley system's speed were influenced by increasing forces. The relationship between the force increase and the resultant decelerating effect was investigated with a spiral spring of 7.82 cm length and 2.4 cm diameter. This was a steel spring with a diameter of 0.165 cm and was found to have a value of Young's modulus which approximates that of the specimen. From this data, the true cross head speed was evaluated from the following relationship:

$$\nu_{ht} = c \cdot v_h \tag{15}$$

wehre, ν_{ht} (cm/sec) is the true value of the crosshead speed, and c is a factor. The value of this factor was found to change in two ways, namely from the origin to a point of force 8.2 X 10^5 dyn, c=1.0 and thereafter decreased exponentially. The value of this factor could be represented by the expressions:

$$F \leqq c_1 : \quad c = 1 \tag{16}$$

$$F > c_1 : \quad c = \exp[-c_2(F - c_1)] \tag{17}$$

where, c_1 and c_2 are constants.

2. Data for the compression test

The compression tests using this apparatus with agar gel samples were done at 20° C, this means the same temperature at that where in the samples were maintained in the water bath. The samples were compressed till they broke. The resulting compression force-time relationship is shown in Fig. 2. In the same figure, the effect of crosshead speed on the force-time curve is illustrated too. Points on the curves represent the mean value of three to six readings. To show the effect of time on the reliability of the readings, for any given time, three reading were plotted representing the minimum, maximum and the mean reading. With progress in the time of compression, the points became widely spread, a phenomenon that could be explained by the changes in the dimensions of the samples as wll as the decelerating effect of the increasing force on the crosshead. It appears that at higher crosshead speeds, higher compression forces are registered. These results are in agreement with the work done on agar gels by Omura et al[21]. The experimental results shown later are for the lower crosshead speed. Agar gels of different concentrations were examined namely, 1, 2 (g) of agar in 100 ml of water. The force- time data for this are shown in Fig. 3. As is expected, with increasing concentrations, higher forces are registered. In this graph, not only does the force increase for any given time, but the duration of the compression is prolonged too. This tendency is similar to the results obtained by Omura et al[21].

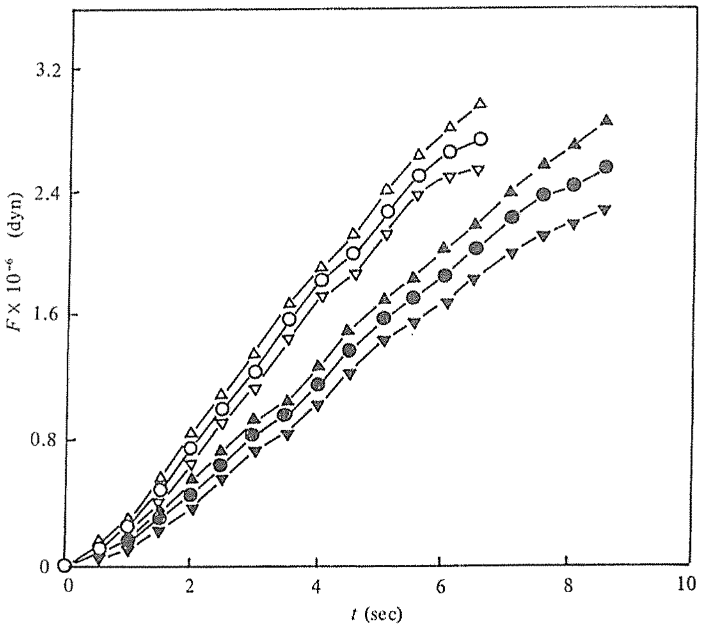

Fig. 2

Force-time relationships of compression curve of a agar gel at different crosshead speeds.
Samples: 2g agar/100ml water (20.0°C)
$D_0 = 2.7\text{cm}$, $L_0 = 1.0\text{cm}$
Crosshead speed:

		ν_h(cm/sec) 0.0700	0.0995
Experimental results	maximum	▲	△
	average	●	○
	minimum	▼	▽

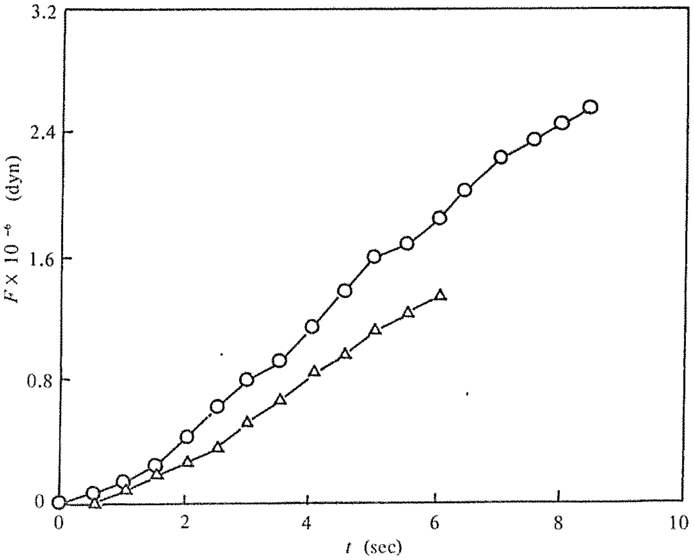

Fig. 3

Force-time relationships of compression curve of agar gels
Samples: a(g) agar/100ml water (20°C)

a(g)	1	2
	△	○

Crosshead speed: $\nu_h = 0.0700\text{cm/sec}$.

For the data in Fig. 3, stress and strain have been derived and these plots are shown in Fig. 4. To test the effect of using original dimensions and the corrected dimensions, Eq. (2) and (3) have been used on one hand, and Eq. (4) and (5) on the other hand to derive stress and strain. It can be seen that values obtained by using the equation that incorporate the original dimensions: Eq. (4) and (5), yield lower readings than the calculations based on the true dimensions. The corresponding strain values are in reverse of the case just mentioned. Omura et al [21] obtained stress at break point, strain and energy based on original values, their data points are shown in Fig. 4. These are lower than the results obtained in these experiments. The dimensions of the specimens used by Omura et al experiments were different from ours, diameter 3.0 cm and length 2 cm. The deviations could be explained mostly by this variation in dimensions among other things. Culioli and Sherman[12] evaluated compression tests on Gouda cheese, and showed that the true stress levels can be influenced not only by the sample dimensions, temperature and deformation rate but also by the shape of the specements and the friction at the surfaces between the specimen and the support surfaces of the testing machine.

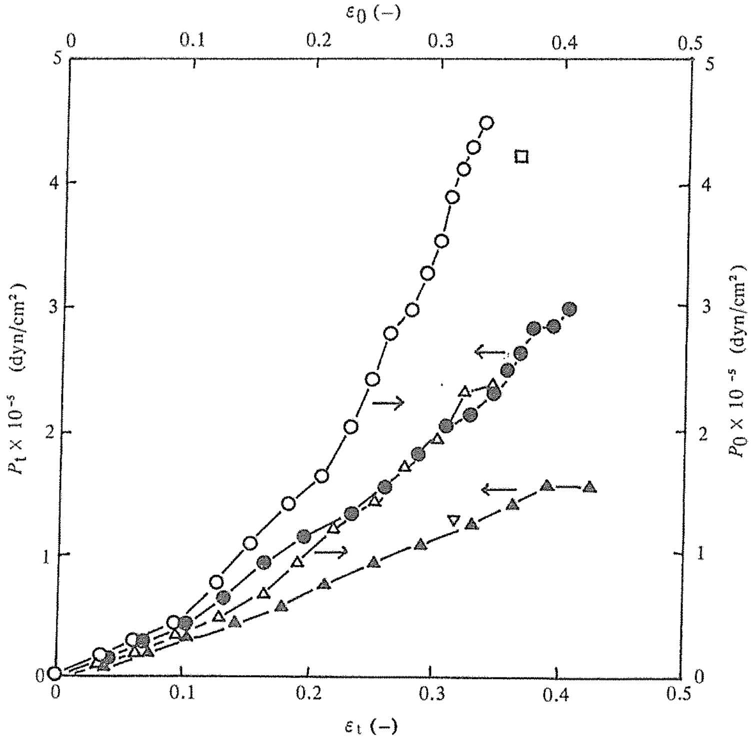

Fig. 4 Stress-strain relationships of compression curve of agar gels

Samples: a(g) agar / 100ml water (20°C)

a(g)	P_t vs. ε_t	P_0 vs. ε_0
1	▲	△
2	●	○

Crosshead speed: $\nu_h = 0.0700$cm/sec

Omura et al. (1978) : agar gel (22~23°C)

a(g)	P_0 vs. ε_0
1	▽
2	□

Crosshead speed: $\nu_h = 0.067$cm/sec.

3. Compressive breaking properties

The effect of the sugar concentration on the compressive breaking properties in the range of 5 ~ 10% was investigated for 2 g agar in 100 ml water gel. Salt levels of 0.2 and 0.4% were also investigated. The shapes of the curves were nearly similar for both sugar and salt at all levels. The data values for the compressive breaking properties of agar, agar-salt and agar-sugar for true stress, strain, and energy are given in Table 1. The same data based on original values, L_0 and A_0, are given in Table 2. The compressive breaking strain and energy in Tables 1 and 2 increased with increasing of the agar concentration, but negligible change happened in the stress. With increase of crosshead speed, all the properties in both Tables increased. These results agree with the ones obtained by Omura et al[21]. The properties in Table 1 and 2 were barely affected by the addition of salt and sugar, to the extent of the ranges of our investigation. Close study of the properties indicate that sugar could have an increasing effect on all other properties whereas salt decreases the strain. Omura et all who have used up to 60 g of sugar in 1.0 g agar/100ml water gel found that these properties increased with the increasing of the sugar concentration.

Table 1 Compressing breaking properties

Samples: *a*(g) agar + *b*(g) others / 100ml water

a(g)		ε_{tf}(−)	P_{tf} (dyn/cm^2)	E_{tf} (erg/cm^3)
1		0.421	1.56×10^5	3.22×10^4
2		0.407	3.00×10^5	5.09×10^4
2*		0.421	3.15×10^5	5.36×10^4
a(g)	Sugar *b*(g)	ε_{tf}(−)	P_{tf} (dyn/cm^2)	E_{tf}(erg/cm^3)
2	5	0.392	3.38×10^5	5.06×10^4
2	10	0.430	3.01×10^5	5.26×10^4
a(g)	Salt *b*(g)	ε_{tf}(−)	P_{tf} (dyn/cm^5)	E_{tf} (erg/cm^3)
2	0.2	0.406	2.86×10^5	5.43×10^4
2	0.4	0.438	2.65×10^5	5.63×10^4

*: vh = 0.0995cm/sec (others; vh = 0.0770cm/sec)

Table 2 Compressing breaking properties

Samples: *a*(g) agar + *b*(g) others / 100ml water

a(g)		ε_{of}(−)	P_{of} (dyn/cm^2)	E_{of} (erg/cm^3)
1		0.344	2.38×10^5	3.23×10^4
2		0.334	4.51×10^5	5.10×10^4
2*		0.344	4.80×10^5	5.37×10^4
a(g)	Sugar *b*(g)	ε_{of}(−)	P_{of} (dyn/cm^2)	E_{of} (erg/cm^3)
2	5	0.324	5.00×10^5	5.07×10^4
2	10	0.349	4.63×10^5	5.27×10^4
a(g)	Salt *b*(g)	ε_{of}(−)	P_{of} (dyn/cm^2)	E_{of} (erg/cm^3)
2	0.2	0.334	4.30×10^5	5.43×10^4
2	0.4	0.354	4.11×10^5	5.63×10^4

*: vh = 0.0995cm/sec (others: vh = 0.0700cm/sec)

Working with salt of 0.2N in 1.0g/100 ml water agar gels, Nakahama[28] found that Young's modulus decreased with the salt concentration in creep and stress relaxation experiments. In the experiments by Nakahama, the Hook's strain showed 61.4% of the total 13.0% for 1 g agar/100 ml water gel. If elastic deformation is assumed for our data of 2 g/100 ml water gel, Young's moduluses are obtained as $k_{tf}=7.37 \times 10^5$ and $k_{of}= 1.35 \times 10^6$ dyn/cm². For the addition of 0.2 and 0.4 g salt in the same concentration of agar gel, these values are $k_{tf} = 7.04 \times 10^5$ and 6.06×10^5, $K_{of} = 1.29 \times 10^6$ and 1.16×10^4 dyn/cm² respectively. The increasing salt concentration has a decreasing effect on these values. Our results are in accordance with those obtained by Nakahama.[28]

A general element mechanical model for force deformation curves has been proposed by Peleg [30)-32)]. However, for obvious reasons of standardisation of the experimental conditions, this model cannot be used for the description of the curves in Fig. 4.

This paper was presented at the occasion of the 48th Annual meeting of the Society of Chemical Engineers of Japan, Kyoto Japan (7th April, 1983).

NOTATIONS

A_o, A_t : original and actual cross sectional area (cm²)
a, b, c, c_1 and c_2 : constants
D_o : original diameter (cm)
E_{tf} : true breaking energy (erg/cm³)
E_{of} : breaking energy based on A_o and L_o (erg/cm³)
F : force (dyn)
h : recording chart hight (cm)
k_{tf} : true Young's modulus (dyn/cm²)
k_{of} : Young's modulus based on A_o and L_o (dyn/cm²)
L_o : original length (cm)
ΔL : absolute deformation length (cm)
ΔL_1 : compressing length by the cross head (cm)
ΔL_2 : influencing length of lower support plate (cm)
P_t, P_{tf} : true stress and true braeking stress (dyn/cm²)
P_o, P_{of} : stress and breaking stress based on A_O (dyn/cm²)
t : compressing time (sec)
v_h : crosshead speed (cm/sec)
v_{ht} : true crosshead speed (cm/sec)
v_r : recording speed (cm/sec)
x : recording chart length (cm)
ε_t, ε_{tf} : true strain and true breaking strain (dyn/cm²)
ε_o, ε_{of} : strain and breaking strain based on L_o (dyn/cm²)

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SUMMARY

The texture of foods is an important physical property for designing equipment for controlling various food processes and for product quality control. In previous papers[33)] we studied the properties of liquid foods with particular reference to their flow and to their related equations.

In this investigation, a simple and reliable apparatus was assembled and used for studying the rheological properties of solid foods, paying particular attention to compression properties. The rheological properties of agar, agar-sugar, and agar-salt gels were invesigated. The results show an increase of compressive breaking stress with agar concentration and crosshead speed. In the limited ranges of our study, addition of salt and sugar has little significance, if any, for the properties of agar gels.

食品の力学的特性測定を目的とした簡便な実用的測定装置に関する研究

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食品のテクスチャーは，食品製造の工業装置の設計計算，プロセス制御に対して重要なパラメータである。前報[33]において，液状食品の流動方程式の設定に関する研究を行ってきた。

本研究では，固体状食品のレオロジー的特性測定に対して有用となる簡便な圧縮破断特性装置の利用に関する研究を行った。寒天，寒天－砂糖および寒天－食塩ゲルのレオロジー的特性の測定を行った。圧縮破断における応力，ひずみおよびエネルギーの値を測定した。圧縮破断応力は，寒天の濃度の上昇と圧縮速度の上昇に伴って増加する結果が得られた。砂糖と食塩の添加の影響は，本研究における添加量に対してはほとんど影響がみられなかった。