食品ゲルのエントロピー弾性に対する応力-歪曲線による証明

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Entropy Elasticity of Food Gels Certified by Stress-strain Relation

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The cross-sectional area of elongated or compressed food gels can be corrected by equation, $A_c=A_o/\alpha$, where A_c is the cross-sectional area of the deformed gel, A_o is the original area, and α is the strain expressed by elongation ratio (elongated length divided by original length). Therefore, the stress-strain relationship for the food gel is expressed by equation, $F/A_o=E_o(\alpha-1)/\alpha$, where F is deformation force and E_0 is initial Young's modulus. Within the range of strain applicable for usual food gel, a theoretical stress-strain curve plotted by the right-hand side of the second equation so closely resembles another curve plotted by the right-hand side of equation, $F/A_o=E_o(\alpha-\alpha^{-2})/3$ derived from the entropy elasticity theory that these curves are indistinguishable. Therefore, the entropy elasticity of the food gels is not always certified by the last equation alone.

A linearity exists, as well known, between stress and strain as follows:

$$F/A_o=E_o(\alpha-1) \tag{1}$$

where F is the deformation force, Ao is the cross-sectional area of the undeformed sample, therefore, F/Ao is the stress, Eo is the initial Young's modulus and α is the strain expressed as the elongation ratio (L/L_o, L: the elongated sample length, L_o: the original length). With increasing deformation, however, this linearity is lost due to the change in cross-sectional area of the sample. Therefore, the elasticity measurement for food gel is carried out usually in such a small strain as the change in the cross-sectional area is negligible (usually, 0.9–1.1). In the previous paper,[1],[*2] we described that the cross-sectional area of some compressed food gels (Ac) could be approximately corrected by equation 2.

$$A_c=A_o/\alpha \tag{2}$$ [*3]

Replacing Ao in equation 1 with Ac, equation 3 was derived, which expressed the stress-strain relationship, where the change in the cross-sectional area was corrected.

$$F/A_o=E_o(\alpha-1)/\alpha \tag{3}$$

Therefore,

$$E_o=F\alpha/A_o(\alpha-1) \tag{4}$$

Thus obtained initial Young's modulus was held constant through wide range of the compression strain.

On the other hand, it is known that the following stress-strain relationship exists for the entropy elastic bodies.[2-4]

$$F/A_o=E_o(\alpha-\alpha^{-2})/3 \tag{5}$$

Surume (dried cuttle-fish) swollen in water[3] and Kamaboko[4] have been respectively proved entropy elastic body from the finding that the respective experimental stress-strain curve resembled the curve plotted by this equation rather than the curve plotted by equation 1.[*4] In this paper, we describe that the equations 2, 3 and 4 are applicable also to elongation of the food gels and that the entropy elasticity of the food gels is not always certified by the equation 5 alone.

Experimentals

Materials

Kamaboko (fish flesh gel) and fish sausage from Alaska pollack and kon-nyaku were purchased at a supermarket. Gelatin gel (8%) was prepared as previously.[1] The materials were cut with a knife to 1.6 cm high cylinder (fish sausage), 1.6×1.6×1.6 cm cubes (the others for compression

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[*2] In the previous paper, the compression strain was expressed as a Cauchy measure, $\alpha=(L_v-L)/L_o$.

[*3] If the compression is small ($\alpha\doteqdot1$), $A_c\doteqdot A_o$, therefore, $F/A_c\doteqdot F/A_o$.

[*4] It is not fair to discuss the equation 1 and equation 5 on an equal footing, because the change in cross-sectional area is corrected in the latter, while it is not in the former. However, another evidence has been given for the entropy elasticity of these two gels.[3,5]

test) or 1×1 cm width ×1.6 cm cubes (the others for elongation test).

Elasticity Measurements

Force-deformation measurements were carried out on a food rheometer (Fudoh Kogyo NRM-2010-CW) at room temperature. For the compression test, a flat type of plunger was used, whose tip was fitted with a square glass plate (3.5×3.5 cm^2). The gel was put on a smooth plastic plate laid on the sample platen. In the case of elongation, the gel was fixed between the plunger and the plastic plate with an instant binder (Tosa Gosei, Aron alpha). The sample platen was moved up to compress the gel or moved down to elongate at the speed of 6 cm/min and the force-deformation curve was recorded.

The diameter (D) or breadth (B) of the gels elongated to a prescribed strain was measured

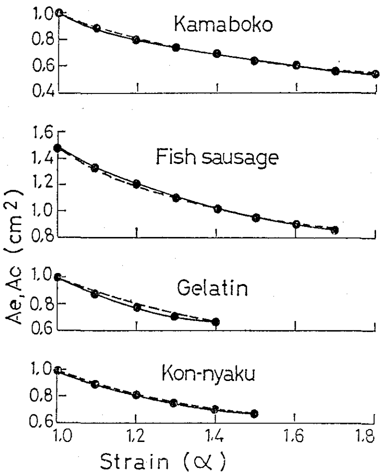

Fig. 1. Influence of elongation on the cross-sectional area of various food gels.

A_e: Experimentally corrected area —, A_c: Approximately corrected area – – –, $A_c=A_0/\alpha$, where A_0 is the cross-sectional area of undeformed gel and α is the strain.

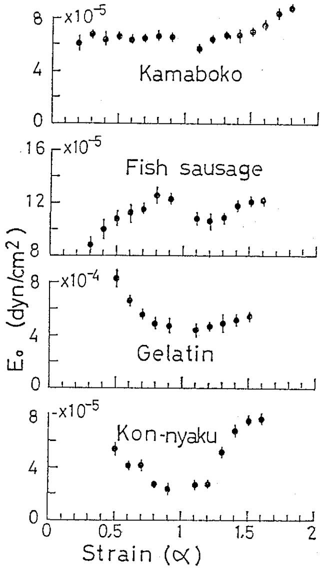

Fig. 2. Relationship between strain (α) and initial Young's modulus (E_0) calculated by equation 4, $F\alpha/A_0(\alpha-\alpha)$ from the results of force-deformation measurements. F: Deformation force. Vertical bar in the figure shows standard deviation.

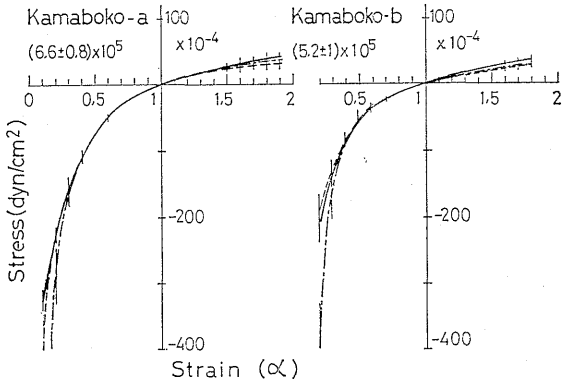

Fig. 3. Stress-strain relationship for two types of kamaboko.

Kamaboko-a: Steamed kamaboko, Kamaboko-b: Steamed and broiled one. —: Curve-a, plotted by F/A_0 from the result of the measurements, ---: Curve-b, plotted by the right-hand side of equation 3, $E_0(\alpha-1)/\alpha$, —·—: Curve-c, plotted by that of equation 5, $E_0(\alpha-\alpha^{-2})/3$. Figures described bellow gel's name are E_0 obtained from the equation 4 within the range of strain where the linearity exists between stress and strain. Vertical bar in the figure shows standard deviation.

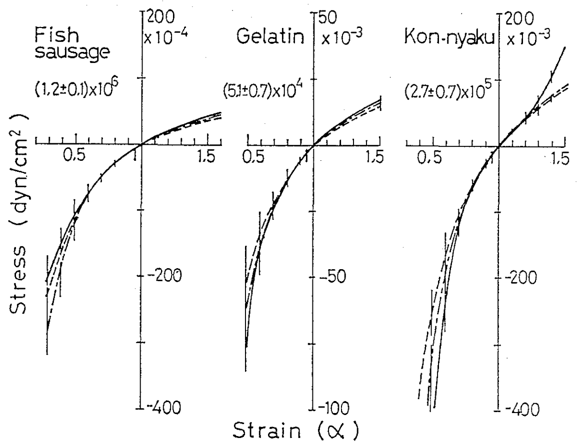

Fig. 4. Stress-strain relationship for fish sausage, gelatin gel and kon-nyaku. Symbols should be referred to Fig. 3. Vertical bar in the figure shows standard deviation.

with a calipers near their half height, and the experimentally corrected cross-sectional area (A_e) was calculated by $0.785 \times D^2$ for the cylinder or B^2 for the cube and square pillar.

Results and Discussion

Influence of the elongation of various food gels on their cross-sectional area is shown in Fig. 1. Because A_c and A_e closely resembled each other, the equation 2 is considered to be applicable also to correct the cross-sectional area of the elongated gel. In Fig. 2, the relation between E_c and α is shown for various food gels, where E_0 was calculated substituting F in the right-side hand of equation 4. Obviously, E_0 was held nearly constant within the range of the strain, 0.2–1.5 for the kamaboko, 0.4–1.4 for the fish sausage, 0.7–1.5 for the gelatin gel and 0.8–1.2 for the kon-nyaku, that is, the linearity between stress and strain exists within these range of strain and this range is considerably wider than that usually reported except for the kon-nyaku from which water oozed out at large deformation.

Figs. 3–4 show the three different stress-strain curves for each food gel.* The curve-a (—) is the experimental curve plotted by F/A_0. The curve-b (---) and curve-c (—・—) are the theoretical curves plotted by substituting E_0 in the right-hand side of the equation 3 and that 5, respectively. The value of E_0 was obtained from the equation 4 within the range of the strain where the linearity existed in Fig. 2. The curve-a nearly resembled the other two theoretical curves within that range of strain. For the case of the kon-nyaku, the curve-a separated considerably from the theoretical curves with increasing deformation. Especially for the kamaboko, the curve-a clearly resembled the curve-c as pointed by Takagi and Simidu,[4] but resembled the curve-b too. In Fig. 5, the two theoretical curves, curve-b and curve-c, are shown, plotted with a personal computer respectively, where the value of E_0 was arbitrarily selected within the range of the modulus

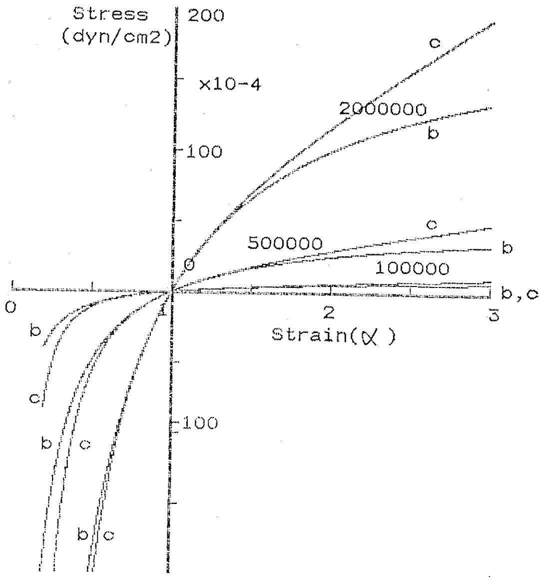

Fig. 5. Theoretical stress-strain curves plotted on a personal computer.
b: plotted by the right-hand side of equation 3,
c: plotted by that of equation 5.
Figures near each curve are E_0 selected arbitrarily.

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* Kamaboko,[4] gelatin gel[6] and kon-nyaku[7] have been proved to be the entropy elastic body, respectively.

of the actual food gels. These two curves too closely resembled each other to be distinguished at relatively small deformation (α=0.5–1.5), but separated gradually with increasing the deformation (less than 0.5 or more than 2 as α). As mentioned above, the equation 5 shows the stress-strain relationship for the entropy elastic bodies and it is derived from the three dimensional elasticity theory by correcting the change in cross-sectional area upon deformation.$^{2)}$ But the equation 3 is derived only by correcting the cross-sectional area in the equation 1 which is independent of the entropy elasticity, and fundamentally differs from the equation 5, although the curves plotted by these two equations resembled each other. In the range of the strain where the linearity exists, the food gels are narrower than the rubber, a typical entropy elastic body, whose E_0 is held constant even elongated to more than 3 times its original length. Moreover, the food gels are easily broken by relatively small deformation. For example, the kamaboko was torn off by a strain less than 2. Therefore, it is practically impossible for the actual food gels to compare the curve-a with the curves-b and -c at the large deformation where significant difference was detected between the latter curves. Furthermore, for the elasticity measurement for the food gels, the experimental error is considerably large as understood also from the results in Figs. 2–4 (The standard deviation sometimes reaches ±30% the mean value). In such the circumstance, it is hard to distinguish which of the two different theoretical curves the experimental stress-strain curve resembles. Therefore, another evidence should be given for the certification of the entropy elasticity of the food gels, because the equation 5 is not necessarily conclusive for that certification, that is, this equation is not sufficient condition, though it must be necessary condition.

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