On Rheological Properties and Structure of Kamaboko—I. Application of Rubber Elasticity Theory to Kamaboko*

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Elastic behavior in both cases of extension and compression of kamaboko was expressed well in application of the rubber elasticity theory. That is, the relation between stress and strain of kamaboko which does not contain starch is given to a first approximation by the equation

$$f = K(\alpha - \alpha^{-2}),$$

where f (dyn/cm²) is the stress, α is the extension ratio and K (dyn/cm²) is one-third of the initial Young's modulus. This relation does not depend upon the kinds of raw fish or the moisture content of kamaboko.

In Japan, kamaboko, heat coagulated gel of salt-paste of fish muscle, are widely consumed, the whole of which are factory products.

Kamaboko makers used to estimate the commercial quality of their products in terms of organoleptic value usually *ashi*.

Much has been published about some of mechanical properties for kamaboko such as the elongation, the compression, the rupture and the vibration in the relation to their commercial quality, and about some of trials of the measuring apparatus of *ashi*. Especially, the Food Rheometer developed by SHIMIZU and SIMIDU¹⁾ and the Jelly-strength Tester developed by OKADA²⁾ have diffused fairly well. Principle of both apparatus bases on measuring the stress-strain behavior, but the former is at tension side and the latter is at compression side. Both were examined as estimating apparatus of *ashi* of kamaboko which take the place of organoleptic judgment, and their results were crowned with success.

But there is little about the systematized rheological investigations on properties of kamaboko and their measuring apparatus.

This series of works is therefore made concerning the rheological properties of kamaboko and the methods of determination in accordance with their various rheological behaviors. The results obtained will be made some contribution to the food science, the food technology and the psycorheology. Moreover, they will give suggestion on the gel construction and the network structure of kamaboko.

In the present paper, the rubber-like behavior in both cases of extension and compression of kamaboko was examined by the application of the rubber elasticity theory.

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As indicated by SCOTT BLAIR³⁾, food scientist and food technologist could not consider the physical properties of the food of sol and gel in close relation to the results of rheology, by the reason that almost all of sol and gel state food are unhomogeneous from physical and physico-chemical view points. In the case of kamaboko, although not single phase, the texture of kamaboko is pretty homogeneous from the results of the phase contrast microscopic³⁾ and the electron microscopic⁴⁾ observations. More, the physical property of kamaboko is thermo-rheologically simple from a result of creep measurement^{5,6)}. It may be therefore preestimated that elastic or viscoelastic behaviors of kamaboko are able to treat as object of polymer science.

In the case of vulcanized rubbers, Eq. (1) is derived on the basis of the theory of statistical thermodynamics:

$$f = \nu k T (\alpha - \alpha^{-2}) \quad (1)$$

where f is the stress, α is the extension ratio (deformed length divided by original length; in case of tension side $\alpha \geq 1$, in case of compression side $\alpha \leq 1$), ν is the number of chain molecules per unit area, k is the Boltzmann constant and T is the absolute temperature.

It was seen in the preliminary experiment⁷⁾ that deformation of kamaboko is satisfied with some conditions of rubber-like properties proposed by TRELOAR⁸⁾ and BUECHE⁹⁾, though kamaboko is complex high polymeric hydrogel. More, on a number of non-single phase polymeric materials such as swollen rubber, swollen fibrous collagen and swollen cuttle-fish, a similar tendency was obtained by GEE¹⁰⁾, WIEDRRHORN¹¹⁾, KISHIMOTO and FUJITA¹²⁾, respectively. Thus the equation of stress at tension and compression sides of kamaboko may be given as follows:

$$f = K(\alpha - \alpha^{-2}). \quad (2)$$

On the other hand, Eq. (3) has been derived semi-empirically as the relation between stress and extension ratio for the bridged rubber-like polymer by TRELOAR¹³⁾:

$$f = \frac{1}{3} E (\alpha - \alpha^{-2}) \quad (3)$$

where E is the initial Young's modulus, *i.e.*,

$$E = \left(\frac{\partial f}{\partial \alpha} \right)_{\alpha=1}. \quad (4)$$

Therefore the value of K in Eq. (2) may correspond to one-third of E ,

$$K = \frac{1}{3} E. \quad (5)$$

Materials and Method

Tension-compression tester The stress-strain behavior at tension and compression sides of kamaboko was determined automatically by the tension-compression tester which

was developed for application to gel state food. Mechanism, electric system and electronic system of this tester were designed according to the principle of the *Instron Tester*. The stress signal was recorded continuously with the electronic polyrecorder TOA-EPR-10A in suitable chart speed.

The test specimen was placed in a thermo-hygrostat which maintains the temperature constant within $\pm 0.05^\circ\text{C}$ and the relative humidity constant within $\pm 2\%$.

Kamaboko Kamaboko used in this experiment are shown in Table 1.

Table 1. Kamaboko used for the tension-compression measurement.

Sample	Raw fish	Place of production	Moisture (%)	Starch (%)	Gel-strength* ⁴ (gw·cm)	Jelly-* ⁵ strength (gw/cm ²)
A	Lizard fish* ¹	Hagi City	78.0	0.0	2.5×10^3	2.4×10^3
B	Lizard fish* ¹	Nagato City	75.3	0.0	2.7	2.5
C	Croaker* ²	Osaka City	77.5	0.0	2.3	2.0
D	Jack mackerel* ³	Author	78.0	0.0	2.3	1.8

*¹ *Saurida argyrophanes* RICHARDSON.

*² *Argyrosomus argenteus* HOUTTUYN.

*³ *Trachurus japonicus* TEMMINCK & SCHLEGEL.

*⁴ See Reference (1).

*⁵ See Reference (2).

Results and Discussion

In a preliminary experiment, it was observed that stress relaxation, creep and temperature dependence of kamaboko were remarkable, and effect of drying of test specimen during measurement on their viscoelastic behaviors was considerable. According to these results, the tension-compression measurements were made in following condition: stretching and compressing deformation rate are 5.00×10^{-2} cm/sec, temperature is $25 \pm 0.05^\circ\text{C}$, relative humidity is 98–100%.

The test specimen for tension side was used in the shape of cube having thickness of 3.0×10^{-1} cm, width of 1.00 cm, height of 1.50 cm, for compression side was used in the shape of cylindrical having diameter of 2.00 cm, height of 2.00 cm.

Table 2 and Fig. 1 show the results of the tension-compression measurements for some kinds of kamaboko at 25°C . The same measurements being repeated many times without changing the condition, difference on the stress-extension ratio curves were not recognized.

The values of K are calculated from each initial Young's modulus which is obtained from initial slope of curve on the recording chart paper.

As can be seen from Fig. 1, any stress-extension ratio curve agrees well with the the-

Table 2. Results of the tension-compression measurement for samples A, B, C and D at 25°C, 98–100% humidity.

Sample	Initial Young's modulus* E (dyn/cm ²)	K (dyn/cm ²)	Ultimate extension ratio* α_B	Ultimate stress* f_B (dyn/cm ²)	Toughness** (erg/cm ³)
A	$\times 10^5$ 11.1	$\times 10^5$ 3.7	2.40	$\times 10^5$ 8.14	$\times 10^5$ 6.3
B	10.8	3.6	2.45	8.20	6.4
C	11.7	3.9	2.19	7.77	5.5
D	12.9	4.3	2.10	8.20	4.9

* at tension side.

** Toughness = $\int_{\alpha=1}^{\alpha_B} f(\alpha) d\alpha = \frac{1}{3} E \int_{\alpha=1}^{\alpha_B} (\alpha - \alpha^{-2}) d\alpha$

Fig. 1. Stress vs. extension ratio curves for samples A, B, C and D at 25°C, 98–100% humidity; Solid lines represent theoretical curves which are expressed by Eq. (2) and Eq. (5). Open circles indicate experimentals.

oretical scheme Eq. (2) and Eq. (5) within the experimental errors, irrespective of species of raw fish and quantity of moisture, irrespective as to whether the tensile deformation or the compressed deformation.

Formerly, it was shown by TRELOAR⁸⁾ that the stress-extension behavior of vulcanized rubber in the extension range $0.4 \leq \alpha \leq 1.6$ can be expressed by the equation

$$f = 3.9 \times 10^6 (\alpha - \alpha^{-2}) \text{ dyn/cm}^2.$$

But, in case of extension ratio over 1.6, the behavior does not conform to the equation. This unconformity is due to the crystallization of chains in network structure by molecular orientation.

On the contrary, in the case of kamaboko, the experimentals almost conform to Eq. (2) and Eq. (5) to the extent of each ultimate strain point.

It is suggested from the results of present experiment that the segments of network which take part in the deformation of kamaboko can be considered as the random coil

model. In other words, orientation of segments of kamaboko's network does not occur, or is negligible, in similar manner as behavior of the vulcanized rubber in small deformation.

Moreover, the elastic force of kamaboko may be composed of the entropy force component. It will be discussed more fully in a later paper.

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