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Rheological Properties of Cooked Noodles with Different Starch Content Using Tensile Tests

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Abstract Several rheological terms were introduced to estimate the properties of cooked noodles with different starch content using tensile tests. Ring-shaped specimens were prepared by connecting both ends of the noodle strip before cooking. Hencky strain and rate, as well as true stress were applied in constant deformation tests. The elastic region on the curves of strain vs. stress was not clearly identified. Strain hardening in the subsequent plastic region was more prominent in low-starch noodles. Elongational viscosities at lower strain rates were used to differentiate noodles with different starch content, representing the dominant effect of protein content in the range of lower strain rates. In stress relaxation tests, the reciprocal of Peleg's constant K_1 (initial decay rate) and K_2 (asymptotic level) increased and decreased respectively, with an increase in starch content. This indicated that addition of starch contributed to the noodles becoming viscous liquid rather than elastic solid.

Keywords: noodle rheology, tensile test, strain hardening, elongational viscosity, stress relaxation

Introduction

Noodle texture is known to be very difficult to measure because of the irregularity in size and shape of the samples. A variety of instrumental tests have previously been applied for the textural analysis of cooked noodles, but the data obtained lacked in reproducibility and accuracy due to the inherent properties of the samples studied. The results of these studies also showed a low degree of relation with sensory properties (1). Tensile tests could be used under conditions of larger deformation, which are more favorable for noodle-like samples, but the problem lies during preparation of the specimens for the test primarily due to a weakness in the area that is gripped during the analysis.

In compression tests, which are the most common, noodle specimens of a single strip are generally placed on a platform, and a resistance force is measured (2). However, the size of a noodle strip is usually too small in thickness to allow for accurate measurements. Furthermore, Voisey and Larmond (3) and Voisey *et al.* (4) noted that the variation in diameter of cooked noodles affected the texture measurements. Thus, irregularities in size and shape of the noodle strip could cause errors in data reproducibility and accuracy. To overcome such deficiencies in the compression tests, an instrumental modification of probes and sample holders, and a mathematical analysis of data were attempted in the measurements of firmness (5), work to cut (2), and stickiness (6).

Tensile mode is an alternative of the compression mode to test the rheological properties of foods. Although the tensile test has the benefit of adopting a wide range of deformation characteristics, the main difficulty is in gripping the samples with tension. Specially-devised test geometries have been developed, such as dumbbell with right-angle or tapered shoulder, locking clamp for strips or dumbbells, shelf-tightening grips, and pulley arrangements for circular test pieces (7). Pasta dough (8) and *chapatti* (9) were tested with simply devised grips, and cooked noodles with pneumatic-action grips (10,11) as well as a set of notched grip and L-shaped hook (12,13). Recently, a new method to measure cutting force of cooked noodles by tension was developed, where a ring-shaped specimen were formed before cooking by connecting both ends of the noodle strip (1).

The rheological properties of foods using the tensile test has previously been measured in terms of strain hardening, elongational viscosity, parameters of stress relaxation, creep, etc (7). Typical curves of force vs. deformation in tension have two regions: elastic and plastic. The initial elastic region reflects elastic solid properties, whereas the subsequent plastic region displays viscous liquid properties. In the plastic region, food samples undergo strain hardening. If strain hardening occurs to a large extent, this indicates resistance of samples to becoming plastic in nature (7). Strain hardening provides stability without necking over a large extension (14). It indicates that the strain hardening can play a role in protecting food materials against necking or cutting in any processing in tensile deformation.

Viscosity of noodles is an important rheological parameter in determining sensory properties and even in handling of cooked noodle production lines. Viscosity is a rheological term relating to the physical properties of liquid-like materials, but not solid-like materials such as noodles. Even test geometries for the viscosity measurements are usually in flow patterns, which are different from those for solids. But uniaxial extension tests that are usually used for solids can make measurements of viscosity possible. This special viscosity is the elongational viscosity, which describes the resistance to uniaxial extensional flow (15).

Stress relaxation tests have usually been adopted to measure the viscoelasticity of various materials. In the stress relaxation test, the samples, once deformed, are held

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to measure how the stress attenuates without additional deformation. The stress relaxation patterns are complicated to analyze in terms of rheological principles, hence simplified and even more practical methods using Peleg's model, generalized Maxwell model, Burger's model, etc, were developed (16). The creep test is an alternative to stress relaxation tests for viscoelasticity, in which the deformation of the sample under constant stress is measured according to time (17). Usually the stress relaxation test is preferred to the creep because of limited availability of the creep option on test modes.

In the present study, the texture of the noodle was studied by applying several rheological principles to tensile test data on cooked noodles. The test geometry, with a ring of cooked noodle stretched between 2 cylindrical rigs, was adopted to avoid clamping the sample in the tensile test. The rheological parameters of cooked noodles were analyzed in terms of strain hardening, elongational viscosity, and stress relaxation.

Materials and Methods

Materials The wheat flour used in this study was a commercial product (for noodle use, Samhwa Flour Mills Co., Incheon, Korea) of 70% dark northern spring (DNS) and 30% soft white (SW) wheat harvested in 2007 in the United States. Protein and ash contents of DNS and SW, which were provided by the supplier, were 13.4 and 0.414%, and 7.2 and 0.410% on a 14% moisture basis, respectively. Potato starch (food grade, Haepyo Co., Seoul, Korea) was added at 10, 20, and 30%, respectively, on a 500 g basis of flour-starch mixtures. A 2% NaCl (purified grade I, CJ Ltd., Seoul, Korea) solution and 40% distilled water was added to the 500 g mixture.

Preparation of noodle A lab scale noodle machine (YMC-102; Seoju Engineering Co., Gwangju, Korea) was used for the preparation of the noodles. Noodles were made using 500 g of the mixed flour, 200 g of distilled water, and 4 g of salt. The ingredients were mixed in a mixer (SM200; Sinmag Bakery Equipment Co., Wuxi, China), in which the salt solution was added to the flour for 30 sec at a low speed mixing (107 rpm). Mixing continued for 4.5 min at low speed, followed by 8 min at high speed (365 rpm) and an additional 2 min at low speed. The dough was then allowed to rest in a plastic bag at room temperature for 15 min to distribute water uniformly throughout the flour particles. The dough was passed uni-directionally through 2 rollers in 6 successive steps with decreasing roll gaps of 4.0, 3.7, 2.9, 2.0, 1.6, and 1.3 mm. The final sheeted noodle dough was cut into strips 1.3 mm thick, 6 mm wide, and 17 cm long.

Preparation of ring type specimen For the tensile test, the ends of the noodle strip were connected together to form a raw noodle ring. One end was "glued" onto the other end with a little water, using the fingers to press them together. The ring circumference, width, and thickness were 15.5 cm, 6 mm, and 1.3 mm, respectively. Five ring samples were boiled in a container with 500 mL of distilled water for 7 min and cooled in tap water for 30 sec. Cooked samples were drained on a plastic strainer with apertures of 0.5 mm for 10 sec. Each starch-flour mixture series was analyzed in 5 replicates.

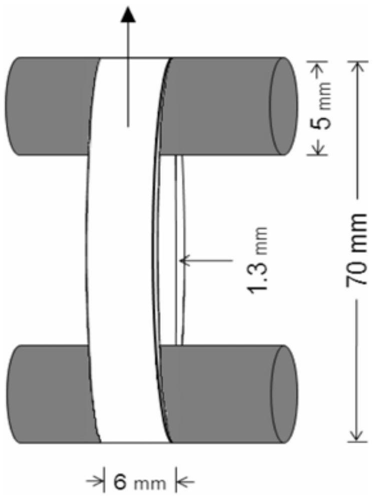

Fig. 1. Schematic presentation of the device used to extend cooked noodle ring samples.

Uniaxial extension The measurements were performed with a texture analyzer (TA-XT2; Stable Micro Systems Ltd., Surrey, UK) at a crosshead speed of 6 mm/sec in extension mode. The tensile test geometry consisted of 2 cylindrical rigs of 5-mm diameter, attached to the crosshead and a part of the platform, respectively (Fig. 1). A ring of cooked noodle was stretched in between 2 rigs. The rigs were cleaned and lubricated with vegetable oil after each run to remove any end effect caused by friction between the surfaces and the test sample.

If a ring sample is excessively extended, the glued end region may rupture, as it is the weakest part on the sample. To ensure that the glued part was safe during extension, a valid test range was determined using specifications elaborated in a previous study (1). It was found to be up to 5 cm extension. So, the tensile force was measured until the crosshead moved upward by 5 cm from the starting position, detected by the auto mode with 10 g-force (g_f) trigger force setting. The extension and force were converted into Hencky strain and stress, respectively. The Hencky strain was adopted because it was shown to be more suitable for highly deformed materials like noodles (7).

$$\varepsilon_H = \int_{l_0}^{l} dl/l = \ln(l/l_0) \qquad (1)$$

$$\sigma = F/A = F \cdot l/(A_0 \cdot l_0) \qquad (2)$$

where ε_H is the Hencky strain, l_0 the initial length, and l the instantaneous length. σ is the true stress, F the resistance force, A_0 the initial cross-sectional area of noodle, and A the instantaneous area of noodle. The initial noodle length was measured at the moment the measured force exceeded 10 g.

Using the true stress and Hencky strain, several rheological parameters were estimated in the uniaxial extension, including the strain hardening index (equivalent to the strain beyond which unstable necking and eventual fracture during extension occur) (7) and elongational viscosity (viscous property) (15). Strain hardening is described in the function between the stress and strain as follows (7):

$$\sigma=K(\varepsilon_H)^n \tag{3}$$

$$\ln\sigma=\ln K+n\cdot\ln\varepsilon_H \tag{4}$$

where K is the strength constant and n the strain hardening index. The elongational viscosity (η_E) is a function of the stress (σ) and strain rate ($\dot{\varepsilon}_H$) as follows:

$$\eta_E=\sigma/(\dot{\varepsilon}_H) \tag{5}$$

$$\dot{\varepsilon}_H=d\varepsilon_H/dt=(dl/dt)/l=v/l \tag{6}$$

where t is the instantaneous time and v the deformation rate, i.e., the crosshead speed.

Stress relaxation The measurements were performed at a crosshead speed of 6 mm/sec in the tension mode of 'hold until time'. The instrumental geometry and test samples were the same as the uniaxial tension. The extension was stopped at 80 g_f, and then the sample was held for 60 sec while the remaining force was measured. This operation was conducted using auto mode with 80 g_f trigger setting in tension. The Peleg's model was adopted to analyze the relaxation curve (16).

$$\sigma_i\cdot t/(\sigma_i-\sigma)=K_1+K_2\cdot t \tag{7}$$

where σ_i is the initial stress, t the relaxation time, and K_1 and K_2 the Peleg's constants.

Results and Discussion

A method to prepare specimens as rings of noodles was applied (1), which made it possible to analyze the detailed rheological properties of noodles. It had been reported that the tensile test could increase data validity with high precision in fiber materials (18). The rheological parameters of cooked noodles were rigorously analyzed in terms of strain hardening, elongational viscosity, and stress relaxation.

Strain hardening In the stress-strain curves (Fig. 2), a yield point, which divides into 2 regions, elastic and plastic (7), was not present. The curve appeared nonlinear, which falls into plastic region. The stress increased with the strain according to a power law with index less than one, reflecting strain-hardening phenomena. The strain hardening properties were analyzed in terms of strain hardening index (Fig. 3). The strain hardening index of the material was mathematically derived to be equal to a critical strain which was an extension before failure occurred (7). In Table 1, the strain hardening index decreased with an increase in starch content. This indicated that the noodles with higher starch contents might be fractured more easily when extended. In addition, the strength constants decreased with an increase in starch content. This indicated that the added starch could weaken the noodle strength.

When a material is extended, all its parts are not uniformly extended with the same degree of deformation. In physical aspects, strain hardening means that resistance against extension on the more extended part, which becomes weaker, increases relative to the other less extended parts. This allows for the extension of the weak part to be restricted against subsequent necking, whereas the other parts are extended continuously. A sample with a lower starch content, which is inversely related to protein content, showed higher degree of strain hardening. This indicated that the gluten network within the noodle contributed to restricting the extension, leading to strain hardening.

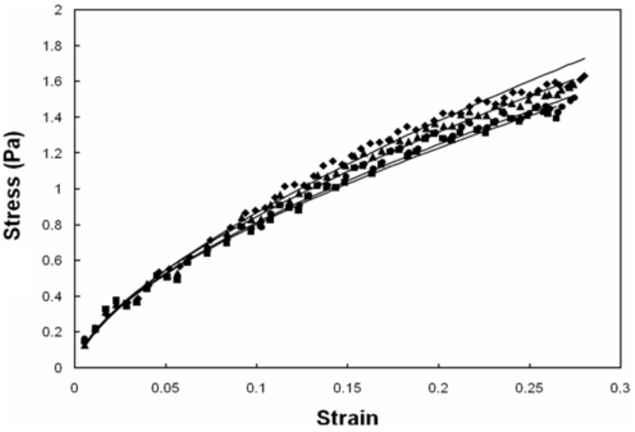

Fig. 2. Curves of true stress vs. Hencky strain in tensile tests for cooked noodles with different starch contents. The dots represent the experimental data and the solid lines the predicted estimates from Eq. 3 and Table 1 (◆, ▲, ●, ■=0, 10, 20, and 30%, respectively).

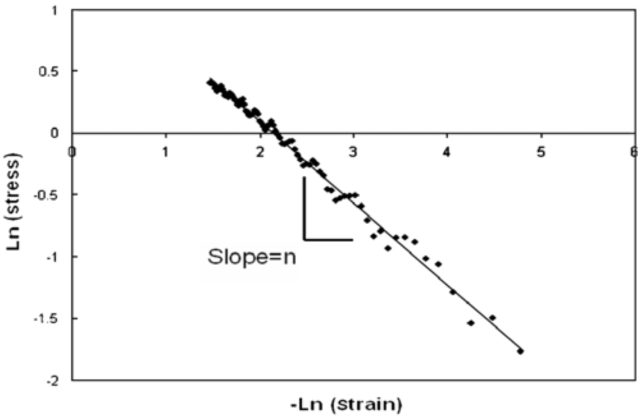

Fig. 3. Graphical depiction for calculating strain hardening index by linear regression with Eq. 4 on stress-strain data from tensile tests for cooked noodles.

Table 1. Parameters of strain hardening from tensile tests on cooked noodles with different starch contents: strain hardening index (*n*) and strength constant (*K*)

	Starch content (%)			
	0	10	20	30
n	0.668±0.012[1]	0.637±0.013	0.621±0.016	0.615±0.011
K	4.148±0.097	3.789±0.086	3.370±0.069	3.314±0.058

[1] Mean±SD with 5 replicates.

Within the practical aspects, strain hardening is necessary for stability in any operation that requires large extension. Such extension occurs when picking up the noodles from a bowl with chopsticks while eating, or dragging the flow of noodle strands in a continuous instant noodle-making system from steaming to frying processes. Noodles with a higher starch content showed less strain hardening, which

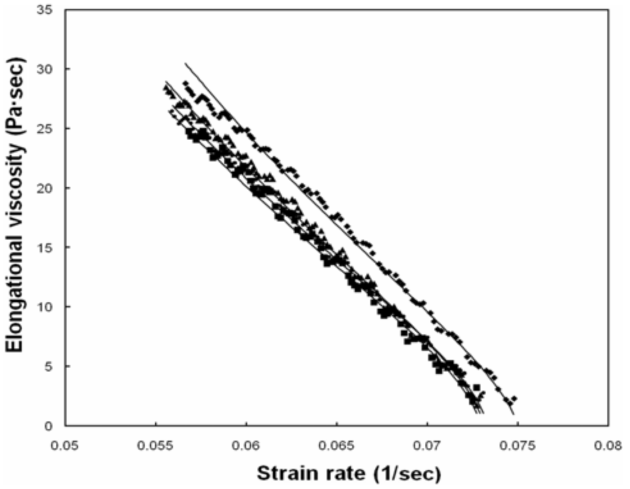

Fig. 4. Curves of elongational viscosity vs. Hencky strain rate in tensile tests for cooked noodles with different starch contents. The dots represent the experimental data and the solid lines the predicted estimates from Eq. 3 for the stress, Eq. 6 for the strain rate and Table 1 (◆, ▲, ●, ■=0, 10, 20, and 30%, respectively).

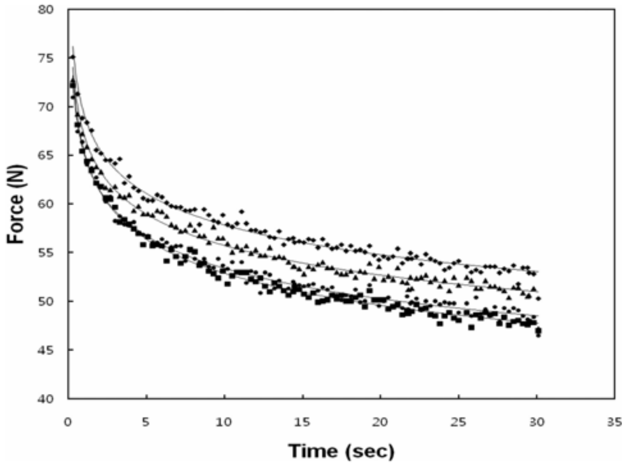

Fig. 5. Curves of force vs. time in stress relaxation tests for cooked noodles with different starch contents. The dots represent the experimental data and the lines the predicted estimates from Eq. 7 and Table 2 (◆, ▲, ●, ■=0, 10, 20, and 30%, respectively).

would lead to necking and eventual failure. Thus the starch contents of the noodle would affect the quality of processing either in consumption or production. Baik *et al.* (19) reported that high protein cooked noodles, which were equivalent to low starch noodles, had high scores of several texture profile analysis (TPA) parameters such as hardness, cohesiveness, gumminess, and chewiness, indicating that the starch weakened the structure of cooked noodles. Our finding of less strain hardening in high starch noodles was consistent with this weakening in high starch noodles.

Meanwhile, the elastic region prior to the plastic region did not appear clearly. The elastic region represents elastic solid property, indicating that noodles are not purely elastic solids. This also reflects the viscoelastic nature of noodles, due to the complex mixture of cooked starch and protein.

Elongational viscosity The elongational viscosities could be correlated with some product qualities of peanut butter (20), cheese (21), and set yogurt (22), such as spreading with a knife on bread and squeezing with tongue. Even during the consumption of noodles, the elongational viscosity of the product might affect some properties associated with deformation like handling with chopsticks, or sucking of the noodles. Therefore we included this parameter in our studies.

In Fig. 4, the elongational viscosity increased with a decrease in the strain rate, which was explained by Eq. 5, representing proportional and inverse proportional relations with the stress and strain rates, respectively. The strain rate decreased with extension according to Eq. 6, though the probe moved at a constant deformation rate.

The elongational viscosities were lower with higher starch contents (Fig. 4). This difference between 10, 20, and 30% starch contents became smaller at higher strain rates. This indicated that the test range appropriate for distinguishing the samples with different starch contents was at low strain rates. Theoretically, if the strain rate is low in tension at a constant deformation rate, where the strain is large, it is the solid property that governs the deformation system (7). Thus it was reasoned that the starch content would change the solid property of the noodle, which is phenomenally expressed as elastic property. An indicator of the elastic property of the noodle would be the elongational viscosity at relatively low strain rates.

In microstructural aspects, the cooked noodle consists of a gluten matrix in which starch is swollen with water and gelatinized during cooking. Niihara and Harigai (23) and Konik *et al.* (24) noted that if the protein content was low, its matrix structure might loosen, which would allow for increased space of the matrix to accommodate the swollen starch. The starch swollen to larger degree weakens and has lower viscosity in shear. Although our findings on the viscosity were for elongation, the effect of the addition of starch was likely to agree with the above facts. Basically, elongation is a flow system with uniaxial extension by tension or biaxial extension by compression or squeezing without shear (7). The majority of noodle deformation in eating noodles is in elongation rather than shear and therefore the elongation viscosities would be more directly related to noodle qualities.

Stress relaxation properties In the initial stage of relaxation (Fig. 5), the force decreased more quickly for noodles with higher starch content. An asymptotic level of stress at the infinite relaxation time was lower with higher starch content. The curves were transformed to the variables of Peleg's model, which underwent a linear regression to estimate 2 parameters, Peleg's constants K_1 and K_2 (Fig. 6). The reciprocal of Peleg's constant K_1 meant an initial stress decay rate representing a liquid behavior. If $1/K_1$ increased, the sample would act more like a liquid. In Table 2, $1/K_1$ increased with an increase in the starch content, indicating that the addition of starch enhanced the liquid property of the final material, which was phenomenally expressed in terms of its paste-like viscosity. K_2 meant the asymptotic stress level representing a solid behavior. That is, if a residual force still remained even after infinite relaxation

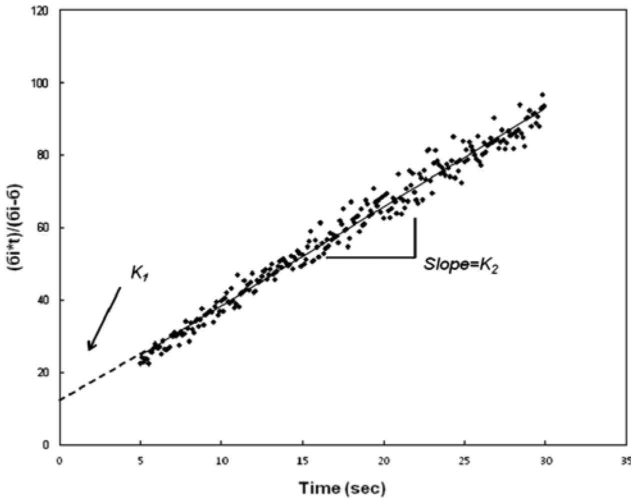

Fig. 6. Graphical depiction for calculating Peleg's constants by linear regression with Eq. 7 on force vs. time data from stress relaxation tests for cooked noodles.

Table 2. Peleg's constants from stress relaxation tests for cooked noodles with different starch contents: initial stress decay rate ($1/K_1$) and a hypothetical asymptotic stress level (K_2)

	Starch content (%)			
	0	10	20	30
$1/K_1$	0.088±0.005[1)]	0.096±0.005	0.110±0.004	0.119±0.004
K_2	2.768±0.022	2.717±0.024	2.503±0.024	2.421±0.021

[1)] Mean±SD with 5 replicates.

under a fixed load, this could be attributed to the presence of an elastic component like spring. In Table 2, K_2 decreased with an increase in the starch content, indicating that the addition of starch lowered the elasticity of the noodle. This confirmed that noodles with increased starch content showed a lower protein content, which decreased the overall elasticity. Therefore, the stress relaxation parameters could also determine noodle textural characteristics in terms of viscous and elastic properties.

In conclusions, here, we attempted an analysis of the physical properties of cooked noodle in terms of its rheological parameters by applying several rheological models and an experimental method to extend specimens as noodle rings. Noodle properties could be more rigorously expressed in rheological terms than just by phenomenal terms. First of all, force and deformation, which were primarily measured, were converted to a true stress and Hencky strain, which is also a true strain. The strain hardening index was estimated in an attempt to understand the texture of the noodle based on increased addition of starch. It was effective in determining how much the noodles could be extended without necking and cutting. Elongational viscosities at lower strain rates were used to differentiate the noodles with different starch addition, representing a dominant effect of protein contents in the range of lower strain rates. Lastly, stress relaxation was applied to examine the viscous or elastic properties of noodles. Namely, the sensorial viscoelasticity of noodles to oriental individuals especially Koreans remains a mysterious term to wheat growers, millers, or food processors in Western countries. Using Peleg's model, we determined 2 parameters for viscous and elastic properties, respectively. The viscous property of the noodles increased and the elastic property decreased, with an increase in the starch content.

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