The effect of milk fat substitution on the rheological properties of Edam-type cheese

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Abstract

In cheese-like products, milk components (in particular fat) are partially or completely replaced with non-dairy substitutes. An attempt was made in this study to determine whether Edam-type cheese can be distinguished from its substitute, where milk fat was replaced with palm oil, based on rheological properties. The rheological properties of Edam cheese and its substitute were analyzed during a 16-week ripening period, based on the results of a stress-relaxation test. The values of the rheological parameters were estimated with the use of the generalized Maxwell model and a non-linear model proposed by the authors, which accounted for the plastic deformation of the analyzed samples. The study revealed that both methods were equally effective in describing the stress relaxation process; therefore, they can be regarded as equivalent. Excluding the initial stage of ripening (which is not important from the consumers' point of view), the replacement of milk fat with palm oil did not influence the rheological properties of Edam-type cheese and the cheese-like product. In subsequent stages of ripening, no significant differences were found in the rheological properties of both products, which could only be used to evaluate their ripeness.

Keywords Edam-type cheese · Cheese substitute · Cheese ripening · Rheological properties

Abbreviations

E	Apparent elasticity (Pa)
n	Flow index
t	Time (s)
T_{rel}	Relaxation time (s)
ε	Relative strain
η	Apparent viscosity (Pa s)
κ	Consistency index (Pa s ⁿ)
σ	External load (Pa)
σ_E	Elastic stress (Pa)
σ_N	Viscous stress (Pa)
σ_V	Plastic deformation (Pa)

Introduction

The growing competition on the market of processed foods, including dairy products, has increased the supply of foods where selected natural ingredients are replaced with substitutes. Such products are introduced to meet consumer demand for innovative foods with altered dietary properties [1] and to decrease production costs [2–4]. The costs associated with the production of ripened cheese are most frequently reduced by substituting milk fat with vegetable oil and shortening the ripening time [5].

Various sensory and instrumental methods are deployed to identify the properties of food products [6–15]. According to the literature, textural and rheological properties, which are often correlated with the chemical composition of foods, support rapid and low-cost identification of products and evaluations of food quality in industrial applications [16, 17]. Adulteration in dairy products (e.g., with vegetable oil) can be detected with the use of various instrumental methods, including chromatographic, immunological, physical, and mechanical techniques [5]. Spectroscopic techniques have also been applied to determine cheese quality and authenticity [18] and to discriminate Emmental cheeses belonging to different brand products [19]. The textural

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properties of cheese where milk fat was substituted in whole or in part with vegetable oil were investigated by Yu and Hammond [20], Lobato-Calleros et al. [21], Cunha et al. [22], Arslan et al. [23], Abd El-Salam [24], Al-Ismail et al. [25], Felfoul et al. [26], Hjalmarsson [27], Badem and Uçar [28], Yagoub et al. [29] and Abd El-Wahed and Hassanien [30]. The rheological properties of cheese were discussed by Lee et al. [31], Budiman et al. [32], Liu et al. [33], Sadowska et al. [34], Oliveira et al. [35], Sołowiej [36], Cunha et al. [37], Farbod et al. [38], Hanáková et al. [39], Karaman et al. [40], Henno et al. [41], Rafiq and Ghosh [42], and Giri et al. [43]. Changes in the viscoelastic properties of cheese were also evaluated during ripening. In semi-hard, ripened rennet-coagulated cheese, such changes were examined in Gouda [44, 45], Cheddar [46, 47], Monterey Jack [48] and Edam cheese [49]. The rheological properties of low-fat (17% fat) and high-fat (27% fat) Edam cheese were analyzed.

The rheological properties of cheese are determined in compression tests [8, 10, 13, 27, 33, 38, 42, 44, 46], stress relaxation tests [13, 33, 40, 44, 50–52] and creep tests [1, 6, 7]. Rheological parameters are usually estimated based on the generalized Maxwell model [13, 32, 34, 40, 50–53] and the Kelvin-Voigt model [54–57], but the Herschel-Bulkley model [1, 58–60], Burgers model [40, 61, 62] and Peleg's empirical model [40, 52, 63, 64] are also applied. According to the above models, the deformed sample returns to its original state after a given period of time, once the stress/load is removed. However, cheese (and other biological materials) exhibit permanent plastic deformation. Therefore, the model that accounts for this type of deformation was used in the present study.

Although cheese-like products have been relatively well researched, still little is known about potential differences in the rheological properties and ripening of Dutch-type cheeses and their substitutes where milk was completely replaced with palm oil. To fill this knowledge gap, the present study was designed to determine whether cheese ripeness and the type of fat applied in the production process can be determined based solely on the rheological properties of Edam-type cheese and its substitute.

Materials and methods

Materials

The study was performed on commercially available blocks of full-fat Edam-type cheese (Edam) and a cheese substitute (Substitute) where milk fat was substituted in its entirety with palm oil. Both products were purchased from the same

dairy plant in north-eastern Poland. Both Edam-type cheese and the cheese substitute were produced in the same season (winter), on the same day, from the same milk batch, and with the use of the same equipment and technology.

After production and ripening, cheese and cheese substitute samples were transported to a laboratory and stored in a refrigerating unit at the same temperature (8 °C). Before the rheological analysis, the cheese was tempered at 20 °C for 20 min. During this time and during the test, the samples were stored in ziplock kitchen plastic bags. Two cheese blocks were analyzed at each stage of the analysis.

Chemical analysis

Water content was determined by dehydration at 105 °C for 4 h in the SML 32/250 drying oven (Zalmed, Poland) according to AOAC [65] method No 926.08. Total fat content (TF) was determined according to AOAC method No 933.30. Fat was extracted from dried samples by the Soxhlet method, with petroleum ether as the extraction solvent. The time of fat extraction was 8 h. Total nitrogen (TN) was determined according to the micro-Kjeldahl method (AOAC No. 920.105). TCA-soluble nitrogen (TCASN) was determined according to the method proposed by Tavarria et al. [66] and was expressed as a percentage of total nitrogen. pH values were determined in a 1:1 mixture of grated cheese and deionized water, using the CX-501 multifunction meter (Elmetron, Poland) with an ERH-11S electrode (Hydromet, Poland). Three samples of cheese and its substitute were analyzed in each stage of ripening.

Rheological analysis

Cylindrical samples with a diameter of 10.0 ± 0.5 mm were cut from cheese blocks with a cork-borer and divided into segments with a height of 5.0 ± 0.5 mm. Cheese samples were placed in ziplock kitchen plastic bags to prevent moisture loss, and they were kept in a thermostatic chamber (18 °C) for around 20 min before the analysis of temperature distribution within the sample. The rheological properties of the samples were determined in a relaxation test in the Instron 1011 testing machine (Juston, UK) equipped with a 50 N load cell with a 25 mm cylinder probe. Each sample was compressed at a rate of 50 mm/min to 25% of its original height. Each test lasted 420 s. Time-dependent changes in stress were recorded twice a second in a computer application. Stress relaxation tests were conducted on the day of production and after 2, 4, 7, 10, 13, and 16 weeks of ripening. Each test was conducted in six replicates.

Rheological model

The influence of fat substitution and ripening time on the rheological properties of the examined materials was determined with the use of two methods. The first method involved the generalized Maxwell model which is based on the superposition of two distinctive contributions describing the distribution of relaxation times (*Method I*). The second method was developed based on the laws of physics and direct analysis of test results, which supported the formulation of a rheological model (*Method II*).

Method I

A semi-empirical Maxwell model comprising a Hookean element and three Maxwell (Fig. 1a) elements connected in parallel was developed based on the results of previous experiments [34, 51] to describe the elastic and viscous properties of cheese. Assuming that only the spring is initially deformed in three Maxwell bodies, the solution for the generalized Maxwell model was described by Eq. (1):

$$E(t) = \frac{\sigma(t)}{\varepsilon_0} = \left[E_0 + E_1 \cdot \exp\left(\frac{-E_1 \cdot t}{\eta_1}\right) + E_2 \cdot \exp\left(\frac{-E_2 \cdot t}{\eta_2}\right) + E_3 \cdot \exp\left(\frac{-E_3 \cdot t}{\eta_3}\right) \right] \quad (1)$$

It was assumed that apparent elasticity is the sum of all of modeled elastic elements and that apparent viscosity is the sum of all of modeled viscous elements.

Method II

The analyzed phenomena were described with a non-linear rheological model [67] combining the properties of an ideal Hookean elastic solid, ideal Newtonian viscous fluid, and ideal Saint–Venant plastic solid (Fig. 1b). The stresses appearing in the material were treated as a vector sum of the

stresses resulting from elastic stress σ_H , viscous stress σ_N and plastic deformation σ_V :

$$\sigma(t) = \sigma_H + \sigma_N + \sigma_V \quad (2)$$

The analyzed phenomena occur at constant values of relative deformation $\varepsilon(t)$, which implies the absence of changes in stress $\sigma_{(H+V)}$ resulting from the material's elasticity and plasticity:

$$\varepsilon(t) = \text{const} \rightarrow \sigma_H + \sigma_V = \sigma_{(H+V)} = \text{const} \quad (3)$$

Therefore, stress $\sigma(t)$ is caused by material flow. No significant changes in the material's density, composition or structure are observed during flow; therefore, it can be assumed that the value of the dynamic viscosity index is also constant. The above assumption implies that the material's unknown flow rate changes in a non-linear fashion. This phenomenon is generally described with Peleg's empirical model [68], but a modified version of that model produces much better results in biological materials [69]:

$$\sigma(t) = \sigma_0 \left(1 - \frac{t^n}{k_1 + k_2 t^n} \right), \quad (4)$$

where: $\sigma_0 = \sigma(t=0) = \max[\sigma(t)]$, n – flow index, k_1 – initial rate of stress relaxation, k_2 – the hypothetical asymptotic value of normalized stress at the end of the stress relaxation phase.

Equation (4) can be used to determine total stress resulting from the viscoplastic properties of the examined material:

$$\sigma_{(H+V)}(t) = \lim_{t \rightarrow \infty} \sigma(t) = \sigma_0 \cdot \left(1 - \frac{1}{k_2} \right), \quad (5)$$

and when Eqs. (4) and (5) are substituted into Eq. (2), the result is:

$$\sigma_N(t) = \sigma_0 \cdot \left(\frac{1}{k_2} - \frac{t^n}{k_1 + k_2 t^n} \right) \quad (6)$$

Fig. 1 Rheological model: (a) – Method I, (b) – Method II

Parameters k_1 and k_2 are estimated, and stress relaxation time:

$$T_{rel} = \left(\frac{(e-1)k_1}{k_2} \right)^{\frac{1}{n}} \cong \left(\frac{1.7183k_1}{k_2} \right)^{\frac{1}{n}} \quad (7)$$

and the consistency index:

$$\kappa = \frac{k_1 \sigma_0}{k_2}, \quad (8)$$

which is equivalent to the power-law index in the Ostwald de Waele model, are calculated.

Results and discussion

Chemical properties

The chemical composition of the analyzed products is presented in Table 1. Water, fat, and total nitrogen content remained fairly constant between the beginning and the end of the period considered. Chemical compounds are transformed during ripening (proteolysis and lipolysis), which induces clear changes in structure, texture, and sensory attributes. Proteolysis leads to a steady increase in peptide concentration, an important indicator of cheese ripeness [70]. The observed increase in peptide concentration (expressed by TCA-soluble nitrogen) in all samples was indicative of normal ripening, but the ripening of the cheese-like product (Substitute) proceeded at a slower rate. After ripening, the pH of both products was somewhat higher, which suggests that the analyzed samples had adequately ripened [71–73].

Rheological properties

The unknown values of the parameters in Eqs. (1) and (4) were estimated by the least-squares method with the use of

the Levenberg–Marquardt algorithm in the Statistica v. 12 program (StatSoft, USA). In each case, calculations were performed at a significance level of $p=0.05$ and a sample size of $s=5046$. A preliminary analysis of the parameters in Eq. (4) revealed that the flow index remained constant at $n \cong 0.47 \pm 0.01$ in all cases; therefore, only the remaining parameters in Eq. (4) were estimated in successive steps. The adopted research methods were used to determine the following rheological properties: apparent elasticity E , apparent viscosity η [Eq. (1)], stress relaxation time T_{rel} [Eq. (7)] and consistency index κ [Eq. (8)].

The uncertainty of measurement of rheological parameters was determined by calculating the total derivative, i.e., by summing up the products of partial derivatives [Eq. (1), (7) and (8)], and the standard error of the estimate of the parameters in Eqs. (1) and (4). The results of the simulations conducted with both methods were compared with the results of the measurements involving the root mean square (RMS) calculated with the following formula:

$$RMS = \sqrt{\frac{\sum_{i=1}^n (Exp_i - Mod_i)^2}{\sum_{i=1}^n Exp_i^2}} \quad (9)$$

The results are presented in Table 2 and Fig. 2. Both methods were equally effective in describing the stress relaxation process; therefore, they can be regarded as equivalent. The above was confirmed by partial simulations as well as RMS values relating to the entire ripening process.

The rheological properties of both products varied significantly until the fourth week of ripening (excluding the relaxation time). The fourth week of ripening was a characteristic period during which the values of all estimated parameters in both models were significantly higher in the samples where milk fat was replaced with palm oil. In subsequent stages of ripening, no significant differences were found in the rheological properties of both products. A similar trend was observed in Cheddar cheese [47] and Edam-type cheese [41], where more pronounced changes in

Table 1 Proximate chemical composition (average value $\pm$ standard deviation) and changes in ripening indices

Parameter		Edam-type cheese		Substitute	
		Week 0	Week 16	Week 0	Week 16
Water	[%]	40.9 $\pm$ 0.70	41.7 $\pm$ 0.81	41.2 $\pm$ 0.77	39.8 $\pm$ 0.91
Total fat	[%DM]	43.1 $\pm$ 1.49	44.8 $\pm$ 0.72	47.3 $\pm$ 3.27	47.8 $\pm$ 1.71
Total nitrogen	[%DM]	6.79 $\pm$ 0.29	7.07 $\pm$ 0.31	7.18 $\pm$ 0.31	6.75 $\pm$ 0.28
TCA-soluble nitrogen	[%Nt]	2.45 $\pm$ 0.21	9.45 $\pm$ 0.24	2.09 $\pm$ 0.08	8.20 $\pm$ 0.18
pH ^a	[–]	5.45 $\pm$ 0.03	5.61 $\pm$ 0.01	5.36 $\pm$ 0.02	5.75 $\pm$ 0.02

DM dry matter

^arange of values between the beginning and end of ripening

Table 2 Rheological properties (value $\pm$ uncertainty of measurement)

Type of cheese	Model	RMS	Rheological properties	Cheese ripening time							
				Week 0	Week 2	Week 4	Week 7	Week 10	Week 13	Week 16	
Edam-type Cheese	Method I	0.189	E [MPa]	0.355 ± 0.013	0.481 ± 0.012	0.331 ± 0.019	0.350 ± 0.042	0.331 ± 0.032	0.350 ± 0.032	0.245 ± 0.027	
			η [MPa s]	23.53 ± 1.26	28.55 ± 1.24	17.78 ± 1.69	21.87 ± 5.08	20.39 ± 3.50	21.17 ± 3.89	15.16 ± 2.48	
	Method II	0.189	T_{rel} [s]	111.3 ± 3.9	86.6 ± 2.7	71.3 ± 5.3	98.8 ± 15.6	98.4 ± 11.1	76.9 ± 9.4	102.2 ± 12.0	
			κ [MPa s ^{0.47}]	0.50 ± 0.01	0.60 ± 0.01	0.38 ± 0.02	0.46 ± 0.05	0.44 ± 0.03	0.41 ± 0.03	0.33 ± 0.03	
Substitute	Method I	0.153	E [MPa]	0.450 ± 0.017	0.390 ± 0.022	0.509 ± 0.017	0.401 ± 0.036	0.428 ± 0.029	0.322 ± 0.014	0.254 ± 0.032	
			η [MPa s]	29.67 ± 1.73	22.30 ± 2.16	29.85 ± 1.72	23.58 ± 3.87	25.91 ± 3.28	18.50 ± 1.38	14.60 ± 3.41	
	Method II	0.153	T_{rel} [s]	107.6 ± 3.8	78.8 ± 5.6	96.3 ± 4.2	93.4 ± 10.7	95.7 ± 7.7	81.6 ± 4.4	100.6 ± 13.7	
			κ [MPa s ^{0.47}]	0.63 ± 0.02	0.470 ± 0.02	0.66 ± 0.02	0.51 ± 0.04	0.56 ± 0.03	0.39 ± 0.01	0.33 ± 0.04	

RMS Root Mean Square [Eq. (9)]

the viscoelastic properties were also noted during the first 4 weeks, and the analyzed parameters stabilized in successive weeks of ripening.

From the consumer's perspective, the differences in rheological properties observed at the beginning of the ripening process are not important since the product is not yet ready for consumption. Since both analyzed products were made with the use of the same production technology, they were analyzed together to determine whether a correlation exists between their rheological properties and ripening time. An analysis of both products revealed a gradual decrease in the values of elasticity E (Fig. 3a), viscosity η (Fig. 3b), the consistency index η (Fig. 3c), and stress resulting from plastic deformation σ_v (Fig. 3d) in successive weeks of ripening. However, in the overall stress balance (Eq. (5)), the ratio of elastic stress to the stress resulting from the plastic deformation of the analyzed material remained constant throughout the entire ripening period, at approximately 67%.

Conclusions

The values of RMS indicate that both research methods were equally effective in describing the stress relaxation process, and therefore they can be regarded as equivalent. However, the proposed non-linear model (method II) accounts also for the permanent plastic deformation of Edam-type cheese and its substitute, and the estimated value of the flow index is close to that determined for highly-processed meat products [67], thus indicating that the viscous properties of both analyzed products may correspond to the behavior of a non-Newtonian shear thinning fluid [74, 75].

The rheological properties of Edam-type cheese and its substitute differed significantly only in the initial stage of ripening (until week 4). The fourth week of ripening was a characteristic period during which the values of all estimated parameters in both models were considerably higher in the samples where milk fat was replaced with palm oil. However, in successive weeks of ripening, the replacement of milk fat with vegetable oil had no significant influence on the rheological properties of cheese and the cheese-like product, which were indistinguishable in this respect. After the above period, rheological properties can only be used to evaluate ripeness because in subsequent stages of ripening, a gradual decrease is observed in the values of apparent elasticity and apparent viscosity (method I), and the consistency index and stress resulting from plastic deformation (method II).

Fig. 2 Rheological properties: (a) – apparent elasticity, (b) – apparent viscosity, (c) – relaxation time, (d) – consistency index

Fig. 3 Rheological properties (trend lines): (a) – apparent elasticity, (b) – apparent viscosity, (c) – consistency index, (d) – plastic deformation

Compliance with ethical standards

Conflict of interest All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Compliance with ethics requirements This article does not contain any studies with human or animal subjects.

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