Axial Compression Properties of Kamaboko

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ABSTRACT

Kamaboko, gelled seafood product from frozen surimi, has distinctive textural properties. Characterization of those properties, using an integrated approach to rheological studies, was accomplished by means of an instrumental texture profile analysis and evaluation of resultant stress-strain relationships. The material had near-ideal area expansion even at compressions of 60% while retaining its highly elastic texture. Apparently the product did not yield through 80% compression. Hardness of the kamaboko at 80% compression was characterized by a local maximum at 37.5°C which may have been related to processing temperature of the initial surimi gel-set used in a double-gel-set procedure. Evaluation of stress-strain relationships confirmed the incompressible nature of the gel and showed relatively slight variations between the Young's modulus and the deformability modulus. The elastic limit of the kamaboko increased significantly as temperature increased from 25 to 50°C.

INTRODUCTION

KAMABOKO, frequently referred to as steamed fish cake, is a typical Japanese seafood. Its origin dates from 1100 A.D. in Japan where it was developed as a method of preserving the gelling properties of washed, minced fish (Suzuki, 1981). Over the centuries many species have been used in its production and recent research has been aimed at determining species-dependent gel characteristics (Hastings et al., 1990; Roussel and Cheftel, 1990; Hastings, 1988; Kim et al., 1987; Suzuki, 1981). The frozen surimi of Alaska Pollock is the major source in the creation of kamaboko because of its ready availability and acceptable gelling properties (Mitchell, 1984). Kamaboko is a homogeneous protein gel made from fish myofibrillar protein, primarily actomyosin, that has been washed to remove the water soluble proteins, ground with sodium chloride to solubilize the actomyosin and heated to form a gel. The unique characteristics of kamaboko are its cohesive and highly elastic texture and the strength of its gel. Lanier (1984) postulated that the relative strength of the gel was due to its instability with respect to heat and the ordered conformation that takes place at relatively low temperatures (40°C). The ordering and lack of heat stability was established using DSC thermograms which, unlike mammalian and avian muscle proteins, show an initial transition temperature at about 37°C.

Current testing procedures for surimi/kamaboko gels involve use of a penetration (punch) test which was adopted by the surimi industry because of its simplicity and traditional use (Lee and Chung, 1989). This method, however, is susceptible to local heterogeneity. The characterization of the rheological properties, which are related to the integrity and cohesiveness of the gel matrix, has been approached using several test methods; penetration (Okada and Yamazaki, 1958), compression (Lee, 1984) and torsion (Wu et al., 1985). Most previous research was centered on the raw material (i.e. species) and its condition (i.e. freshness, temperature abuse) and their effects on the resultant product.

The objective of our research was to use integrated methodology to evaluate the rheologial properties of kamaboko as a function of temperature, rate and degree of deformation using an instrumental texture profile analysis (ITPA) and the resultant stress strain curves and to develop empirical model equations that would predict instrumental texture response.

MATERIALS & METHODS

KAMABOKO LOAVES (Hana Brand, Rhee Bros., Inc., Columbia, MD) used for our studies were "Itatsuki" variety from Alaska Pollock, and purchased locally. Samples were prepared by slicing whole kamaboko loaves to the desired height (15 mm) using a parallel wire slicer. Cylindrical samples were extracted from the slices using a 15 mm diameter #11 cork borer. To minimize deformation of the sample during slicing and cylinder extraction, all sampling was at 4°C. Length to diameter ratios, (L/D) $\geq$ 0.95, were used for all analyses. Samples were rejected when major flaws were detected (air pockets on surface) or when deviation from upright cylinder geometry was observed. Samples were maintained in sealed containers submerged in a heated water bath at temperatures appropriate to the experimental design.

Instrumental Texture Profile Analysis (double compression) (ITPA) was used to determine rheological responses, using a Model 4201 Instron Universal Testing Machine (UTM), Canton MA, with 5.6 cm lucite plates. The rate, degree of compression and number of compression cycles were controlled using the INSTRON Cyclic Foam Compression software with a Model 86B Hewlett Packard Personal Computer. A 500N load cell was used for all analyses. Sample temperatures within the UTM were maintained using an INSTRON Model 3111 Environmental Chamber. Interpretation of ITPA data, from the INSTRON force — deformation curves, was accomplished using standard definitions (Bourne, 1978; Szczesniak, 1966). Hardness was the force, in Newtons, necessary to achieve a specific deformation represented by peak height of the first compression cycle. Cohesiveness, a ratio of positive force areas under the first and second compression, was a measure of the material binding properties or strength of the internal bonds. Gumminess was the product of hardness and cohesiveness. Degree of elasticity was a measure of the material recovery and was quantified by evaluating the ratio of recoverable to total deformation (Mohsenin, 1970).

Measurement of dimensional changes in the compressed samples was achieved by first marking the samples with vertical diametrically opposed lines, then compressing the samples to the desired degree of compression. After desired deformation was reached, the crosshead of the INSTRON was maintained in position for a short time to allow for diameter measurements. Calipers, modified with leads to an ammeter, were used for these measurements with the vertical lines providing a target for the caliper tips. Measurements were made once continuity was established, as manifested by deflection on the ammeter. Accuracy of measurements made in this manner was high due to elimination of the potential to compress or penetrate the sample with the caliper tips.

Stress strain data was derived from the force deformation data (INSTRON Output) in terms of true stress and Hencky strain using the following calculations:

$$\text{Hencky Strain} = \ln [H_o/(H_o - \Delta H)] \quad (1)$$

$$\text{True Stress} = (1000\ F_c/A_o) \times (H_o - \Delta H)/H_o \quad (2)$$

where H_o = original height of sample (mm); ΔH = change in height (mm); F_c = compressive force (N); A_o = original cross sectional area (mm^2); ln = natural logarithm.

The factorial experiments were designed to evaluate the response of the dependent ITPA parameters and the stress-strain relationships to temperature (25, 37.5, and 50°C) degree of deformation (10, 50, and 80%) and the rate of deformation (10, 50 and 100 mm/min). Statistical analyses were performed using the General Linear Methods (GLM) procedure (SAS, 1985).

Table 1—Dimensional analyses

Compression	Height	Original diameter	Volume	Height		Compressed diameter	% CV[a]	Volume	Change volume
	mm	mm	mm^3	mm		mm		mm^3	
14%	15.25	15.35	2822.1		T[b]	16.20			
					M[c]	16.70			
					B[d]	16.52			
				12.96	Avg	16.47	1.5	2761.0	−2.2%
30%	15.40	15.34	2846.2		T	18.20			
					M	18.60			
					B	18.55			
				10.78	Avg	18.45	1.2	2882.1	+1.3%
50%	15.40	15.26	2816.6		T	21.90			
					M	22.40			
					B	21.95			
				7.70	Avg	22.08	1.0	2948.3	+4.6%
60%	15.35	15.35	2840.6		T	24.20			
					M	24.50			
					B	24.10			
				6.14	Avg	24.27	0.8	2840.5	−0.0%

[a] CV – Coefficient of Variation.
[b] T – Top diameter of cylindrical sample.
[c] M – Middle diameter of cylindrical sample.
[d] B – Bottom diameter of cylindrical sample.

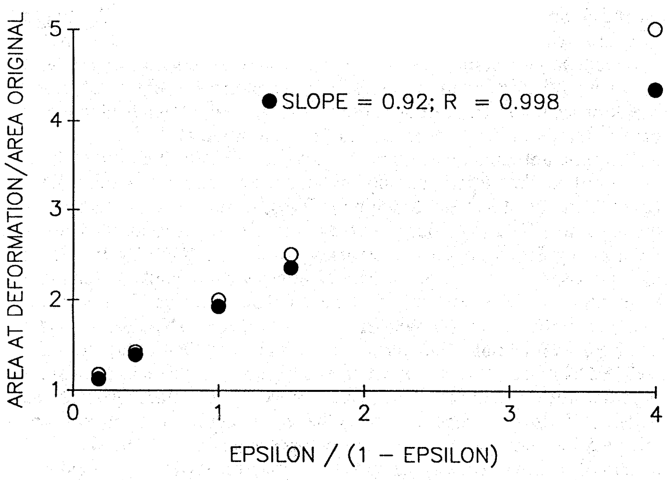

Fig. 1—Ideal area expansion of kamaboko. ○—Ideal expansion; ●—Actual expansion.

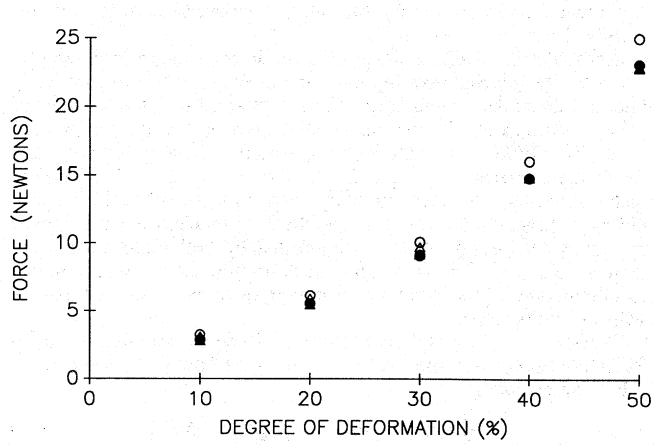

Fig. 2—L/D effects on kamaboko strength. ○—L/D = 0.64-0.70; ●—L/D = 0.95-1.05; △—L/D = 1.30-1.38; ▲—L/D = 1.60-1.70.

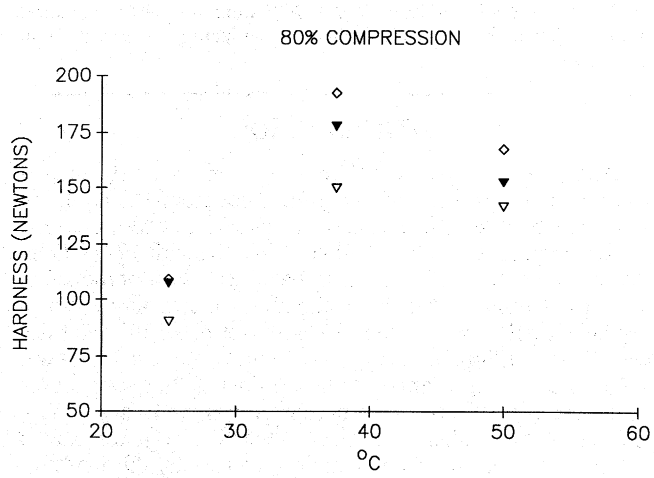

Fig. 3—Kamaboko hardness as a function of rate and degree of deformation and temperature. ▽—10 mm/min, ▼—50 mm/min, ◇—100 mm/min.

RESULTS & DISCUSSION

Dimensional changes

Measurement of dimensional changes in the kamaboko samples shows that the material deformed maintaining upright cylinder geometry. Measurements of the diameters were made, in triplicate, at the top, middle and bottom of each sample at 0, 15, 30, 50 and 60% compression (Table 1). Difficulties were experienced with measurements at 80% compression due to the narrow INSTRON plate gap; these data are not presented. Replicate measurements, at any given location, showed a coefficient of variation (CV) less than 2%. Data indicated that sample diameter variations at the middle location and those at the top and bottom, were not significantly different ($P < 0.05$, $CV \leq 1.5\%$) and "barreling" was not evident. Since barreling is a prime indicator of significant frictional forces between contact surfaces and instrument plates (Bagley et al., 1985), no sample lubrication was needed for TPA analyses.

Upright cylinder deformation could be further confirmed by evaluating the proximity of expansion of the cross sectional area of kamaboko to the ideal, during compression. Olkku and Sherman (1979) derived a linear relationship for evaluating area expansion

$$A_c/A_o = b_0 + b_1\epsilon/(1-\epsilon) \quad (3)$$

where A_c = compressed cross sectional area (mm^2); A_o = original cross sectional area (mm^2); b = regression coefficients; ϵ = axial strain.

The ideal occurs when both slope and intercept of Eq. (3) are unity. Evaluation of the increase in area for kamaboko in compression is shown in Fig. 1. The material behaved ideally

Table 2—Cohesiveness[a] and gumminess[a,b] of kamaboko

Deformation %	Rate of deformation (mm/min)	Temperature 25.0 (°C)		37.5 (°C)		50.0 (°C)	
		Cohesiv.	Gumminess	Cohesiv.	Gumminess	Cohesiv.	Gumminess
	10	0.870	1.244	0.866	1.290	0.871	1.315
10	50	0.866	1.403	0.866	1.455	0.867	1.457
	100	0.864	1.512	0.865	1.583	0.856	1.566
	10	0.754	9.802	0.739	10.110	0.758	10.516
50	50	0.752	11.047	0.737	11.571	0.750	12.001
	100	0.735	11.393	0.725	11.716	0.736	12.226
	10	0.633	57.261	0.663	99.360	0.694	98.370
80	50	0.620	66.500	0.615	109.374	0.636	97.103
	100	0.603	65.79	0.558	107.403	0.622	104.422

[a] Average of three measurements, CV <5%.
[b] Gumminess (N) = Hardness × Cohesiveness

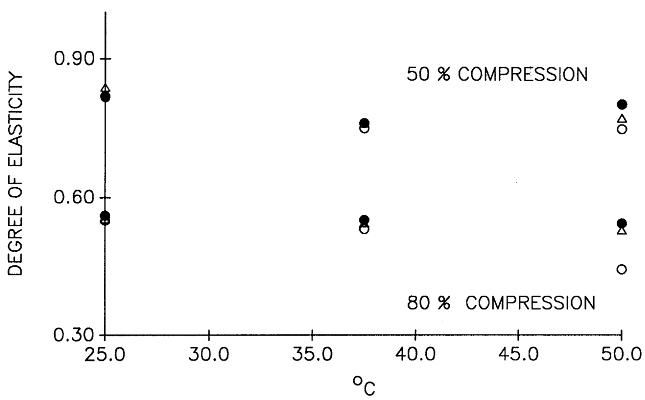

Fig. 4—Kamaboko elasticity as a function of rate and degree of deformation and temperature. ○—10 mm/min; △—50 mm/min; ◇—100 mm/min.

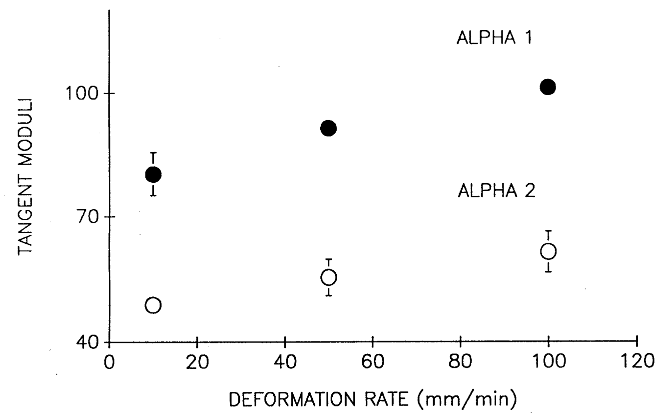

Fig. 6—Elastic Moduli as a function of deformation rate. ●—Youngs (Alpha 1) Modulus; ○—Deformability (Alpha 2) Modulus.

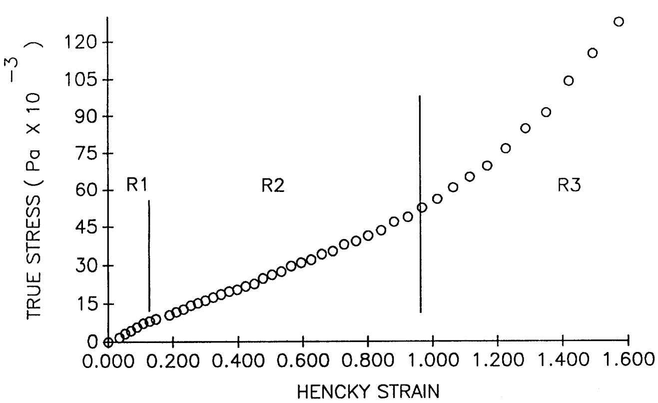

Fig. 5—Stress strain curve for kamaboko. R1—ideal elastic region; R2—Yield region; R3—Compressible region.

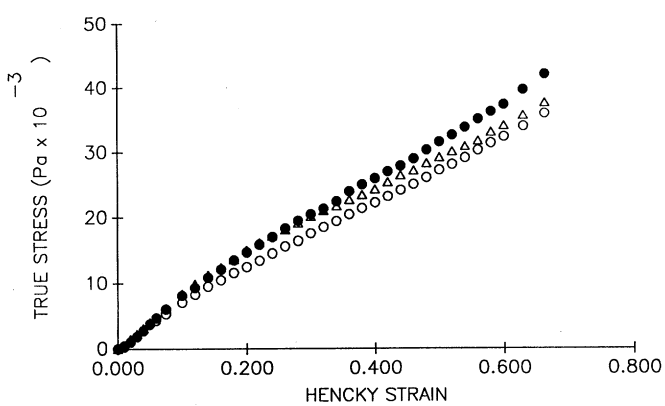

Fig. 7—Kamaboko stress strain as a function of temperature. ○—25°C, △—37.5°C, ●—50°C.

through 60% deformation (epsilon ratio = 1.5). Sample volumes of the undeformed and deformed material were calculated and compared (Table 1). Volumes did not change significantly during deformation indicating kamaboko was essentially incompressible through 60% compression. Peleg (1987) described the manifestation of higher apparent strength or stress for flat samples with length to diameter ratios (L/D < < 1) due to frictional forces at the contact surfaces and hydrostatic pressure build-up. Figure 2 shows a force deformation curve for kamaboko at various L/D ratios. At L/D ≥ 0.95, the data are coincidental. Flat samples, however, showed a greater strength that increased as degree of deformation increased. Samples with dimensions < 0.95 were therefore rejected.

Texture profile analysis

This method was chosen for several reasons. First, the ITPA is a widely accepted method for texture evaluation of a variety of foods and it is an imitative test that has been shown to correlate very well with sensory texture profile data. Second, it provides one of the more precise definitions of overall response of the material, whereas penetration tests are susceptible to local heterogeneity. Finally, the ITPA is a good measure of binding or cohesive properties of gel materials.

Figure 3 details the effects of degree and rate of deformation as well as temperature on kamaboko hardness. At all deformations, apparent strength increased as deformation rate increased. This is a well established observation that has been fect (T, X, C). The statistical significance of the coefficients shown in Table 4 agreed fully with data presented in earlier portions of this study.

CONCLUSIONS

THE LINEAR STRESS strain relationship demonstrated the unique elastic properties of kamaboko. The extent of the elastic/near elastic behavior and the incompressible nature of the material (to 60% compression) is found in few food materials. The relationship of temperature, degree of deformation and rate of deformation are important in characterizing the material and the integrated analysis presented a good empirical picture of the response of the material to deformation. This information will be useful in modifying product formulation or in imitative processing.

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Table 3—Elastic limit of kamaboko

Temp °C	Strain at elastic limit	n[a]	% CV[b]
25.0	0.116	10	7.9
37.5	0.166	10	4.8
50.0	0.201	10	4.9

[a] n — number of replicates.
[b] CV — Coefficient of Variation.

shown for many foods (Boyd and Sherman, 1975; Olkku and Rha, 1975; Shama and Sherman, 1973). At 10 and 50% deformation, hardness increased as temperature increased from 25 to 37.5°C, and showed no significant change as temperature increased further (data not shown). At 80% compression, a perceived softening of kamaboko occurred at 50°C at all deformation rates, that may be attributable to reduction of hydrogen bonding in the myosin. Montejano et al., (1983) found a similar, but not as extensive, reduction in hardness in the 40 to 45°C range for not fully cooked, gelled comminuted fish muscle, compressed to failure. They attributed this to structural changes unrelated to hydrogen bonding. Possibly the plateau (at low deformation) and decrease (at higher deformations) of the hardness may be related to a minor reversibility of the gel set.

Kamaboko cohesiveness is shown in Table 2. Temperature showed no apparent effects on binding properties whereas deformation rate showed a slight but significant ($P < 0.05$) inverse effect. The most significant, and most obvious, reduction in cohesiveness occurred when the degree of deformation was increased. Note, however, no evidence of yield or external fracture occurred in any of the samples tested.

The gumminess response, also shown in Table 2, was similar to and correlated highly with cohesiveness with the exception of temperature effects at 80% compression and 25°C. The resilience of the kamaboko, as measured by degree of elasticity, is shown in Fig. 4. The elasticity response in the 10 to 50% deformation range was unchanged and only the 50% data are presented. A significant reduction in elasticity was observed as the material was deformed beyond 50% to 80% and these data agreed with the observed incompressibility found in the kamaboko dimensional analysis. The impact of deformation rate was slight, causing increased elasticity as the material was deformed more rapidly whereas the effects of temperature were not significant.

Stress-Strain Relationships

True stess — Hencky strain relationships were developed from the force deformation data for all runs. A typical stress strain curve is shown in Fig. 5. The implications of the sigmoid shape were addressed by Peleg, 1987. The first region (R_1) is linear, and represents the ideal elastic range that continues until the elastic limit is reached. The second portion (R_2) of the curve shows a slight concave downward tendency at the low strains of the region and a relatively linear trend through the remainder of the region. Peleg (1987) described the concave downward response as a region of predominant yield and internal structural breakdown whereas a linear or almost linear relationship implies a predominantly elastic or rubbery material. The slight degree of concavity that we found in region 2 for kamaboko indicated that limited plastic behavior occurred. The deviation from the initial linear, or ideal, elastic region is significant ($P < 0.05$), but a near-elastic behavior predominates and transcends relatively large deformations (Hencky strain of 1.0 = 60% deformation). The concave upward characteristic of region 3 (R_3) was indicative of a predominantly compressible material that compacts and becomes more dense as deformation continued. The stress strain relationship exemplified the high degree of elasticity that is characteristic of kamaboko.

The evaluation of the elastic moduli are shown in Fig. 6, where alpha 1 is the initial tangent (Young's) modulus, or slope of the stress strain relationship in the elastic region (R_1) and alpha 2 is the tangent (deformability) modulus or slope in the yield region (R_2). The increase in moduli, in the range studied, was linear and showed a slight increase as the material was deformed more rapidly. Temperature effects on alpha 1 were slight but significant ($P < 0.05$) The increase in the elastic modulus with temperature was expected for ideal elastic materials/regions according to the theory of rubber elasticity (Flory, 1953; Treloar, 1975). Alpha 2 was independent of temperature which may be related to non-ideal elastic behavior. The moduli were not affected by the degree of deformation. The effects of temperature on the stress strain ratio are shown in Fig. 7. An increase in the ratio occurred as temperature increased. Since the alpha 2 modulus was independent of temperature, this change must be related to changes in the elastic region. In addition to the direct proportionality of the alpha 1 modulus to temperature, there was evidence of an extension of the elastic range as temperature increased. To evaluate this expansion, an intersection analysis of the slopes in both regions was used to define the elastic limit. Table 3 shows those data and clearly establishes an increase in elastic limit as a function of temperature.

Integrated analysis

Analysis of the TPA and stress-strain data was accomplished in an integrated fashion using a factorial design with a second order mode which assessed not only linear and curvilinear effects, but some interactions as well. Results of these empirical analyses are shown in Table 4 and indicated an excellent fit ($r \geq 0.800$, df = 80) for all response variables except cohesiveness which, although it exhibited a lower degree of correlation, provided adequate prediction of response. The rate of deformation was the predominant independent variable which confirmed the need to specify this parameter in any rheologial analysis. The two level interactions (i.e., TC, TX, XC) played a major role in the modeling of the TPA responses, whereas the stress-strain relationships relied primarily on the main ef-

Table 4—Coefficients of the second-order model regression equation developed from the ITPA and stress-strain curves. Model: $Y^a = b_0^b + b_1T^c + b_2X^d + b_3C^e + b_4TX + b_5TC + b_6XC + b_7T^2 + b_8X^2 + b_9C^2$

Response Variable	Regression coefficients b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	r[f]
Hardness	−55.08	5.56*	6.14E-2*	−4.30*	9.02E-4	2.84E-2*	3.49E-3*	−8.32E-2*	−1.43E-3	5.60E-2*	0.981
Cohesiv.	1.56	−4.38E-2	−1.64E-3*	−1.20E-2*	−6.97E-5	2.30E-4*	−2.74E-5	4.74E-4	5.69E-5*	1.86E-5	0.603
Deg. Elas.	9.31E-1	−7.85E-3	−5.49E-5*	5.71E-3*	1.98E-5	−5.78E-5*	−6.58E-7	1.21E-4	−1.87E-6	−9.20E-5*	0.968
Alpha 1	10.39	3.24*	3.17E-1*	−9.99E-2	1.02E-3	6.28E-3	−1.11E-3	4.00E-2*	−6.50E-4	−5.22E-4	0.800
Alpha 2	−23.48	2.32E-1	1.13E-2*	2.08*	−3.21E-5	1.81E-3	2.05E-3	−3.98E-3	−1.88E-4	−.154E-2*	0.984

[a] Response variable.
[b] Regression coefficient.
[c] T — Temperature °C.
[d] X — Deformation rate (mm/min).
[e] C — Degree of deformation (%).
[f] r — Correlation coefficient.
* Statistically significant ($P<0.05$, df = 80).