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Studies on the Rheological Property of Korean Noodles

II. Mechanical Model Parameters of Cooked and Stored Noodles

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한국 재래식 국수류의 유체 변형성에 관한 연구

제 2 보 : 삶음시간과 저장기간에 따른 기계적 모델 상수들의 변화

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Abstract

The mechanical models representing the theological property of traditional Korean noodles; i.e. wheat flour noodle and wheat-sweet potato starch noddle, were investigated from the data obtained by creep and creep recovery test using a tensile tester. The rheological behavior of the noodle products could be expressed by the 6-elements Voigt model. The instantaneous elasticity, retarded elasticity, retardation time, retarded viscosity and Newtonian viscosity of the noodle products were evaluated. With the increasing cooking time, 4-elements Burger's model was applicable to represent the mechanical behavior of wheat-sweet potato starch noodle.

Introduction

In the previous paper, the mechanical behavior of traditional Korean noodles, both wheat flour noodle and wheat-sweet potato starch noodle, were approximated to have a linear viscoelastic property for a short time of enlongation at low level of stress range.(1)

If the material shows linear viscoelastic behavor, a mathematical expression of the mechanical property is possible by using creep test. In creep experiment, load (stress) is suddenly applied and maintained constant, and deformation is measured as a function of time. A particular interest is the case where a creep expriment has progressed for some time and the stress is then suddenly removed. The rate of deformation will change sign and the body will gradually return more of less toward its initial state. The course of this reverse deformation is called creep recovery. The creep curve for viscoelastic materials has an overall creep compliance D (t) at any time t, where D is the ratio of strain r (t) to stress (τ).

A creep curve of viscoelastic materials normally consists of three regions of compliance, as shown in Fig. 1, and their mathematical interpretation is as follows.(2,3,4)

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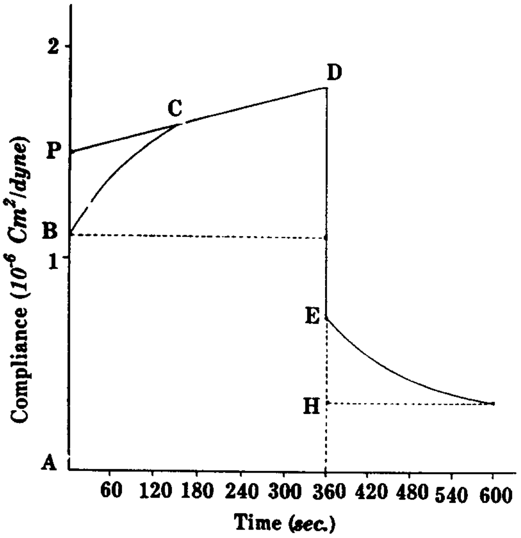

Fig. 1. Creep compliance curve for wheat noodle cooked for 6 *min*

i) A region of instantaneous elastic compliance D_0 (in the region AB of Fig. 1) in which bonds are stretched elastically.

$$D_0 = \frac{1}{E_0} = \frac{\gamma_0(t)}{\sigma} \quad \cdots\cdots(1)$$

ii) A time-dependent retarded elastic compliance D_R (BC of Fig. 1.), associated with a retarded elastic modulus, E_R, retarded viscosity, η_R and retardation time τ_R ($= \eta_R/E_R$) during which bonds break and reform. All bonds do not break and reform at the same rate, so that should be replaced by a spectrum of retardation times. Consequently, E_R and η_R should be replaced by a distribution spectrum of retarded elastic moduli E_1, E_2, ...E_i, and viscosities η_1, η_2, ...η_i, assuming i components.

In its expanded form

$$D_R = \sum_{i=1}^{n} D_i (1 - e^{-t/\tau_i}) = \sum_{i=1}^{n} D_i (1 - e^{-t/\eta_i D_i}) \quad \cdots\cdots(2)$$

where D_i is the number of viscosity components associated with retarded elastic compliance.

Applying the graphical procedure of Inokuchi(4) to eq. (2), let

$$Q = \sum_{i=1}^{n} D_i - D_R \quad \cdots\cdots(3)$$

This corresponds to the distance bewteen the extrapolated straight line DCP and the creep curve DCB at any time t, because of the exponential decay or relaxation of compliance.

$$Q = \sum_{i=1}^{n} D_i e^{-t/\tau_i} \quad \cdots\cdots(4)$$

When ln Q is plotted against t a straight line should be obtained at large values of t, from which a single retardation time (τ_1) and creep compliance (D_1) can be calculated. These values are inserted in eq. (2), and if it does not adequately define the form of the experimental curve, a second plot is required of ln (Q-D_1 e^{-t}/τ_1) against to to determine the magnitude of the second retardation time (τ_2) and the second creep compliance D_2. Eq. (4), indicates that this second plot should be linear when τ_1 τ_2. Similarly, if it is necessary a third retardation time, $_3$ can be determined by plotting ln (Q-D_1 e^{-t}/τ_1 -D_2 e^{-t}/τ_2) against t. This procedure is repeated until that sufficient retardation times and compliances have been calculated for eq. (2), to represent adequately the form of the experimentally determined retarded elastic compliance.

iii) A region of Newtonian flow CD with compliance D_n . Once the bonds have ruptured, i.e. the time for them to reform is much longer than the test period, individual particles or units flow passed one another.

Newtonian flow is proportional to the time of loading in this region of the curve, so that

$$D_N = \frac{t}{\eta_N} = \frac{\gamma_N(t)}{\sigma} \quad \cdots\cdots(5)$$

where γ_N is the shear strain in the linear region of the creep curve. Thus the gradient of this region equals $1/\eta_N$

When the stress is removed recovery follows a similar pattern to compliance. An instantaneous elastic recovery DE is followed by a retarded elastic recovery EH. Since bonds are broken in the compliance curve a part of the structure is not recovered, which is equal to Newtonian viscosity. The present study examined the selection of mechanical models, which could express the rheological behavior of noodle products in simple elongation. The changes in mechanical model parameters by cooking time and subsequent storage period were evaluated.

Materials and Methods

Test samples

The noodle samples used in this study were same as in the previous paper, i.e. wheat flour noodle and wheat-sweet potato starch noodle.(1) The selected samples were cooked by direct immersion in water pot filled with 1 *l* of tap water maintained at 99 ± 1 °*C*. One test sample was used at a time to minimize mechanical damage. Cooking time was controlled by stop watch. The sample was cooled by soaking in tap water for 3 *min* at 25 °*C*. The noodle was drained and tested within 2 *min*.

The optimum cooking time was determined by the time when a thin white line representing the core of the noodle strand was just disappeared.(5) The optimum cooking time of wheat flour noodle was 6 *min*, and samples were prepared with varying cooking times from 2 to 12 *min*. Similarily, the optimum cooking time of wheat-sweet potato starch noodle was 3 *min*, and samples were prepared with varying cooking times from 1 to 10 *min*.

In order to study the effect of storage periods the noodles were stored for 2, 4, 6, 12 and 24 *hr* at 25 ± 1 °*C* after cooking for their optimum cooking time. To prevent mechanical damage and drying during storage cooked sample was placed in a small cubic cylinder. Then, the cylider was wrapped and sealed with plastic film completely. The weight and diameter of noodle at each cooking time and after storage periods were measured.

Measurements

Creep and creep recovery tests were made on noodle strands using a tensile tester as described in the previous paper.(1)

All measurements were made at a single stress, $8 \times 10_4$ *dyn* cm^{-2}, and stress was removed after 360 *sec* of creep time to minimize deviation from the linear viscoelastic region.

Results and Discussion

The creep and recovery curves at different cooking time for wheat flour noodle and wheat-sweet potato starch noodle are shown in Fig. 2. and 3, and those at different storage periods are shown in Fig. 4, and 5, respectively. Each plots of strain vs. time was mean value of 5 tests.

The rheological parameters of each conditions were calculated by the method described above. Fig. 1 is a typical creep and creep recovery for wheat noodle cooked for 6 *min*, and the way in which this is treated will now be described in detail.

From Fig. 1.

$$D\,(AB) = \frac{1}{E_o} = 0.11 \times 10^{-5}\, cm^{-2}\, dyn^{-1}$$

$$\text{So that } E_O = 9.09 \times 10_5\, dyn\, cm^{-2}$$

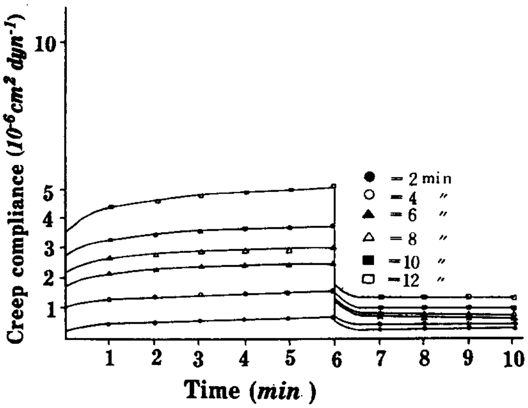

Fig. 2. Creep compliance curves for wheat noodles with different cooking time

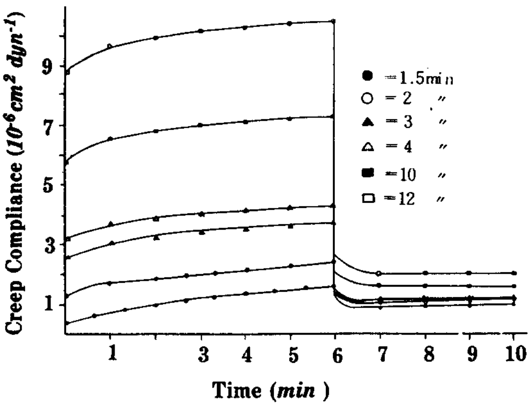

Fig. 3. Creep compliance curves for wheat - sweet potato starch noodles with different cooking time.

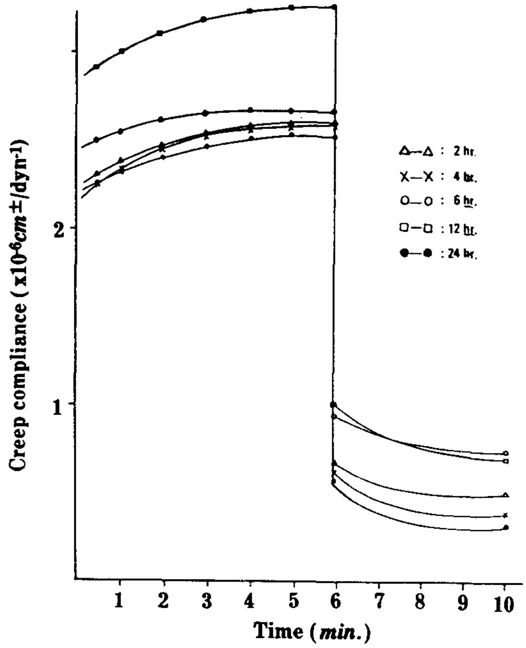

Fig. 4. Creep compliance curves for wheat noodles with different storage period

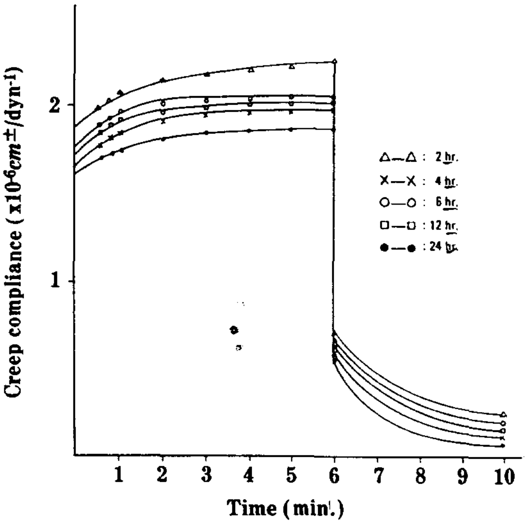

Fig. 5. Creep compliance curves for wheat-sweet potato starch noodles with different storage period

Table 1. Analysis of retarded elastic compliance by Inokuchi's method for wheat flour noodle cooked for 6 *min*

t (*sec*)	Q (10^{-6} *cm*² dyn⁻¹)	ln Q
5	0.3650	-14.8234
10	0.2550	-15.1820
20	0.1888	-15.4828
30	0.1475	-15.7294
40	0.1300	-15.8557
50	0.1100	-16.0228
60	0.1138	-16.9893
70	0.0938	-16.1826
80	0.0975	-16.1434
90	0.0813	-16.3570
100	0.0813	-16.3257
110	0.0763	-16.4397
120	0.0763	-16.3892
130	0.0788	-16.3570
140	0.0600	-16.6289
150	0.0500	-16.8112
160	0.0538	-16.7389
170	0.0450	-16.9116
180	0.0250	-17.5044
190	0.0175	-17.8611
200	0.0113	-18.3029
210	0.0138	-18.1022

Analysis of retarded elastic modulus was carried by the successive residual method known as Inokuchi's procedure.(4) Table 1 gives detailes of Q for different time intervals t. When these data were plotted in the form of *ln* Q anainst t, a straight line was obtained over 50 *sec* of creep, but within 50 *sec* the curves deviated upwards as shown in Fig. 6 (circle plots). Extrapolating the linear parts of the graph back to the ordinate axis gave D_1

Since $Q = \sum_{i=1}^{n} J^i e^{-t/\tau_i}$

Also, in this case

$\ln Q = \ln D_1 - t/z_1$

From the value of the intercept

$D_1 = 1.63 \times 10^{-7}\ cm^2\ dyn^{-1}$

Therefore

$E_{r_1} = 6.14 \times 10^{6}\ dyn\ cm^{-2}$

And from the gradient of the straight line

$\tau_1 = 127.7\ sec$

and $\eta r_1 = 7.84 \times 10^{8}$ poise

Since these data did not adequately reproduce the whole graph, a second plot was necessary. In this case ln $(Q - D_1 e^{-t/z_1})$ was plotted against t (Table 2).

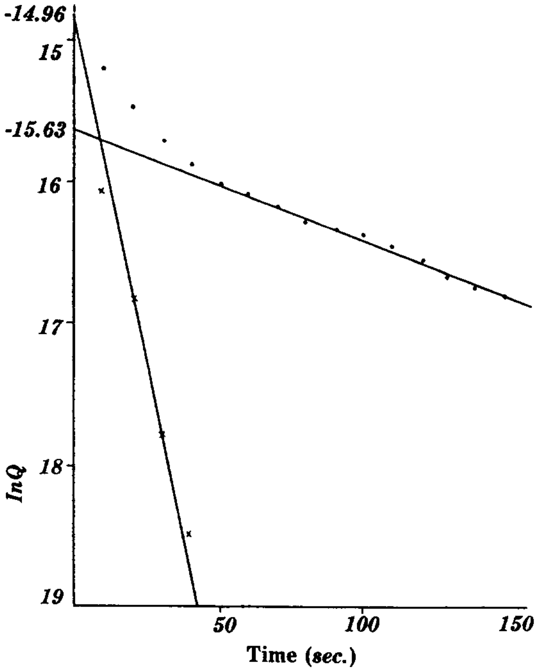

Fig. 6. In Q vs. T plot

Another straight line was obtained, as shown with cross plots in Fig. 6, and no further curve fitting were required. The intercept on the ordinary axis yielded

$D_2 = 3.18 \times 10^{-7}\ cm.\ dyn^{-1}$

then $Er_2 = 3.14 \times 10_6\ dyn\ cm^{-2}$

And from the gradient of the graph

$\tau_2 = 10.5\ sec$

and $nr_2 = 3.30 \times 10^8$ poise

The newtonian viscosity, η_N, is calculated from the value of $\frac{t}{\eta_N} = 0.6 \times 10^{-6}\ cm^2\ dyn^{-1}$

Therefore,

$\eta_N = 5.76 \times 10^6$ poise

Table 2. Analysis of retarded elastic compliance by Inokuchi's method for wheat noodle cooked for 6 *min*

t	t/τ_1	$D_1 e^{-t/\tau_1}$ $(10^{-7} cm^2/dyn)$	Q	$Q-D_1{}^{-t/\tau_1}$	$l_n(Q-D_1 e^{-t/\tau_1})$
5	0.0392	1.567	3.650	2.083	-15.3843
10	0.0783	1.506	2.550	1.044	-16.0750
20	0.1567	1.393	1.888	0.495	-16.8213
30	0.2350	1.2880	1.475	0.187	-17.7947
40	0.3133	1.1910	1.300	0.109	-18.3350

The rheological behavior of noodles under constant stress could be represented by a six-elements mechanical model (Voigt Model). The equation representing the mechanical behavior was

$$D(t) = D_0 + D_1(1-e^{-t/\tau_1}) + D_2(1-e^{-t/\tau_2}) + \frac{t}{\eta_N}$$

The rheological parameters of the noodles at various cooking time and storage time are shown in Table 3 for wheat flour noodle and in Table 4 for wheat-sweet potato starch noodle.

For wheat flour noodle, as cooking time increased, E_0 decreased rapidly, and Er and η_r decreased sharply at the beginning of cooking whereas η_N decreased slowly. When wheat flour noodle was stored after cooking, the retardation time and η_N decreased rapidly with increasing storage time but other parameters did not show consistent changes.

Similar results were shown in wheat-sweet potato starch noodle. The E_0 and E_r decreased consistently with the increasing cooking time, whereas η_N showed a higher value at the optimum cooking time. With the increasing cooking time, the 4-elements Burger's model could be used to represent the mechanical model of wheat-sweet potato starch noodle. When wheat-sweet potato starch noodle was stored, E_0, E_r, η_r, an η_N tended to increase.

Generally speaking, the sensory quality of noodle products are high at the optimum cooking time and it decreases when stored. As shown in Table 3 and 4, both wheat flour noodle and wheat-sweet potato starch noodle showed a reduction in both elasticity and viscosity by over cooking. But the opposite situation was observed during the storage of cooked noodles i.e. the elasticity and viscosity tended to increase by storage. This might indicate that the changes in the mechanical characteristics of noodles during cooking has different mechanism from those taking place during the storage after cooking.

요 약

한국 재래식 밀국수와 냉면국수의 유체 변형성을 규명하기 위하여 실험실에서 제작한 tensile tester를 이용하여 creep test를 실시하였다. 국수를 삶는 시간과 삶은후 저장하는 시간에 따라 기계적 모델파라 메터의 크기가 변하는 정도를 측정 하였다.

Table 3. The mechanical model parameters of wheat flour noodle for vairous cooking time and storage time

	E_0	Mechanical model parameters						η_N
	$(10^6$ *dyn* $cm^{-2})$	Er_1	η_{r1}	τ_1 (*sec*)	E_{r2}	η_{r2}^{*}	τ_2	$(10^8$ poise)
Cooking time								
(*min*) 2	8.00	10.70	13.90	130.08	7.28	0.37	5.08	6.40
4	1.40	3.80	4.36	114.81	1.71	0.05	3.18	5.90
6	0.91	6.14	7.84	127.66	3.14	0.33	10.50	5.76
8	0.66	5.90	2.93	49.69	6.58	0.45	6.82	5.21
10	0.54	5.13	4.38	85.43	3.87	0.69	17.70	5.18
12	0.42	4.93	4.32	87.56	2.40	0.15	6.33	4.07
Storate time[a]								
(*hrs*)	0.91	6.14	7.84	127.66	3.14	0.33	10.58	5.76
2	1.08	7.28	3.05	41.48	4.33	0.11	2.57	14.80
4	1.14	5.23	1.94	37.10	0.84	0.02	1.86	20.10
6	1.00	6.99	2.17	31.07	8.37	0.37	4.38	9.83
12	0.90	6.14	4.39	71.43	4.78	0.30	6.22	12.40
24	1.14	9.82	6.70	68.18	5.55	0.33	5.97	18.70

[a] Samples were stored after cooking for 6 *minutes.*

Table The mechanical model parameters of wheat and sweet potato starch noodle for vairous cooking time and storage time

	E_0	Mechanical model parameters						η_N
	$(10^6$ *dyn* $cm^{-2})$	Er_1	η_{r1} τ_1	E_{r2} (*sec*)	η_{r2}	τ_2		$(10^8$ poise)
Cooking time								
(*min*) 1.5	1.90	3.84	2.03	52.82	12.50	1.82	14.56	2.92
2	0.89	4.11	3.59	87.43	3.95	0.14	3.47	3.25
3	0.38	2.45	1.55	63.35	5.84	0.54	9.26	3.30
4	0.30	2.00	1.00	50.00	-	-	-	3.54
6	0.18	1.48	0.54	36.55	-	-	-	2.36
10	0.14	1.25	0.53	42.49	-	-	-	2.71
Storate time[a]								
(*hrs*)	0.38	2.45	1.55	63.35	5.84	0.54	9.26	3.30
2	0.57	6.58	3.40	51.63	4.41	0.24	5.36	14.90
4	0.65	7.65	3.71	48.44	6.39	0.62	9.69	25.00
6	0.62	8.62	4.39	50.91	5.67	0.47	8.33	18.00
12	0.62	12.10	7.47	61.73	3.61	0.21	5.70	18.90
24	0.73	12.10	8.36	69.12	7.42	0.40	5.35	34.39

[a] Samples were stored after cooking for 3 *minutes.*

대부분의 삶은 국수 시료는 6-element Voigt 모델로 설명될 수 있었다. 밀국수의 경우 국수를 삶는 시간이 경과함에 따라 순간탄성(instantaneous elasticity)이 감소 되었으며, 지연탄성(retarded elasticity)과 지연점성(retarded viscosity)은 삶음 초기에 크게 감소되었다. 반면에 뉴우턴 점성은 삶음 시간에 크게 감소되었다. 반면에 뉴우턴 점성은 삶음 시간에 따라 서서히 감소되었다. 삶은 밀국수를 저장하는 시간에 따라 지연시간(retardation time)과 뉴우턴 점성이 급격히 감소되었다.

냉면국수와 삶음시간이 경과함에 따라 순간탄성과 지연탄성이 계속적으로 감소하는 반면 뉴우턴 점성은 최적 삶음시간에서 최고치를 나타내었다. 삶음시간이 경과함에 따라 냉면국수는 4-element Burger's 모델로 그 기계적 성질을 표현할 수 있었다.

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