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Characterization of Viscoelastic Properties of Rice Cake

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It is highly important to rheologically characterize the factors and structures of gelatinized rice flour gel (rice cake) to control both the qualities of the final products (rice cracker) and the manufacturing process. Accordingly, attempts were made to analyze the rice cake factors and understand the structure by measuring the shear viscosity development after the onset of steady shear flow of various rice cake samples, which were different both in rice cultivars (the primary factors) and in preparation conditions (the secondary factors). As a result, it is considered that the viscosity and elasticity terms in the linear region and the nonlinear region contribute to the analysis of the primary factors and the secondary factors, respectively and furthermore understanding the relationship of each to the pseudo-network structure of rice cake.

Keywords: rice cake, rice cracker, rice starch gel, viscoelastic property

In the industry of manufacturing rice crackers, the qualities of the final products largely depend on the physical properties of the gelatinized rice starch gel (rice cake) (Saito, 1989; Arisaka, 1994). In particular, it is highly important in the quality control (expansion, texture) of rice crackers to continuously prepare rice cake having constant and appropriate extensibility (corresponding to viscosity) and firmness (corresponding to elasticity). Based on experience, the physical properties of rice cake may be produced by the primary factor (cultivar) and the secondary one (preparation conditions; kneading degree, water content, etc.). Furthermore, the primary factor may affect the secondary one. It is considered that the physical properties of rice cake originate in the structures. Therefore, it is necessary to rheologically characterize the viscoelastic properties of rice cake and simultaneously evaluate the two factors affecting the structure formation for both the qualities of rice cracker and the manufacturing process. A number of studies have been performed on rice crackers and the rheological properties of cooked rice, rice starch and rice cake (Nagashima *et al.*, 1990a, b; Arisaka *et al.*, 1991; Yamada *et al.*, 1993; Yoshii *et al.*; 1993; Yoshii & Arisaka, 1994; Horiuchi, 1995; Otobe *et al.*, 1995). However, there has been little rheological study of the two factors. In our previous paper (Isono *et al.*, 1990a), we rheologically studied rice cake samples which differed in preparation conditions (the secondary factor) and described that viscoelastic measurement in the linear and nonlinear regions is effective for evaluating the delicate texture of rice cake samples. In this paper, therefore, we tried to examine how we can characterize the viscoelastic properties with respect to the two factors and estimate the structure of the rice cake samples.

Materials and Methods

Preparation of samples Three glutinous paddy rice cultivars, i.e., Koganemochi (abbreviated K, hereafter) produced in Niigata, Hiyokumochi (abbreviated H, hereafter) produced in Saga and Tannemochi (abbreviated T, hereafter) produced in Hokkaido were used (degree of polishing: 90%). The rice cake was prepared by a conventional method, i.e., washing the rice (10 min), soaking in water (12 h), draining (30 min), steaming (25 min) and kneading. Kneading was effected with the use of an electric kneading machine. The water contents of K, H, and T (rice cakes kneaded for 10 min) were 44.5%, 43.7% and 43.8%, respectively. The water contents of K, H, and T (rice cakes kneaded for 15 min) were 42.9%, 43.7% and 43.5%, respectively. The samples were molded, stored and placed in a measurement cell each in the same manner as that described in the previous paper (Isono *et al.*, 1990a).

Measurement method Similar to the case in our previous paper (Isono *et al.*, 1990a), deformation was performed by the simple shear deformation between parallel disks. The diameter and the height of a sample disk were 50 mm and 8 mm, respectively. The apparatus was a rice cake rheometer IU-89070 (Yoshimizu Ltd., Matto-shi, Ishikawa) which had been manufactured in a trial especially for easily measuring the shear viscosity development after the onset of steady shear flow. Figure 1 shows a schematic diagram of the apparatus. Two types (diameter: 50 mm, 28 mm) of parallel disk cells can be placed on the sample-holding part. The sample and disk cells are immersed in a liquid paraffin bath to prevent drying of the sample. When the lower rotation shaft is rotated in a definite direction, a strain is applied to the sample and the torque thus formed is detected. Depending on the level of the torque thus formed, the two cells may be appropriately selected to thereby detect torque over a wider range. To analyze a less elastic sample such as rice cake, it is necessary to detect a low torque with high accuracy. From this point of view, it is advantageous to employ large parallel disk cells. This apparatus makes it possible to measure torque over a wide range (1 to 1000 g·cm). The response time is set to not more than 10 ms to accurately measure the shear viscosity

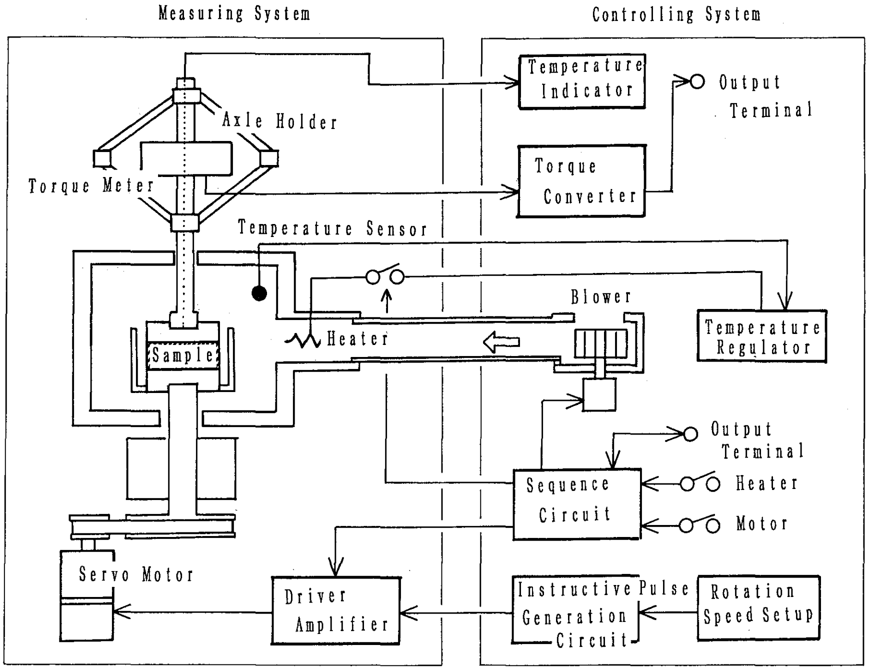

Fig. 1. Schematic diagram of rheometer IU-89070 exclusively for rice cake.

development after the onset of steady shear flow. The speed of the rotation shaft is regulated within a range from 0.0003 to 0.3 rpm to measure the shear rate of the rice cake over a wide range at high temperatures. Temperature is controlled by a PID pulse width proportional controlling system by which the temperature can be controlled at a level of ± 0.1°C. In the practical measurement, the temperature was set to 90°C, the peripheral shear rate of the sample ranged from 3.16×10^{-4} to 1.00×10^{-2} s^{-1} and the measuring time was from 10 to 2000 s.

Calculation method By the measurement of the shear viscosity development, the apparent viscosity development $\eta_a(t, \dot{\gamma}_R)$, true viscosity development $\eta(t, \dot{\gamma}_R)$ and the apparent steady state compliance *Js* are calculated in accordance with the following Eqs. (1), (2), (3), (4), (5), respectively (Kearsley & Zapas, 1976; Isono *et al.*, 1979, 1990b).

$$\eta_a(t, \dot{\gamma}_R) = T(t)/b\dot{\alpha} = T(t)R/bh\dot{\gamma}_R \qquad (1)$$

$$\eta(t, \dot{\gamma}_R) = \eta_a(t, \dot{\gamma}_R)\left\{1 + \frac{1}{4}\frac{\partial \ln \eta_a(t, \dot{\gamma}_R)}{\partial \ln \dot{\gamma}_R}\right\} \qquad (2)$$

$$\psi_{12}(t, \dot{\gamma}) = \Gamma(t, \dot{\gamma}) + \frac{1}{\dot{\gamma}}\int_0^{\dot{\gamma}} \Gamma(t, \dot{\gamma}) d\xi \qquad (3)$$

$$\Gamma(t, \dot{\gamma}) = t\eta(t, \dot{\gamma}) - \int_0^t \eta(s, \dot{\gamma}) ds \qquad (4)$$

$$Js = \psi_{12}/2\eta^2 \qquad (5)$$

In the above formula, $T(t)$ represents the development torque; b $(=\pi R^4/2h)$ represents a shape coefficient; $\dot{\alpha}$ represents the torsion angle velocity; R and h represent the radius and the height of the sample, respectively; and $\dot{\gamma}_R$ represents the peripheral shear rate of the sample; $\psi_{12}(t, \dot{\gamma})$ represents the first normal stress difference coefficient; and $\Gamma(t, \dot{\gamma})$ is an elasticity term representing the area surrounded by the viscosity development curve with the y-axis. Regarding the steady state compliance *Je*, the following relationship is achieved in the linear region.

$$\lim_{\dot{\gamma}\to 0} Js = Je$$

However, the rice cake sample shows a very narrow linear region and a high strain rate-dependency, which makes it impossible to strictly determine the steady state compliance *Je*. Thus, evaluating a rice cake sample on the basis of the apparent steady state compliance *Js* is unavoidable. By measuring the shear viscosity development after the onset of the steady shear flow, both the viscosity and elasticity terms can be estimated over a wide strain range involving the linear region and the nonlinear region.

Results

Figure 2 shows curves formed by plotting the $\eta(t, \dot{\gamma}_R)$ of each rice cake sample at various shear rates. Boxed curves are enlargements of curves over a short time range (i.e., within 100 s starting from the initiation). At every shear rate, the order of the initial slope η/s (viscosity in the linear region) of $\eta(t, \dot{\gamma}_R)$ is K<H<T. As the shear rate increases, however, the difference between K and H becomes smaller and they are finally reversed. The linear region is more closed up at the lower shear rate, which makes it easy to understand the tendency in the initial slopes (K<H<T), although it is assumed that K attains the peak for the first time followed by H and T in this order. When shear rates are low (i.e., 1.00×10^{-3} and 3.16×10^{-4}), no peak is shown within the measurement time (2000 s). Within a shear rate range showing clear peaks (1.00×10^{-2} to 3.16×10^{-3}), the peak viscosities are in the order of T>K>H. Over the long time range (nonlinear region), the tendency of each variety changes in size. Figure 3 is a graph obtained by plotting the $\eta(t, \dot{\gamma}_R)$'s of rice cakes (kneaded for 10 min, 15 min) of varic ɹs varieties at shear rates of 1.78×10^{-3} against time. Similar to our previous paper (Isono *et al.*, 1990b), a sample with a longer kneading time shows a smaller initial slope, lower peak viscosity and lower steady viscosity or a value estimated as the steady viscosity (hereinafter referred to as the apparent steady viscosity) in every variety. In the case of the rice cake samples kneaded for

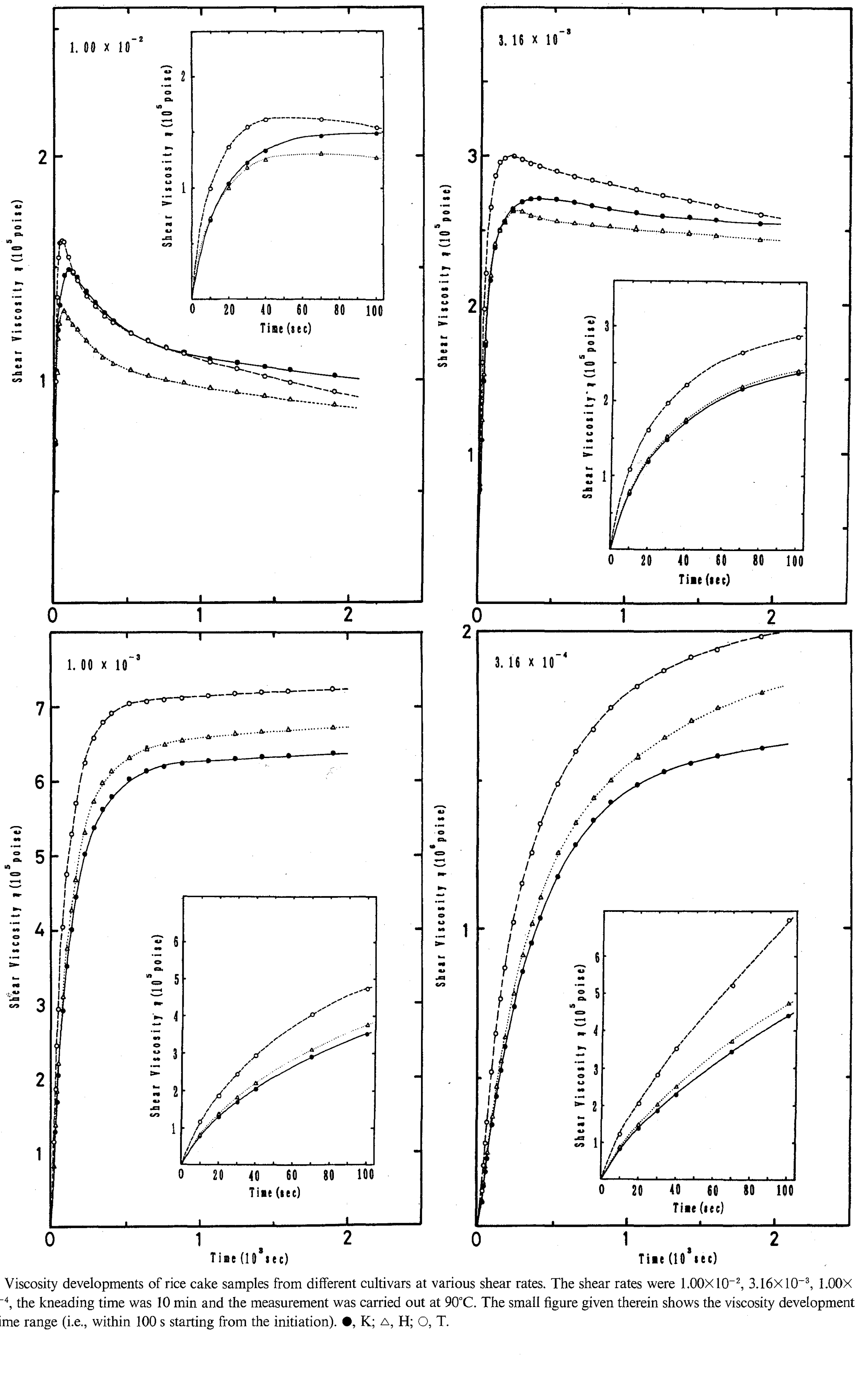

Fig. 2. Viscosity developments of rice cake samples from different cultivars at various shear rates. The shear rates were 1.00×10^{-2}, 3.16×10^{-3}, 1.00×10^{-3} and 3.16×10^{-4}, the kneading time was 10 min and the measurement was carried out at 90°C. The small figure given therein shows the viscosity development curve in a short time range (i.e., within 100 s starting from the initiation). ●, K; △, H; ○, T.

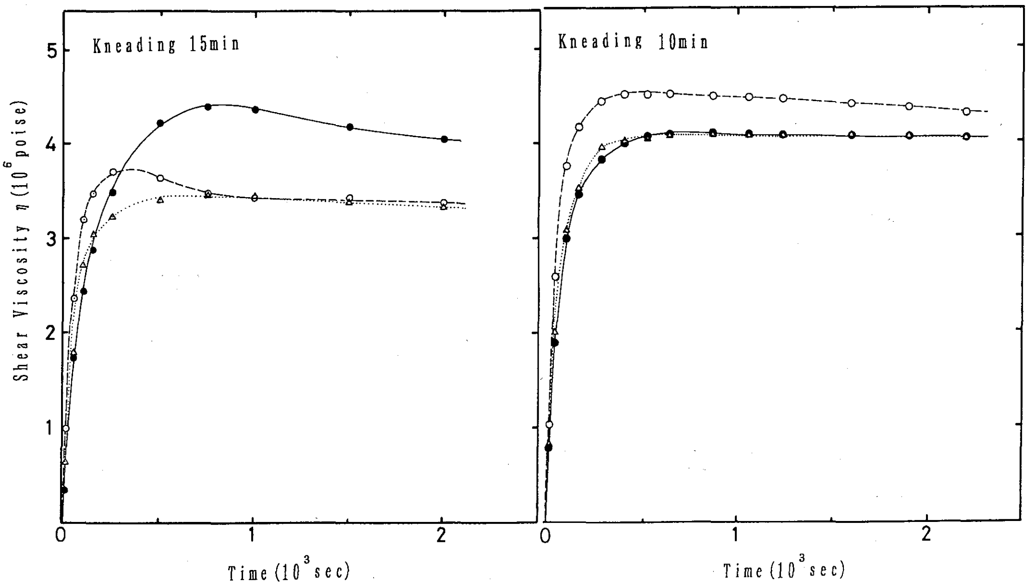

Fig. 3. True viscosity developments of rice cake samples of various varieties. The shear rate was 1.78×10^{-3}, the kneading times were 10 min and 15 min and the measurement was carried out at 90°C. ●, K; △, H; ○, T.

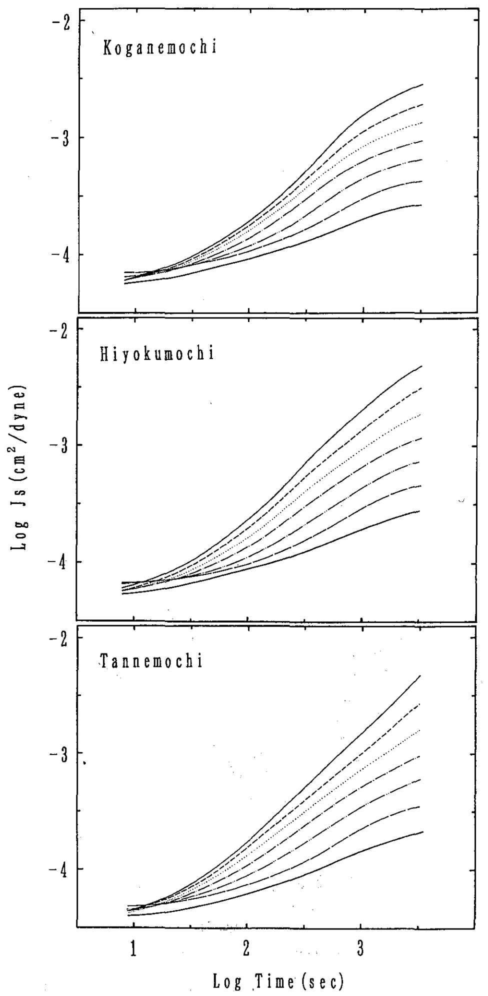

Fig. 4. Apparent steady state compliances of rice cake samples from different cultivars at various shear rates. The kneading time was 10 min, and the measurement was carried out at 90°C. The shear rates were 1.00×10^{-2}, 5.62×10^{-3}, 3.16×10^{-3}, 1.78×10^{-3}, 1.00×10^{-3}, 5.62×10^{-4} and 3.16×10^{-4} in order from the top.

Table 1. Viscoelastic data of rice cake.

Cultivars	Viscosity initial slope (poise/s)	Apparent steady state compliance (cm²/dyne)
Koganemochi	7.62×10^{3}	6.40×10^{-5}
Hiyokumochi	7.99×10^{3}	5.97×10^{-5}
Tannemochi	1.09×10^{4}	4.30×10^{-5}

15 min, the order of the initial slopes is K<H<T, similar to the samples kneaded for 10 min. Regarding cultivars, therefore, the initial slopes show a common order of K<H<T at various kneading times, shear rates and water contents. Because of having a lower (by 0.6 to 0.8%) water content than other samples, the K kneaded for 15 min shows a considerably higher peak viscosity than those of others. Figure 4 shows the log-log plot of the *Js*, of the rice cake samples of each variety kneaded for 10 min at various shear rates. In the case of every variety, a gentle S-curve is observed at low shear rates, and the curve becomes linear as the shear rate is elevated. As the shear rate is elevated, T becomes sharply linear followed by H and K in this order. Table 1 shows the viscoelastic data for 10 s at a shear rate of 3.16×10^{-3}. The *Js* data at the initial stage of the measurement, which correspond to the instantaneous modulus in the common creep compliance measurement, are in the order of K>H>T which is completely contrary to the order in the initial slope.

Discussion

From the viewpoint of the qualities of rice crackers, a preferable rice cake is one having appropriate "firmness" and "extensibility." When evaluated by a sensory test, firmness under stretching is in the order of K>H>T, while the extensibility is in the order of K<H<T. The rice cake samples kneaded for 15 min were all obviously over-kneaded and showed poor firmness. Among these samples, K (kneaded for 15 min) having a low water content had firmness under stretching. The characteristic values of the viscosity and *Js*

curves of rice cake samples and the meanings thereof will now be illustrated.

The initial slope of the viscosity curve, which is the viscosity term in the linear region, seemingly corresponds to the extensibility. The *Js* over the short time range is the elasticity term in the linear region and seemingly corresponds to the firmness. The time required for the appearance of a peak relates to the width of the linear region (i.e., the elasticity term). The peak viscosity seemingly corresponds to the maximum resistance under a large deformation. Next, the relationship between each characteristic value and the structure of the rice cake samples of each variety and sensory evaluation will be analyzed. Compared with other rice cake samples, K showed a small initial slope of $\eta(t, \dot{\gamma}_R)$, required a long time for the appearance of the peak viscosity and showed a large *Js* in a short time range. Based on these results, it may be presumed that K is a highly firm rice cake having a pseudo-network structure of a large breaking resistance relative to the shear rate. T showed a large initial slope of $\eta(t, \dot{\gamma}_R)$, required a short period of time for the appearance of the peak viscosity and showed a small *Js* in a short time range. Thus it may be presumed that T is a highly extensible but less firm rice cake having a pseudo-network structure with a small breaking resistance. On the other hand, H is a rice cake intermediate between K and T. Differences in kneading time and water content are reflected in the initial slope of the viscosity, the peak viscosity and the apparent steady viscosity. However, the peak viscosity and the apparent constant viscosity can be more easily understood sensorially, compared with the initial slope. Thus the linear viscoelasticity function is effective in characterizing rice cake samples of different cultivars. In contrast, the nonlinear viscoelasticity function is effective in rice cake samples of different kneading time or water content. The reason why the characteristics of rice cake samples differing in kneading time or water content can be easily understood in the nonlinear region will now be discussed. It is considered that, with the measurement system employed in this study, in the case of a long time range the process of the breaking of the rice cake structure is monitored. That is to say, the characteristics of the structure consisting of the secondary factors are apt to appear in this process of the breaking of the structure and thus the characteristics of rice cake can be clearly understood in the nonlinear region. When the structure is broken, in contrast, the characteristics of the structure consisting of the primary factors are also affected thereby, which makes it difficult to distinguish cultivars. Namely, it is assumed that the primary factors affect the formation of the microstructure, i.e., smaller than that affected by the secondary factors. Accordingly, it is considered that the viscosity and elasticity terms in the linear region measured in this study seemingly contribute to the analysis of the primary factors and the understanding of the structure. It is further considered that the viscosity and elasticity terms in the nonlinear region contribute to the analysis of the secondary factors and the understanding of the structure. Furthermore, it is suggested that this measurement system is effective in the rheological characterization under large deformation, which is especially important for the manufacturing process.

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