A Viscoelasticity Index for Cheese Meltability Evaluation

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ABSTRACT

A device especially designed for uniaxial creep test was used in this study. Cheddar cheeses of different fat content were used. To study the linear viscoelastic response of the cheese, temperature of 40°C and stress of 1119.5 Pa were chosen. Tests were carried out at cheese ages of 1, 3, 6, and 12 wk after production date. A six-element Kelvin model was used to model the creep data. Instantaneous slope of the creep curve was defined as the viscoelasticity index. The results showed that the viscoelasticity index based on viscoelastic parameters could be used for predicting cheese meltability. From the analysis of variance test, it was evident that that the viscoelasticity index can be used to distinguish the meltability of Cheddar cheeses of different ages and fat levels.
(**Key words:** cheese, meltability)

Abbreviation key: DSC = differential scanning calorimeter, **VI** = viscoelasticity index.

INTRODUCTION

Melting characteristics of cheese, especially varieties such as Mozzarella, Cheddar and process cheeses are the prime factors in determining quality for particular product applications. There are many methods available to study the phenomenon of cheese meltability. The Schreiber (6) and Arnott (2) tests are most commonly used in the industry. These methods are based on measuring the change in the diameter or height of a cylindrical cheese sample after heating it in an oven. Olson and Price (13) modified the Arnott test to measure the melting behavior of pasteurized process cheese. Muthukumarappan et al. (11) proposed some modifications to the Schreiber test. They recommended heating the cheese plug in an oven set at 90°C for 5 min on an aluminum plate and measuring the area of spread of melted cheese as an indicator of cheese meltability. However, all these methods are empirical and poorly controlled. The results from these tests can not be represented by fundamental rheological parameters. Many attempts have been made to measure meltability in specific, objective, and physical terms but none have been entirely successful.

Smith et al. (17) determined the flow curves of Mozzarella cheese at several temperatures by a capillary viscosimeter, but slippage and strong viscoelastic effects played a dominant role, making it impossible to obtain meaningful rheological data. Park et al. (14) studied melting quality of cheese with a differential scanning calorimeter (**DSC**). However, the DSC data were not useful in predicting melting behavior of cheese.

Dynamic rheological testing has many applications in the food industry and has been used with cheese (12, 18, 19). Ustunol et al. (20) correlated the dynamic rheological properties (G′, G” and G*) of Cheddar cheese up to 90°C with the meltability data from the Arnott test. Minimum complex modulus G* was suggested as a possible meltability indicator. Rüegg et al. (16) stated that the loss tangent, tan δ, could be potentially used as a predictor for cheese meltability. However, dynamic testing of cheese is hard to perform at high temperatures as sample slippage may distort the results. A way to overcome the slip and viscoelastic effects while assessing the viscosity of melted cheese is to use squeezing flow rheometry. The squeezing flow technique has been widely used to study cheese meltability (1, 4, 5, 22). The sample and test geometry of the squeeze flow method also make it suitable for performing creep and stress relaxation tests.

Like most solid foods, cheese exhibits viscoelastic behavior under external loading. Creep test is one of the fundamental measurements used to characterize the properties of viscoelastic materials. A creep test is performed by measuring the strain or deformation as a function of time when a constant, instantaneous stress is applied. Typical creep test data can be modeled in terms of various rheological parameters, as well as a series of mechanical elements such as springs and dashpots. Purkayastha et al. (15) fitted the creep curves of potato flesh and Cheddar cheese by a four-parameter model $J(t) = K_0 + K_1t + t/(K_2 + K_3t)$, where J(t) is the compliance, t is the time, and Ks are characteristic constants. The general rheological behavior of the two materials was clearly expressed in terms of the constants (K_0, K_1, and K_3). Ma et al. (8) studied the visco-

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elastic properties of cheeses by using oscillatory dynamic experiments and creep tests. The creep test data was used to identify the differences in viscoelastic properties of cheeses due to fat reduction and addition of lecithin.

The objectives of our study were to use the modified squeezing flow technique for objectively evaluating meltability and viscoelastic behavior of cheese, use a mechanical model to characterize the creep behavior of cheese at high temperature, and determine whether viscoelastic parameters could be used as indicators of cheese meltability.

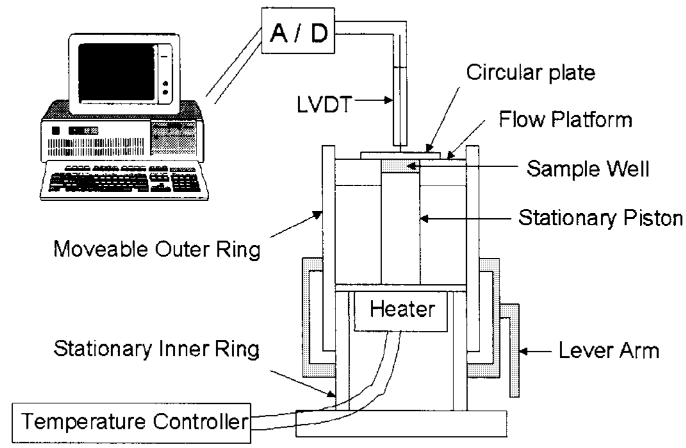

Figure 1. Schematic diagram of the UW Meltmeter (Food and Bioprocess Engineering Laboratory, Department of Biological Systems Engineering, University of Wisconsin, Madison), a modified squeeze-flow apparatus. A/D = Analog-to-digital converter, LVDT = linear variable differential transformer.

MATERIALS AND METHODS

Cheesemaking

Cheddar cheeses of two fat contents (full-fat, 32%, and reduced-fat, 10%) were used. Cheeses were manufactured in the Dairy Plant of the Food Science Department at University of Wisconsin-Madison. Manufactured cheeses were vacuum sealed and stored at 7°C until sample preparation. Moisture content (wet basis) of cheeses containing 32 (full-fat) and 10% (reduced-fat) fat were 37.9 and 50.2%, respectively. Protein contents were 25.2 and 29.1%, respectively. Tests were carried out at cheese ages of 1, 3, 6, and 12 wk after production date.

Sample Preparation

Cheese blocks were cut into thin slices (~7 mm) with a hand-operated slicer (Model No. 1042, Rival Co., Kansas City, MO). Then, cylindrical specimens of 30 mm diameter were cut out with a cork borer. The cheese samples, 7 mm in thickness and 30 mm in diameter, were put into plastic bags and placed in a refrigerator (4 to 6°C) until testing.

Meltability Test

A schematic drawing of the apparatus, UW Meltmeter (22), developed for measuring melting behavior of cheese is shown in Figure 1. It consists of an aluminum body with a doughnut shape heater inside, and temperature controller unit (CN 4400, Omega Engineering Inc., Stanford, CT) to control the heater. The heater is in contact with the stationary piston. The outer ring can be moved up and down around the stationary piston using the lever arm. A circular plate is attached to an LVDT (linear variable differential transformer, Schaevitz Engineering, Pennsauken, NJ) to monitor the flow of cheese upon melting. A personal computer with a data acquisition board (DAS 16G High Speed Analog I/O Board, Metrabyte Corp., Taunton, MA) and software (Easyest LX software, Asyst Technologies Inc., Rochester, NY) were used for data collection and analysis.

The temperature of the meltmeter was set before the specimen was placed. Both meltmeter top surface and circular plate were lubricated with mineral oil to ensure lubricated squeezing flow. The cheese sample was heated while covered with a circular plate to prevent moisture loss. The temperature of the cheese that was in the sample well was monitored by a digital thermocouple thermometer inserted into the sample. The samples took about 10 min to reach the test temperature of 60°C. Once the sample reached the test temperature, the data acquisition system was started, then the lever arm was raised to lower the outer ring and allow the sample to flow under the constant force or 0.67 N (the weight of the circular plate and the LVDT rod). The height of specimen was recorded as a function of time.

Meltability was calculated as the difference between the initial height and the height of melted cheese at one second. Meltability calculated according to this method correlated well with the biaxial elongational viscosity measurements described by Wang et al. (22).

Creep Test

For the creep test, the above test procedures were used with one modification. The circular disk connected to the LVDT was changed to have the same diameter as that of the cheese sample (30 mm). This was done to apply a constant stress as requires for a creep test. However, to stay within the linear viscoelastic range, the test temperature of 40°C and a constant stress of

1119.5 Pa were selected. The generalized Kelvin model was considered for representing the creep data with the S-PLUS software (Version 3.2, MathSoft Inc., Seattle, WA). The mathematical representation of the time dependent compliance of the generalized Kelvin model is (9):

$$J(t) = J_0 + \sum_{i=1}^{N} J_i * \left(1 - e^{\left(\frac{-t}{\tau_i}\right)}\right) + \frac{t}{\eta_V} \quad [1]$$

$$\tau_i = \frac{\eta_i}{E_i} \quad [2]$$

$$D(t) = \frac{\varepsilon(t)}{\sigma_0} = \left(\frac{1}{3}\right) * J(t) \quad [3]$$

where J(t) is the total shear creep compliance at time t, $J_0 = (1/E_0)$ is the instantaneous rigidity compliance, $J_i = (1/E_i)$ are the retarded compliances, τ_i (η_i/E_i) are the retardation times, η_i are the retarded viscosities, E_i are the elastic moduli of springs, and η_V is the Newtonian viscosity. The tensile creep compliance function D(t) is equal to one-third of J(t).

Statistical Analysis

Meltability and creep measurements were replicated two times for each cheese type at all ages. The general linear models (GLM) of SAS (Version 6, Cary, NC) was used for statistical analysis of the entire data set. Least significant difference (LSD) were used with significance established at $P < 0.05$ level.

RESULTS AND DISCUSSION

Since the biological materials typically have more than one retardation time, the behavior of such materials can not be represented by a single Kelvin model or by a four-element Burger model (9). A six-element Kelvin model we used (Figure 2) was found to provide the best fit in designing the experimental creep data according to Equation [1]. Accordingly, the following equation represents the model for the cheese flow data:

$$J(t) = J_0 + J_1 \times \left(1 - e^{\left(\frac{-t}{\tau_1}\right)}\right) + J_2 \times \left(1 - e^{\left(\frac{-t}{\tau_2}\right)}\right) + \frac{t}{\eta_V} \quad [4]$$

where J(t) is the total creep compliance at time t, J_0 is the instantaneous rigidity compliance, J_1 and J_2 are the retarded compliances, τ_1 and τ_2 are the retardation times, and η_V is the Newtonian viscosity. In Figure 3, the fitted values overlaid with the observed data indicates an excellent fit of the model (3).

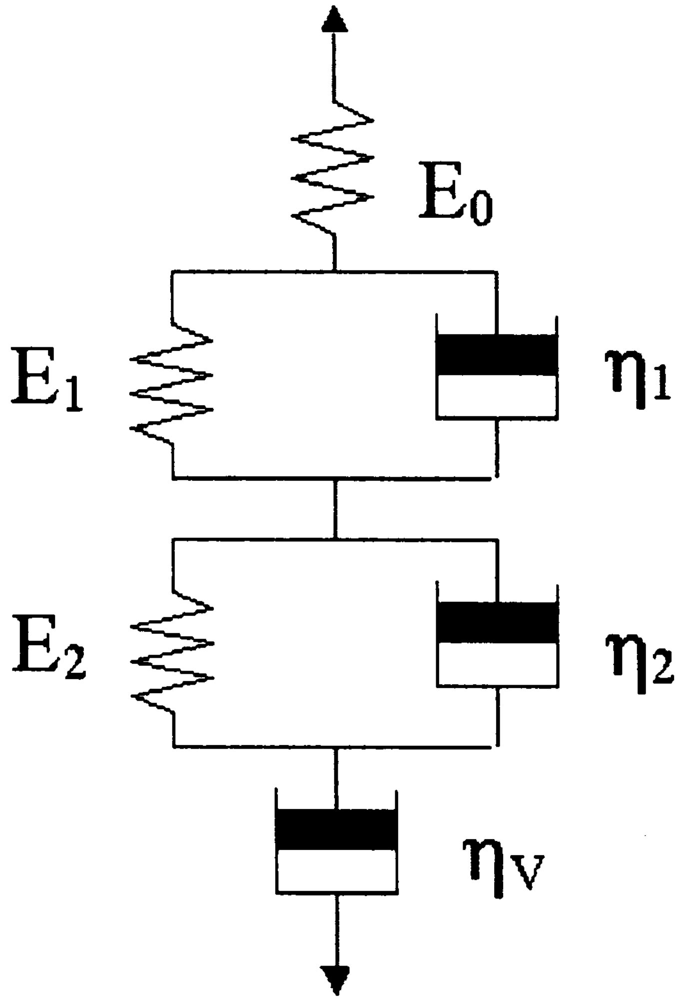

Figure 2. Six-element Kelvin model used for describing creep behavior of Cheddar cheeses. Corresponds to Equation [1] with i = 2. E_0, E_1, and E_2 = elastic modulus of spring, η_1 and η_2 = retarded viscosity, η_V = Newtonian viscosity.

The values of the viscoelastic parameters calculated for both full- and reduced-fat cheeses are given in Table 1. The higher instantaneous compliance reflected a high degree of nonretarded Hookean-type deformation, indicating that the polypeptide strands in the network were relatively free to rearrange between crosslinks (8). The reduced-fat cheese had a lower instantaneous compliance (J_0) than the full-fat cheese. This suggests that a reduction in fat resulted in an increase in the protein content, thus increased the elastic (or solid-like) character of the cheese. The higher Newtonian viscosity (η_V) of reduced-fat cheese suggested a greater resistance to flow at longer time. Thus, the reduced-fat cheese could be considered to

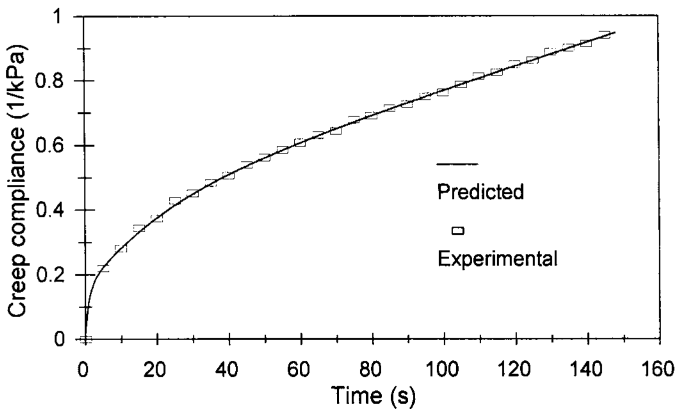

Figure 3. Prediction of creep compliance of Cheddar cheese by a six-element Kelvin model.

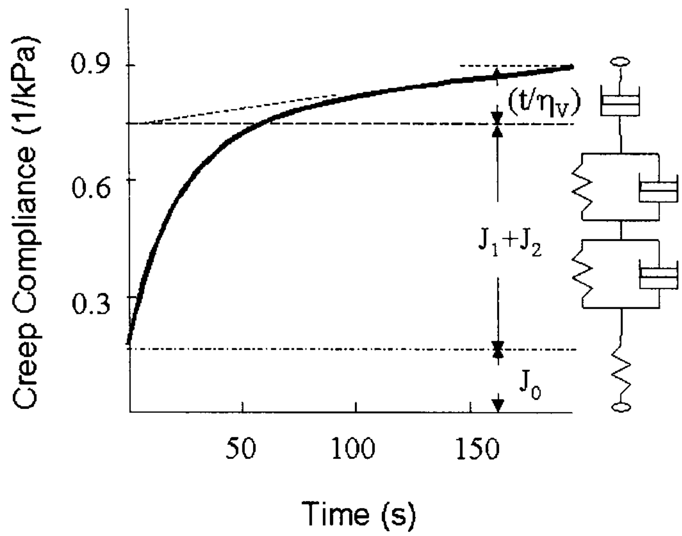

Figure 4. Typical creep response showing correspondence to mechanical elements in the Kelvin model. Corresponds to Equation [4]. J_0 = Instantaneous rigidity compliance, J_1 and J_2 = retarded compliance, η_V = Newtonian viscosity, t = time.

retain more of its solid-like viscoelastic structure than the full-fat cheese. Our results were not similar to those obtained by Ma et al. (8), who reported that the full-fat Cheddar cheeses produced stronger structure than the reduced-fat cheeses at the sample temperature of 20°C.

A typical creep curve and corresponding mechanical model (six-element Kelvin model) are shown in Figure 4. The curve has three segments corresponding to the Hookean, Voigt, and viscous elements. The retarded compliances (J_1 and J_2) represented the principal components of the viscoelastic behavior of Cheddar cheeses. This reflected a high degree of retarded Voigt-type deformation in Cheddar cheese under external loading.

One of our objectives of this study was to explore the effective mathematical expressions to describe cheese meltability. We have thought that combining those principal viscoelastic parameters could provide an objective and physical indicator for Cheddar cheese meltability evaluation. The instantaneous slope of the creep curve was calculated by taking the first derivative of Equation [4] at time zero. This instantaneous slope was defined as the viscoelasticity index (**VI**) which was computed as follows:

$$\mathrm{VI} = \left.\frac{dJ}{dt}\right|_{t=0} = \frac{J_1}{\tau_1} + \frac{J_2}{\alpha_2} + \frac{1}{\eta_V} \qquad [5]$$

In terms of Equation [5], the VI accounts for the constants J_1, J_2, τ_1, τ_2 and η_v.

Both meltability and creep test provided consistent and reproducible results when sample temperature and dimensions were controlled. Regression analyses was conducted on the relationship between the VI and meltability. The VI was related to the meltability of the Cheddar cheese manufactured with varying fat levels during ripening (Figure 5). A strong relationship (R^2 = 0.81) was obtained between VI and meltability of Cheddar cheese. There are some data points, corresponding to both reduced-fat and full-fat cheeses, that seem to skew the linear fit. Additional tests should be performed to more fully investigate the exact nature of the relationship. Nonetheless, the general trend is that the higher the VI, the better the meltability.

Reduction of fat and ripening in Cheddar cheese affected meltability as indicated by VI in Figure 6.

Table 1. Viscoelastic parameters for six-element Kelvin model in creep test for different fat levels in Cheddar cheeses.

Six-element Kelvin model parameters	Cheddar cheese Full fat	Cheddar cheese Reduced fat
J_0 (1/kPa)[1]	0.14^x	0.11^y
J_1 (1/kPa)[2]	0.27^x	0.19^x
J_2 (1/kPa)[2]	0.55^x	0.46^x
τ_1 (s)[3]	3.35^x	3.25^x
τ_2 (s)[3]	28.046^x	23.89^y
η_V (kPa × s)[4]	137.9^x	149.6^y

x,y Within each row, means without a common superscript differ (P < 0.05).

[1]Instantaneous compliance.

[2]Retarded compliance.

[3]Retardation time.

[4]Newtonian viscosity.

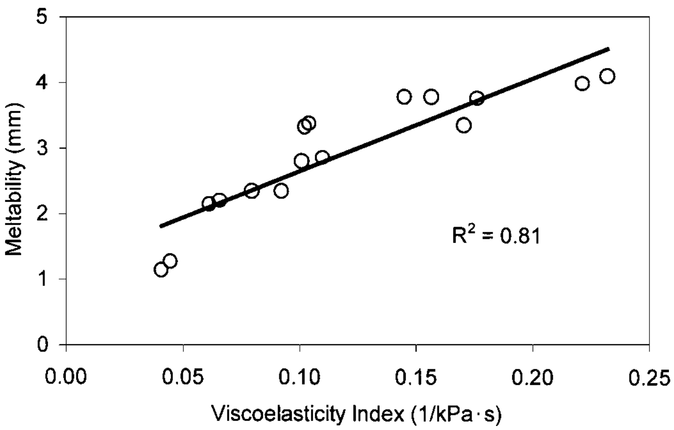

Figure 5. Relationship between the viscoelasticity index at 40°C and meltability determined by the UW Meltmeter (Food and Bioprocess Engineering Laboratory, Department of Biological Systems Engineering, University of Wisconsin, Madison) test at 60°C of Cheddar cheeses.

All cheeses showed an increase in VI with ripening. Proteolysis during ripening contributes to softening of cheese (21) and thus increases in VI for cheese containing 32 and 10% fat. Proteolysis was higher in reduced-fat cheeses than full-fat cheeses that were ripened for 3 mo. Muthukumarappan et al. (10) reported that meltability of reduced-fat cheese increased to a greater extent during ripening as compared to full-fat cheese. According to analysis of variance test, VI can be the significant parameter in distinguishing among the age and the fat levels of Cheddar cheese.

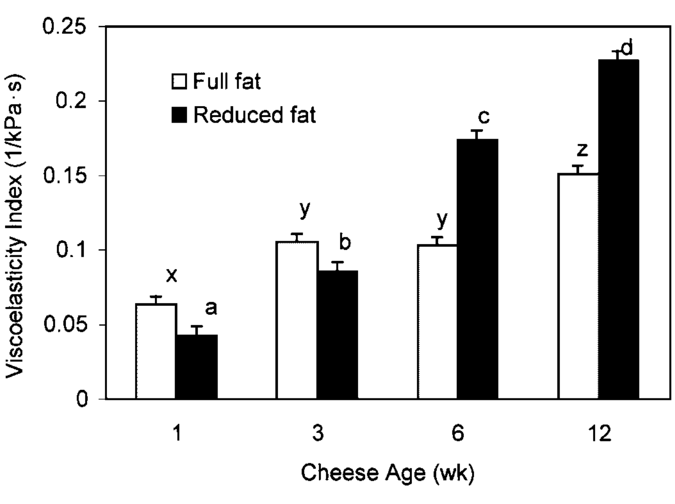

Figure 6. Effect of ripening on the viscoelasticity index of full fat and reduced fat Cheddar cheeses. The standard deviation is indicated on top of the bars. [a,b,c,d,x,y,z]Means within each cheese type without a common superscript differ ($P < 0.05$).

CONCLUSIONS

The six-element Kelvin model was used to describe the creep behavior of cheese at 40°C. Viscoelastic parameters were used to explain structural characteristics and changes in the cheese. The instantaneous slope of the creep curve was defined as the VI to be used as an objective measure of cheese meltability. The VI is a good predictor of Cheddar cheese meltability and can be used to characterize the effect of some experimental and compositional factors to distinguish the meltability of different cheeses.

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