Rheological and textural properties of full-fat and low-fat cheese analogues

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Abstract: The textural properties of the cheese analogues with different fat contents were measured by using TA.XT2i Texture Analyser and the steady state and dynamic rheological parameters of the same samples were measured by using AR1000 rheometer to compare the rheological and textural properties of full-fat and low-fat cheese analogues. As the fat content of cheese analogues decreased, all the Texture Profile Analysis(TPA) parameters except springiness and cohesiveness decreased. The steady state flow analysis showed that all cheese samples exhibited non-Newtonian, pseudo-plastic behavior at all temperatures including 40, 45, 50, 55 and 60℃. Shear stress versus shear rate data was successfully fitted to the Power-law model. The dynamic analysis showed that the full-fat products manifested a more solid-like form. All the samples' rheological parameters were dependent on the oscillatory frequency. The results showed that full-fat and low-fat sampls were significantly different through texture and rheology analysis. The study of rheological and textural properties was evaluable for technology and quality control of cheese products.

Key words: cheese analogue; pectin gel; low fat; rheology; texture; model fit

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0 Introduction

Cheese analogues or imitation cheese contain edible oil or fat emulsified in an aqueous protein phase. Cheese analogues are usually defined as products made by blending individual constituents, including the non-dairy fats or proteins, to produce a cheese-like product which can meet specific requirements. They are being used increasingly due to their cost-effectiveness, attributed to the simplicity in their manufacture and the replacement of selected milk ingredients by cheaper vegetable products[1]. Over the past decade, the consumption of low-fat food products has become more than just a trend. In view of the general consensus that the amount and type of fat consumed is of importance to the aetiology of several chronic diseases (e.g. obesity, cardiovascular diseases, cancer), it is not surprising that consumers more readily adhere to nutritional guidelines concerning fat consumption. Largely influenced by health-related concerns, there has been a pressure on the food industry to reduce the amount of fat, sugar, cholesterol, salt and certain additives in the diet. Food manufacturers have responded to consumer demand and there has been a rapid market growth of products with a healthy image. Low-fat dairy products, such as milk, yoghurt, ice cream and some cheese products have been available for several years. In cheese production, the removal or reduction of fat adversely affects both the flavor and texture[2]. Therefore, several strategies have been proposed to improve the flavor and texture of low-fat cheeses. These strategies can be collected in three titles[3,4]: They are making-process modifications; starter culture selection and use of adjunct cultures; and use of fat replacers. Fat replacers are ingredients that are intended to replace natural fats with the main objective of obtaining a reduction in the caloric value. They are categorized as fat substitutes which are fat-based and

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as fat mimetics which are protein- and carbohydrate-based. Fat mimetics have often been recommended to be used in cheese products consisting of mainly microparticulated protein-and carbohydrate-based materials[5]. As the introduction of Siebel and Sylvia[6], pectin is a purified carbohydrate product obtained by aqueous extraction under mildly acidic conditions of appropriate edible plant material —— usually citrus fruits and apples. Traditionally, pectin is used as a gelling agent for jams and jellies. The major parts of all pectin production are consumed by the fruit processing industry. Other traditional applications are confectionery products, dairy products, fruit preparations, bakery fillings. New applications within the food area are constantly developing, and fat replacement is one of the latest newcomers. SLENDID®, a registered trademark of Hercules Incorporated, was introduced in 1991. The SLENDID® concept covers a range of specialty pectins tailor-made for fat replacement. The production of SLENDID® takes place on the premises of Copenhagen Pectin A/S, a Division of Hercules Incorporated, in Denmark. In 1994, Hercules Incorporated was granted a patent covering a fat simulating composition consisting of heat-stable carbohydrate gel particles, a food product normally containing fat/oil that has been improved by substituting all or a portion of the fat/oil by gel particles, and the process by which the gel particles are formed. SLENDID® may be used in a wide range of food applications such as spreads, mayonnaises and salad dressings, processed meats, ice cream, processed cheeses, soups and sauces, desserts, and bakery products, in which fat may be partly or fully replaced. Textural properties of Cheddar cheese samples were determined using compression and stress relaxation tests carried out on an Instron Universal Testing Machine[7]. It is convenient with instrumental texture analysis in the current accepted form using uniaxial compression. There was some literature introducing the Texture Profile Analysis(TPA) test on food and discussing the properties of the texture of the cheese samples[2,8-11]. Rheology is mainly concerned with the relationship between strain, stress, and time. When subjected to external forces, solids(or truly elastic materials) will deform, whereas liquids(or truly viscous materials) will flow. However, contemporary rheology is more interested in the behavior of real materials with properties intermediate between those of ideal solids and ideal liquids[12]. These industrially important materials are called as viscoelastic materials, which include almost all real materials. Without question, cheeses are viscoelastic materials. The rheology analysis of some kinds of food and cheese samples had been done in much literature[5,13-16]. The physicochemical properties of cheese have always been an important component in assessing cheese quality and value. The food researcher will gain a better understanding of the physicochemical properties of cheese with applications of rheology and texture analysis in general and specifically for cheese.

In this paper, texture analysis of cheese analogues were made. At the same time, steady state flow and dynamic rheological property of cheese analogues at low shear rates and the mathematical models of the shear stress versus shear rate were discussed.

1　Materials and methods

1.1　Materials

The casein and sodium caseinate were supplied by Linxia Huaxia Dairy Products CO. Ltd., China. The citrus low-methoxylated pectin gel was prepared in laboratory, and pectin was from Jiangxi Shangrao Fuda Pectin CO. Ltd., China. Other materials used for manufacture of the processed cheese analogues were (a) emulsifying salt and sodium chloride prepared in laboratory and relative material were from China Medicine (Group) Shanghai Chemical Reagent Corporation. (b) nisin from Tianyu Group, China. (c) cheddar Paste 565-1 and (d) butter flavour from Chr. Hansen, Denmark. (e) pigment from Wuhan Stars Modern Bio-engineering Co. Ltd., China.

1.2　Production of protein bases

The production of protein base and the processed cheese was as introduced by Muir, Tamime, Shenana, and Dawood[17]. The emulsifying salt was dissolved in suitable quantity of water and poured into the glass beaker which was placed in a water bath. The temperature was raised to 50~ 60℃, then a measured quantity casein or sodium caseinate was added to make the protein base using first a low speed mixer, then a high speed mixer until the lubricous cream was formed. After overnight storage for 14 to 16 h at 4℃, the protein bases were used in the production of processed cheese analogue.

1.3 Processed cheese analogue production

After overnight storage, the protein base had formed gels. These gels were placed in a processing kettle (A. Stephan. U. Sohne GmbH, Germany), 2 kg capacity and blended the other ingredients according to the recipes shown in Table 1. The ingredients were first mixed for one minute at low speed, following application of vacuum, the mixture was then heated to 70℃ with direct steam injection. The vacuum was then switched off and continued heating to 90℃ followed by mixing at high speed for two minutes. The melted hot cheese was packaged in rigid plastic cups and heat sealed with aluminium foil. All samples were cooled and stored for two months at 4℃. The complete experiment was replicated twice.

Table 1 Experimental recipes for the production of processed cheese analogues %

Ingredient	Ff	Lf
Casein/Sodium caseinate	15	15
Butter	20	10
Pecin gel	0	10
Emulsifying salt	2	2
Cheddar cheese flavour	1	1
Butter flavour	1	1
Nisin	0.01	0.01
Sodium chloride	1.5	1.5
Water	Approximately 60	Approximately 60

Ff = Full-fat cheese analogue; Lf = Low-fat with cheese analogue pectin gel addition.

1.4 Chemical analysis

The amounts of moisture, and ash in the cheese samples were measured by AOAC Official Method 926.08(1995), 935.42(1995)[18,19] respectively. Total protein and total fat content of the cheese were determined using the Kjeldahl, and the modified Mojonnier method, respectively[20]. The protein content of cheese was calculated by multiplying the total nitrogen content by 6.38.

1.5 Textural analysis

Texture profile analysis (TPA) parameters were determined by using a texture analyser TA-XT2i (Stable Micro System, Ltd., UK). A flat plate probe (P/0.5-Delrin cylinder probe) with 12 cm of diameter was attached to moving crosshead. Samples were not moved from the cup and it was ensured that the height of the samples were identical by cut at least 1 cm away from cheese analogues surface. They were left at 25℃ for about 30 min until they reached the definite temperature. The central temperature of a control specimen was measured by a thermocouple. The operating conditions were: selecting TPA as test mode and option, pretest speed was 2.0 mm/s, test speed was 1.0 mm/s, post speed was 5.0 mm/s, two bite time interval was 5.00 s, trigger(trig.) type was ‘auto’; trig. force was 0.1962 N, acquisition rate was 200.00 point per second (PPS), 20% of compression ratio from the initial height of the sample in two bites. The texture profile parameters were determined by using the TPA curve, an example, given in Fig. 1: the compressive force(N) recorded at maximum compression during the first bite as a measure of cheese hardness[21]; the distance of the detected height of the product on the second compression divided by the original compression distance(length2/length1) as a measure of springiness; The negative force area ($A3$, cm^2) during the first bite as a measure of adhesiveness[22]; The ratio of positive area during the second compression to the positive area during the first compression ($A2/A1$) as a measure of cheese cohesiveness; the

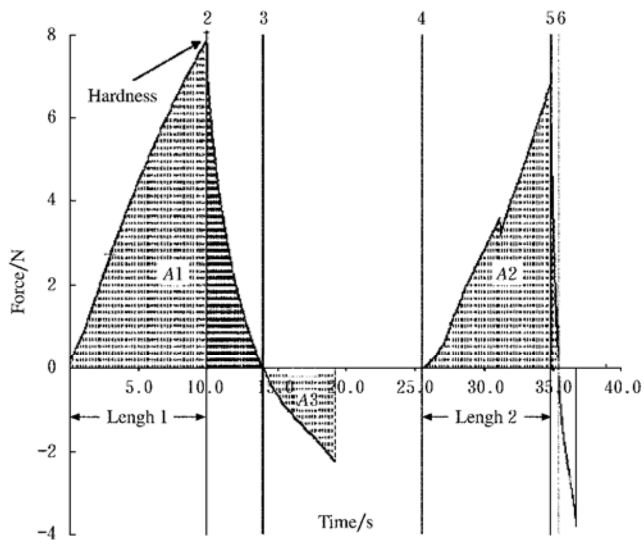


Fig. 1 Typical TPA curve of full-fat cheese analogue (springiness= length2/length1; adhesivness= $A3$; cohesiveness= $A2/A1$; gumminess= hardness×cohesiveness; chewiness= gumminess×springiness)

parameter of hardness × cohesiveness as a measure of gumminess; the parameter of gumminess × springiness as a measure of chewiness[21]. Texture values were the mean of three replicates tested each sampling time.

1.6 Rheological analysis

Samples were put on the bottom plate of the rheometer (TA Instruments AR-1000, UK) which was equipped with a 40 mm, plate-plate measuring system. And the gap was set at 1000 μm. To prevent evaporation and protect against dehydration during test of the samples, low-viscosity silicone oil was applied to the exposed surfaces of the samples. Steady state flow tests were performed under different temperature during shear rate 0 ~ 10 s^{-1}. Preliminary experiments were carried out to determine the linear viscoelastic regions at which the frequency sweep of the samples was obtained. Frequency sweep was performed and measured values obtained included G' (elastic modulus, represent the elastic part of viscoelastic properties of the samples), G'' (viscosity modulus, represent the viscous part of viscoelastic properties of the samples), and η^* (complex viscosity, is related to its viscous and elastic components, η' and η'', as follows: $|\eta^*| = \sqrt{(\eta')^2 + (\eta'')^2}$. The real part of the complex viscosity (i.e., η') is called the dynamic viscosity, and for a Newtonian fluid, it orresponds to shear viscosity.)

1.7 Statistical analysis

A one-way analysis of variance for the data for chemical analysis, textural (the factors were the pectin gel addition and the protein base) were carried out to determine the significance of the individual differences. Significant means were compared using F test and standard deviations for mean values of chemical analysis were also calculated. Simple correlations were performed between the rheology and texture of the cheese analogue samples. All the statistical analyses were conducted using the Matlab (Version 6.5) commercial statistical package.

2 Results and discussion

2.1 Composition of cheeses

The composition of full-fat, low-fat with pectin gel, low-fat control cheese analogues are given in Table 2.

Table 2 Percentage of chemical composition of cheese analogue samples (mean and standard deviation)

Base	Fat type	Moisture		Ash		Fat		Protein	
		mean	std	mean	std	mean	std	mean	std
Sodium Caseinate	FfSC[a]	0.608	0.008	4.707	0.242	17.257	0.086	17.213	0.445
	LfSC[a]	0.705	0.004	4.593	0.047	8.173	0.189	18.260	0.535
Casein	FfC[a]	0.597	0.007	3.573	0.060	18.033	0.110	18.217	0.398
	LfC[a]	0.687	0.012	3.530	0.115	9.690	0.155	17.470	0.780
SSE[b]	Base	–		* * *		–		–	
	Fat	* * *		–		* * *		—	

a: FfSC= Full-fat cheese analogue with Sodium Caseinate as protein base; LfSC= Low-fat cheese analogue with fat mimetic when the protein base is Sodium Caseinate; FfC= Full-fat cheese analogue with Casein as protein base; LfC= Low-fat cheese analogue with fat mimetic when the protein base is Casein. b: SSE= Statistical Significance of Effect (F-test) from ANOVA; (–) —not significant; * —$P < 0.05$; * * —$P < 0.01$; * * * —$P < 0.001$.

The moisture of low-fat control cheese analogue and low-fat cheese analogue with fat mimctic are significantly higher while their fat contents are lower than those of full-fat cheese, as show in the Table 1. The use of different protein base affecte the values of ash. The means of ash content in sample with sodium caseinate as protein base are higher than that in sample with casein as protein base, and the Na^+ may contribute to this result. The protein contents in all samples are not different significantly.

2.2 Textural properties

The mean values of the TPA parameters are given in Table 3. Hardness is defined as the maximum peak force during the first compression cycle (first bite) and has often been substituted by the term firmness. Adhesiveness is defined as the negative force area for the first bite and represents the work required to overcome the attractive forces between the surface of a food and the surface of other materials with which the food comes into contact, i.e. the total force necessary to pull the compression plunger away from the sample. For materials with a high adhesiveness and low cohesiveness, when tested, part of the sample is likely to adhere to the probe on the upward stroke. Springiness (originally called elasticity) is related to the height that the food recovers during the time that elapses between the end of the first bite and the start of the second bite. Chewiness means account of the energy required to masticate a solid food. This is the characteristic most difficult to measure precisely, because mastication involves compressing, shearing, piercing, grinding, tearing and cutting, along with adequate lubrication by saliva at body temperatures. Cohesiveness may be measured as the rate at which the material disintegrates under mechanical action. Tensile strength is a manifestation of cohesiveness. If adhesiveness is low compared with cohesiveness then the probe is likely to remain clean as the product has the ability to hold together. Cohesiveness is usually tested in terms of the secondary parameters brittleness, chewiness and gumminess (from the instruments manual).

The Ff cheese analogues are significantly harder than the Lf cheese analogues. The protein matrix content contributes to the hardness of cheese[19]. Although the protein contents are similar in all samples, it is not a surprising result because water breaks up the protein matrix and plays the role of lubricant to provide smoothness and a softer texture. The positive effect of fat mimetics on the hardness of low-fat cheese analogue can be attributed to both their high contents of moisture and also to total filler volume of the low-fat cheese analogues produced by fat mimetics. As the fat content of cheese analogues decreased, all the TPA parameters except springiness and cohesiveness decrease.

Table 3 TPA parameters for different cheese analogues

ID	Hardness/N		Springiness		Cohesiveness		Gumminess/N		Chewiness/N		Adhesiveness/N·s	
	mean	std	mean	std	mean	std	mean	std	mean	std	mean	std
FfSC	6.67	0.02	0.92	0.0354	0.55	0.0071	3.68	0.03	48.21	0.45	-5.55	0.24
LfSC	1.69	0.06	0.90	0.0200	0.55	0.0100	0.93	0.03	11.69	0.47	-0.86	0.03
FfC	3.01	0.23	0.92	0.0473	0.54	0.0153	1.63	0.04	21.24	0.96	-3.25	0.05
LfC	1.03	0.03	0.96	0	0.59	0.0058	0.61	0	7.70	0.10	-2.40	0.03
SSE[a]Base	*		-		-		*		*		*	
SSE[a]Fat	**		-		-		**		**		**	

[a] Significance of effect (F-test) from ANOVA; (-) —not significant; * —$P < 0.05$; ** —$P < 0.01$; *** —$P < 0.001$.

2.3 Rheological properties

2.3.1 Steady state flow

The rheologyical characteristic of cheese is important as a means of determining body and texture for quality. At the mean time, the quality of prepared foods contain cheeses as an ingredient is mainly determined by the melt and flow characteristic of cheeses. As known that during the food manufacture, the temperature is varied. So it is necessary to study the rheological properties of the cheese analogue under different temperatures. The behavior of shear stress and apparent viscosity of cheese analogues as a function of shear rate are shown in Fig.2~6, the typical pseudoplastic behaviors of all cheese analogue samples at all temperatures are found. The viscosity reduces sharply with the increase of shear rate in a steady state flow. The FfC show higher curves than others except the unique phenomena when the temperature is 45℃ and the protein base are casiein and the reason caused may be made clear after further study. The LfC and LfSC show similar curves and likely flow properties.

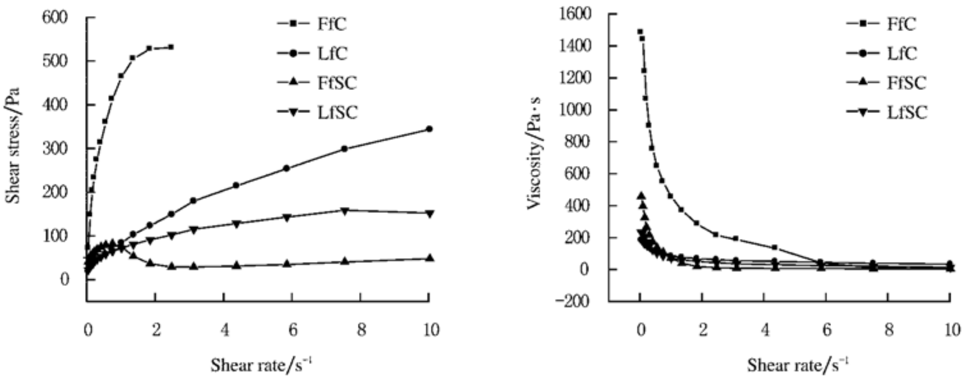
2.3.2 Flow model analysis

In order to perform a quantitative comparison of materials, it is generally required fitting the experimental data to some forms of best fit mathematical equation or model. The model is used to predict the viscosity of a flow as a function of shear stress or shear rate, it is named also constitutive equation of a flow. The most popular flow models are power law equation. The power law equation is the simplest one among the models available. Characteristic equation of power law mode is as follows

$$\tau = K \times \gamma^{n} \quad (1)$$

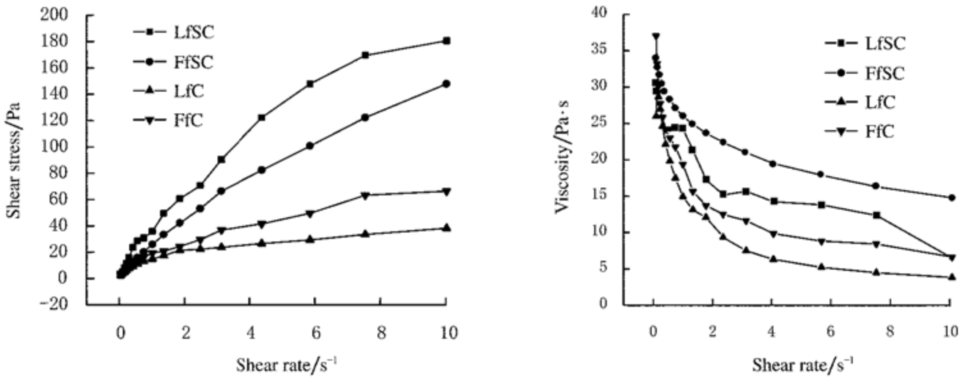
Where τ —— shear stress, Pa; γ —— shear rate,

s^{-1}; K ——consistency coefficient (the higher K is, the thicker flow is), $Pa \cdot s^n$; n ——flow behavior index (is degree measurement of non-Newtonian flow, the farther n is depart from 1, the more distinct the property of non-Newtonian behavior is).



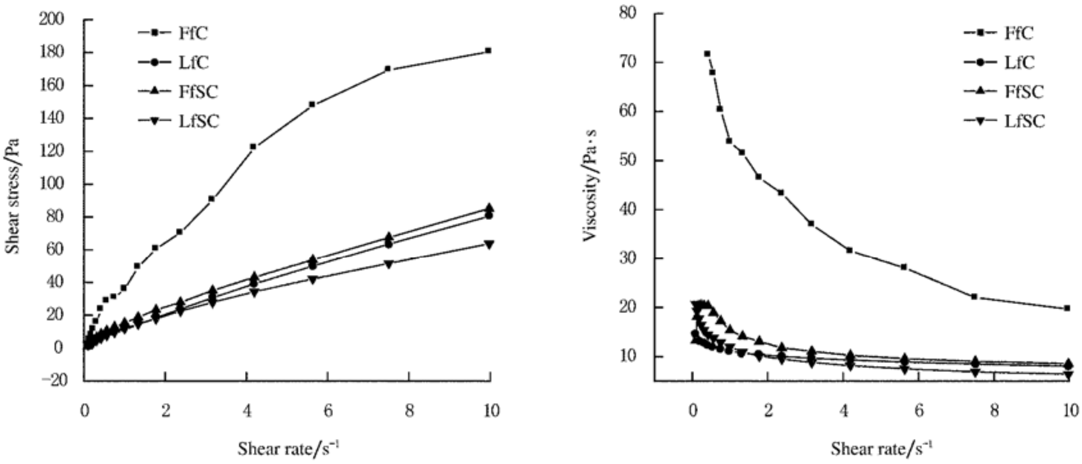
a. Shear stress versus shear rate　　b. Viscosity versus shear rate

Fig. 2　Curves of shear stress and viscosity versus shear rate of cheese analogues at 40℃



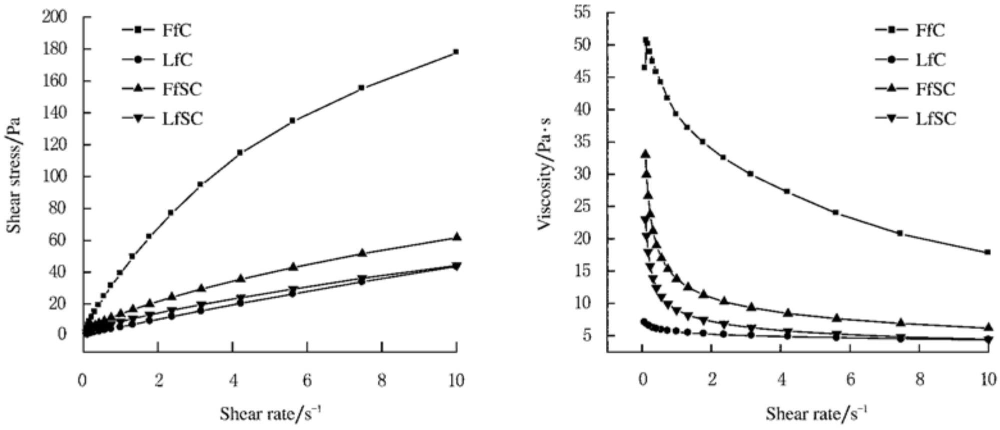
a. Shear stress versus shear rate　　b. Viscosity versus shear rate

Fig. 3　Curves of shear stress and viscosity versus shear rate of cheese analogues at 45℃



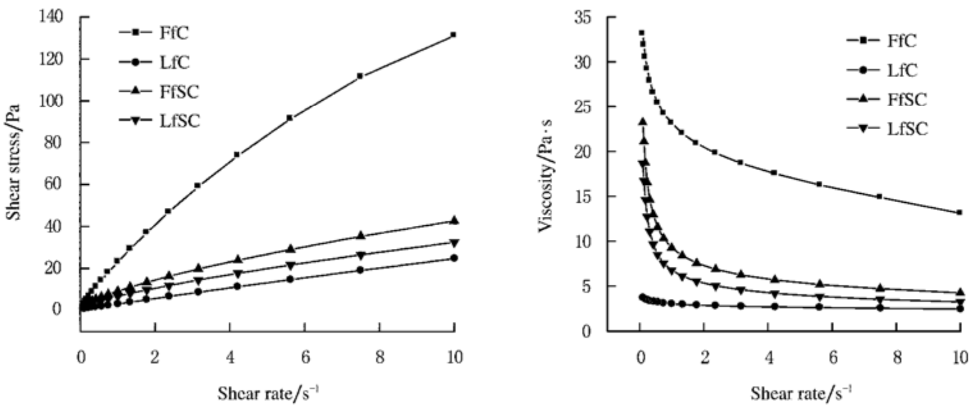
a. Shear stress versus shear rate　　b. Viscosity versus shear rate

Fig. 4　Curves of shear stress and viscosity versus shear rate of cheese analogues at 50℃



a. Shear stress versus shear rate b. Viscosity versus shear rate

Fig. 5 Curves of shear stress and viscosity versus shear rate of cheese analogues at 55℃



a. Shear stress versus shear rate b. Viscosity versus shear rate

Fig. 6 Curves of shear stress and viscosity versus shear rate of cheese analogues at 60℃

The consistency coefficent and flow behavior index of different cheese analogues, obtained by fitting the experimental shear stress-shear rate data to the power law model, as a function of temperature are shown in Table 4. The results show that the shear stress-shear strain relation are non-linear, indicating the cheese analogues behave as a non-Newtonian fluid. Furthermore, the fact that n values are less than unity indicates that these products are pseudo-plastic materials irrespective of temperatures and fat concentrations. The coefficients of determination (R^2) obtained are high which confirm the power law model to be adequately suitable for describing the flow behavior of the samples within the range studied. The value of consistency coefficient, K, range from 3.051 to 415.231 $Pa \cdot s^n$ and the flow behavior index, n, range between 0.358 and 0.908. Substitution of fat in the cheese analogue with pectin gel leads to lower K values at all temperatures tested except when the temperature is 45℃ and the protein base is sodium caseinate. The behavior index values of the samples with lower fat content are higher than that of full fat samples except when the temperature is 45℃ and the protein base is casein, the reason caused this unique phenomena may be made clear after further study. Therefore, it can be concluded that the fat reduction resulted in lower viscosity in comparison with the full fat samples. The smaller the n values the greater the departure from Newtonian behavior. Therefore, the full fat samples is more pseudo-plastic than some reduced fat blends containing pectin gel at all respective temperature except when the temperature is 45℃ and the protein base is caseine just as the comparison of the K value.

2.3.3 Dynamic rheology analysis

Rheological characterisation of cheese is important as a means of determining body and texture characteristics and to determine how these parameters are affected by composition, and processing techniques[24].

Table 4　Effect of temperature on consistency coefficient (K) and flow behavior index (n) of different cheese analogues

Samples at different temperaturek	K /Pa・s^n	n	R-square
40℃			
FfC	415.231	0.358	0.951
LfC	86.549	0.606	0.999
FfSC	90.215	0.240	0.985
LfSC	72.614	0.386	1.000
45℃			
FfC	56.140	0.562	0.982
LfC	14.216	0.437	0.982
FfSC	18.030	0.588	0.993
LfSC	27.445	0.737	0.998
50℃			
FfC	41.963	0.669	0.985
LfC	11.318	0.855	1.000
FfSC	14.803	0.756	0.999
LfSC	11.870	0.732	1.000
55℃			
FfC	41.520	0.655	0.992
LfC	5.647	0.891	1.000
FfSC	13.969	0.647	1.000
LfSC	9.067	0.686	1.000
60℃			
FfC	24.348	0.746	0.998
LfC	3.057	0.908	1.000
FfSC	9.366	0.657	1.000
LfSC	6.849	0.672	0.999

Cheese analogues are viscoelastic materials and their viscoelastic behaviour can be influenced by changes in their formulation caused by the incorporation of fillers which interact with the casein matrix in the curd[25]. Instrumental measurements of food texture are based on the food´s rheological properties. Dynamic low amplitude strain testing offers very rapid result with minimal chemical and physical change. Small strain dynamic rheological methods have been used to define both the elastic and viscous nature of cheese. Such information is useful to characterise and differentiate cheese varieties[26]. Such methods are implemented within the linear viscoelastic region of the material and, therefore, are designed to be nondestructive to the basic structure of the material. Additionally, the elastic and loss moduli become only a function of time and a function of the magnitude of the stress or strain applied by performing tests within the linear viscoelastic region[27]. In low amplitude oscillatory shear experiments, the sample was contained between two parallel plates and underwent sinusoidally oscillating deformation as the lower plate was fixed while the upper plate was oscillating at a specified frequency and transient responses were recorded.

Rheology measurements were carried out in order to investigate cheese heterogeneity and to discriminate between the four cheese analogues. The changes in G', G'' and complex viscosity as functions of the applied frequency for samples are presented in Fig. 7~ 9. Among the investigated parameters, G' and G'' increase when the frequency increase. Storage modulus (G') represents the solid-like or elastic property of a viscoelastic material such as cheeses. As water in cheese acts as a plasticiser, more water will make the cheese analogues plastic and *vice versa*. Lowering the water content increases the intermolecular linkages by concentrating the proteins, whereas a higher moisture content causes a swelling of the casein matrix and decreases the molecular interactions and hence cause a lower G' value. Without considering the protein base type, the Ff cheese analogues have higher G' value. As for G'', the similar trend of the effect of frequency are found, so does the complex viscosity. Based on the results of the dynamic rheolgy analysis of the full fat and low fat with pectin addition cheese analogues, decreased the fat content leads to the decrease of G', G'' and complex viscosity. The cheese analogue with sodium caseinate as protein base shows lower G', G'' and complex viscosity compared with the sample with casein as protein base. This result may be due to the difference of structure of the two proteins.

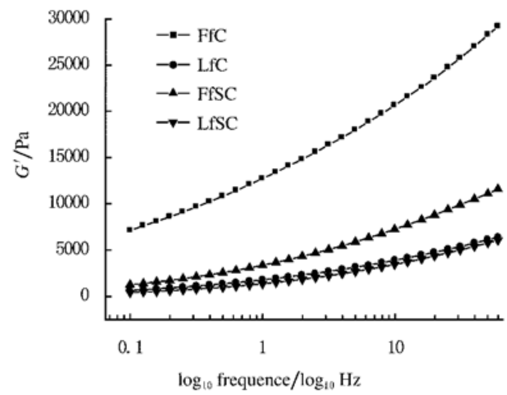


Fig. 7　Curves of G' versus log frequency

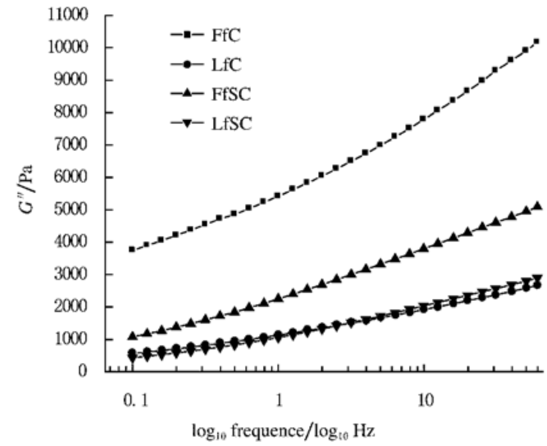


Fig. 8 Curves of G'' versus log frequency

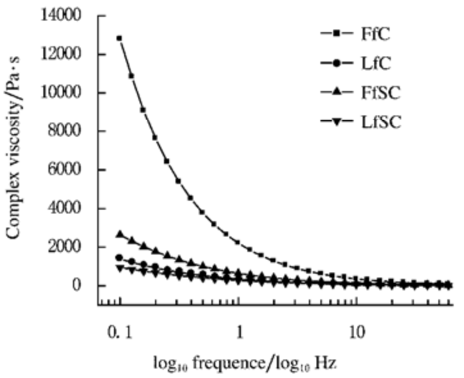


Fig. 9 Curves of complex viscosity versus $\log_{10}$ frequency

3 Conclusions

1) The results of the textural properties of the samples measured by TA.XT2i Texture Analyser show that as the fat content of cheese analogues decreased, all the TPA parameters except springiness and cohesiveness decrease. This is due to the higher moisture content of Lf cheese analouge.

2) The steady state rheological analysis of cheese analogues show that all cheese samples exhibit non-Newtonian, pseudo-plastic behavior at all temperatures including 40, 45, 50, 55 and 60℃. Shear stress versus shear rate data is successfully fitted to the Power-law model.

3) The dynamic analysis show that the full-fat products manifest a more solid-like form. All the samples' rheological parameters are dependent on the oscillatory frequency. Decreasing the fat content leads to the decrease of G', G'' and complex viscosity. The cheese analogue with sodium caseinate as protein base show lower G', G'' and complex viscosity compared with the sample with casein as protein base. This result may be due to the difference of structure of the two proteins.

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全脂和低脂模拟干酪的流变及质构特性研究

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摘　要: 分别通过TA.XT2i质构分析仪和AR1000流变仪对全脂和低脂模拟干酪进行全质构分析以及稳态及动态流变分析。结果表明, 降低脂肪含量, 全质构分析数据除了弹性及内聚性以外全部显著下降。稳态流变结果显示, 模拟干酪在不同温度下均表现出非牛顿假塑性流体特性。采用power- law 模型可以很好地对其数据进行拟合。动态流变分析表明, 相对于低脂样品来说, 高脂干酪更具有固态特性。黏弹性参数如弹性模量、黏性模量、复合黏度均与振荡频率有关。从流变和质构的角度来看, 低脂和高酯干酪有明显区别。因而对干酪样品的流变和质构特性进行分析对于改善其加工工艺及品质保证是非常有意义的。

关键词: 模拟干酪; 果胶凝胶; 低脂; 流变; 质构; 模型拟合