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Viscoelastic properties and overall sensory acceptability of reduced-fat Petit-Suisse cheese made by replacing milk fat with complex coacervate

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Abstract The structural–mechanical–sensory characteristics of cheese can be altered by reducing the fat content, but this can affect product acceptance by the consumer. A potential alternative for improving the characteristics of reduced-fat cheese (RFC) is to reinforce the protein network with biopolymers of complex coacervates which may act as building blocks within the continuous phase. The objective of this work was to determine the chemical composition, dynamic rheological properties, and overall sensory acceptability of four reduced-fat Petit-Suisse cheeses (RFC₂₅, RFC₅₀, RFC₇₅, and RFC₁₀₀) made by partial or total substitution (25%, 50%, 75%, and 100%) of milk fat contained in milk cream (MC) by whey protein isolate–low-methoxyl pectin (WPI–LMP) complex coacervate (CC), in comparison to those of a full-fat Petit-Suisse cheese (FFC). The relative concentrations of the MC to CC determined the extent to which the buildup and rebodilyng occurred in the RFC cheeses, thus affecting their rheological properties and overall sensory acceptability. A linear regression model was determined which estimated the overall acceptability scores of the cheeses as a function of the changes in storage (G') and loss (G'') moduli with storage time. RFC₅₀ and RFC₇₅ cheeses displayed a mechanical–sensory response resembling that of the FFC cheese.

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低脂Petit suisse干酪的粘弹性和感官特性

摘要：干酪的结构特性，生产工艺及感官特性会因其脂肪含量的减少而变化，进而影响消费者对产品的接受度。通过生物大分子的复合凝聚作用来加强蛋白质网状结构，而形成的蛋白质网状结构又构成了连续相的骨架，这种方式可以改善低脂干酪的质构特性。本文测定了四组低脂Petit Suisse干酪(RFC₂₅, RFC₅₀, RFC₇₅ and RFC₁₀₀)的化学成分、流变动力学和整体的感官接受性，低脂Petit Suisse干酪中乳脂肪(MC)分别被不同浓度(25、50、75和100%)的乳清分离蛋白-低甲氧基果胶复合凝聚物(CC)所替代，并将实验结果与全脂Petit Suisse干酪(FFC)进行了比较。MC与CC的相对浓度决定了不同替代度RFC干酪的聚集状态和形变，也影响了干酪的流变特性和感官的可接受性。根据干酪的感官评分与贮存时间内贮存模量(G')和损失模量(G'')变化获得了线性回归方程。实验结果表明，RFC₅₀和RFC₇₅干酪的某些机械感官性质与FFC干酪相似。

关键词 Petit suisse干酪·低脂·合凝聚·流变性·整体感官接受性

Keywords Petit-Suisse cheese · Reduced fat · Complex coacervate · Rheological properties · Sensory overall acceptability

1 Introduction

An ongoing challenge for food scientists and food producers is to obtain novel biomaterials that may be used in the manufacture of processed foods in order to achieve certain expected functionalities, such as increased physicochemical and microbiological stability, improved textural and sensory attributes, protection of sensitive bioactive compounds and ensuring their controlled delivery, and as substitutes of fat in the structuring of low-fat products among others. Processed foods usually are highly complex, multi-phase, multi-component systems, and biopolymers (proteins and polysaccharides) and dispersed particles (droplets, bubbles, granules, crystals, etc.) are the two main structural entities in food colloids. The overall stability, texture, rheology, and microstructure of food colloids depends on the state of the aggregation of the dispersed particles, which in turn depend on the interactions between the food biopolymer molecules (protein-protein, protein-polysaccharide, polysaccharide-polysaccharide, etc.), and on the influence of other food components such as lipids, low molecular weight sugars, and simple salts (Dickinson and Euston 1991). Given the constraint imposed by the restriction to using food grade ingredients (Dickinson 2011), and to the relatively low number of biopolymers in the marketplace which comply with this restriction, it makes sense to try to develop new biomaterials that combine two biopolymers for enhancing their individual functional properties. For example, the combination of protein+polysaccharide would be expected to give optimum results by bringing together the emulsifying role of the protein with the

stabilizing role of the polysaccharide (Dickinson and Euston 1991). The improved functional properties resulting from the protein–polysaccharide complexes in comparison to the proteins and polysaccharides alone could be attributed to the structure of the complexes. Consequently, the interesting hydration (solubility, viscosity), structuration (aggregation, gelation), and surface (foaming, emulsifying) properties of these complexes could be utilized in a number of domains (microencapsulation, fat replacers, texturing agents, stabilization of bioactives and their controlled release, edible films, etc.) (Schmitt et al. 1998). There are many ways in which complex biopolymers can interact at the molecular level, hence it is important to determine which parameters influence the formation of the complexes and coacervates and to investigate the main functional properties of these systems (Espinosa-Andrews et al. 2008; Schmitt and Turgeon 2011).

Petit-Suisse cheese is one of the most favored French soft cheeses due to its mixture of sweet and sour flavor. It is made from pasteurized cow's milk and has a fat content of about 18.8% on dry basis (Prudencio et al. 2008). It is frequently consumed as a food dessert, alone or combined with fruit, and designed to target children as consumers (Cardarelli et al. 2007). The increasing demand and popularity by consumers have given rise to concerns regarding children's health. Child obesity has more than tripled in the last 30 years in the USA. The prevalence of obesity among children aged 6 to 11 years increased from 6.5% in 1980 to 19.6% in 2008, and among adolescents aged 12 to 19 years it has increased from 5.0% to 18.1% (Ogden et al. 2010). Childhood obesity is the result of caloric imbalance and has both immediate and long-term health implications. Children and adolescents who are obese are more likely to have significant risk factors for cardiovascular disease, osteoarthritis, type 2 diabetes, several types of cancer, sleep apnea, and social and psychological problems such as stigmatization and poor self-esteem (U. S. Surgeon General 2001; Daniels et al. 2005; Freedman et al. 2007).

Thus, it is desirable to develop healthy foods, such as low- and reduced-fat products with a healthy saturated–unsaturated fat balance, which also include dietary fiber. Whey protein isolate–xanthan gum complexes have been successfully used as fat replacers in neutral pH cake frostings with textural, rheological, and melting profiles similar to those of a full-fat control (Laneuville et al. 2005). Numerous important health benefits have been associated with an adequate dietary fiber intake, such as the promotion of normal laxation, the reduction of future risks of cardiovascular disease, some cancers, and adult-onset diabetes. A safe range of dietary fiber intake for children has been suggested to be between 5 and 10 g·day⁻¹ (Williams et al. 1995). One way of extending the application of dietary fibers, and perhaps of mitigating some of the unwanted side effects which can arise when products are enriched with too much pure fiber, is to incorporate fiber into food as mixtures with other macromolecules (Redgwell and Fisher 2005). When formulating low- and reduced-fat foods with novel formulation ingredients, one should ensure that the mechanical response (rheological and/or textural) to external factors results in similar or superior properties than those of their full-fat counterparts (Lobato-Calleros et al. 2008).

The objective of this work was to determine the dynamic rheological properties and overall sensory acceptability of reduced-fat Petit-Suisse cheeses, in which milk fat was partially or totally substituted by a whey protein isolate–low-methoxyl pectin coacervate, in comparison to those displayed by a full-fat Petit-Suisse cheese.

2 Materials and methods

2.1 Materials

For the protein (Pr)–polysaccharide (Ps) complex coacervate formation, the following biopolymers were used: whey protein isolate (WPI; HilmarTM 9400, 93% protein in dry basis; Hilmar Ingredients, Hilmar, CA, USA) and low-methoxyl pectin (LMP; Grinsted[®] pectin LC 710, degree of esterification of 48%; Danisco, Dange Saint Romain, France). Other ingredients used for Petit-Suisse cheeses manufacture were skim milk (SM; 0.1 g fat·L⁻¹), pasteurized milk cream (MC; 36% milk fat w/w; Experimental Dairy Farm, Universidad Autonoma Chapingo, Texcoco, State of Mexico, Mexico) acidified from an initial pH of 6.7 to a pH of 4.5 by addition of lactic acid (85.2% w/v; J.T. Baker, S. A. de C.V., Xalostoc, Mexico); lyophilized culture of *Streptococcus thermophilus* (CHOOZIT, TA 54 LYO; Danisco); rennet (1:10,000 strength; Alcatraz, S.A. de C.V., Mexico City, Mexico); coloring agent (McCormick de Mexico S.A de C.V., Mexico City, Mexico); and strawberry flavoring (MK Flavors & Co., Tlalnepantla, State of Mexico, Mexico). Hydrochloric acid (HCl) and sodium hydroxide (NaOH) were purchased from J.T. Baker, S. A. de C.V. Deionized water was used in all the experiments.

2.2 Stock solutions

Biopolymer stock solutions were prepared by dispersing WPI (1 wt.%, initial pH=6.3) and LMP (1 wt.%, initial pH=3.5) in deionized water at room temperature (22±3 °C) under agitation for 30 min. The solutions were stored overnight at 4 °C to ensure complete hydration.

2.3 WPI–LMP complex coacervate formation

In order to obtain a general picture for the coacervation phenomena between WPI and LMP, the impact of the protein (Pr)/polysaccharide (Ps) weight ratios at which maximum phase separation occurred for a given pH value (pH_{ps}) was evaluated using the turbidimetry procedure described by Devi and Maji (2010) with modifications: (1) the stock solutions of WPI and LMP were adjusted separately to different pH values (2.0–6.0); (2) at a given pH, both stock solutions were blended in Pr/Ps proportions ranging from 1:1 to 8:1, while always keeping the total biopolymer concentration of 1% w/w, by gently stirring the mixture for 1 h at room temperature, followed by 48 h of equilibration at 4 °C; (3) the samples were centrifuged (Hermle Z323 k; Hermle Labortechnik, Germany) at 1,350 rpm for 30 min, in order to separate the insoluble WPI–LMP complex coacervate (CC) from the soluble complexes in the supernatant; (4) the absorbance of the supernatant was measured at 400 nm because at this wavelength the WPI–LMP soluble complexes showed significantly higher absorbance than the solutions of either individual biopolymer, employing a UV spectrophotometer (Spectronics Genesys 5 UV/Vis, Spectronic Unicam, Rochester, NY, USA). The optimal Pr/Ps ratio and pH_{ps} at which complex coacervation occurred between WPI and LMP was the point where the supernatant would have the minimum turbidity (absorbance) due to complete phase separation.

2.4 Complex coacervate yield, protein, and moisture content

CC was analyzed for protein by the Kjeldahl method and moisture content by drying with a moisture balance (MB23 model; Ohaus Corporation, NJ, USA) (AOAC 1995). The CC yield (Y_{CC}) was calculated according to the following equation (Xiao et al. 2011):

$$\text{CC yield} = \frac{\text{weight of CC in dry basic}}{(\text{total weight of WPI} + \text{LMP in the dispersion})} \times 100$$

2.5 Cheese manufacture

A full-fat Petit-Suisse cheese (FFC) was manufactured as a control following the procedure proposed by Cardarelli et al. (2008) with slight modifications. Five L batches of pasteurized SM (63 ± 1 °C, 30 min) were used for preparing a quark gel or cheese base. Thirty milligrams of lyophilized culture of *S. thermophilus* per liter and 0.25 g of CaCl_2 per liter were added to the SM batches (37–38 °C) and allowed to stand until pH value of 6.3–6.4 was reached. At this point, 50 mg of rennet per liter was added. The mixture was allowed to stand (37–38 °C) until a curd was formed, and the pH value was 5.5–5.7. The curd was then cut into 20-mm³ cubes, placed in sterilized cotton cheesecloth, and allowed to drain at 15 °C for 10 h. Afterwards, the cheese base was transferred into a glass container, covered with parafilm, and stored at 4 ± 0.5 °C for 24 h. Quark (66 g) was mixed with 20 g of MC, 14 g of sugar, 0.1 g of coloring agent, and 0.1 g of strawberry flavoring, in a Waring 7012S laboratory blender (Waring Laboratory, Torrington, CT, USA) until a smooth and homogeneous product was formed.

Also, four reduced-fat Petit-Suisse cheeses were prepared by substituting MC by CC (obtained as described in “WPI–LMP complex coacervate formation” section) in the following percentages: 25%, 50%, 75%, and 100%, and the reduced-fat cheeses were coded as RFC₂₅, RFC₅₀, RFC₇₅, and RFC₁₀₀, respectively. Because the pH of Petit-Suisse cheese is ~4.5, the complex coacervate formed at this pH value was used in order to ensure its stability. Twenty grams of each blend MC/CC was mixed with the cheese base (66 g), 14 g of sugar, 0.1 g of natural coloring, and 0.1 g of strawberry flavoring. All the cheeses were stored immediately after manufacture at 4 ± 0.5 °C until required for their characterization.

2.6 Cheese chemical composition

Variations in the compositions of the experimental cheeses were analyzed according to the following methods for protein by the Kjeldahl method, fat by the Gerber method, pH on warm macerates, and moisture by oven drying (AOAC 1995) on day 1 after manufacture.

2.7 Rheological properties

The viscoelastic properties of the CC and of the cheeses were measured using a Physica MCR 301 Dynamic Shear Rheometer (Anton Paar Messtechnik, Stuttgart,

Germany) at 4 °C. Truncated cone-plate geometry (1°, 50 mm diameter) was used, in which the truncated cone had a gap of 0.05 mm between the flat surfaces of both elements. CC or cheese samples (~1.5 g) were carefully placed in the measuring system and left to rest for 30 min for structure recovery. Afterwards, amplitude sweeps were carried out to characterize the viscoelastic linear region (LVR) of the samples, with strain ranging from 0.002% to 100% for CC and from 0.009% to 100% for the cheeses at 1 Hz. Frequency sweep was performed from 0.1 to 10 Hz at 0.1% of strain for the cheeses (strain corresponding to the LVR). The storage modulus (G') and the loss modulus (G'') were obtained from the equipment software. Measurements were performed on CC after 1 day and on the experimental cheeses after 1 and 7 days of storage.

2.8 Sensory evaluation

The experimental cheeses were evaluated by a consumer panel of 80 high school students (32 males and 48 females), aged between 15 and 17 years old, who were frequent cheese consumers. Each of the five experimental cheeses aged 7 days were placed into 20-mL plastic glasses completely filling them with the help of a spatula, left to stand for 30 min for structure recovery, coded with three-digit random numbers, and randomly presented to the panelists. The consumers' preference for the cheese was scored on a five-point hedonic scale (1=dislike extremely; 2=dislike moderately; 3=neither like nor dislike; 4=like moderately; 5=like extremely) (Ramírez-Santiago et al. 2010).

2.9 Data analysis

The five experimental cheeses were manufactured in triplicate using a randomized experimental design and independently analyzed in triplicate for chemical composition (after 1 day), rheological properties (after 1 and 7 days), and overall sensory acceptability (after 7 days). Simple classification variance analysis was applied and, whenever it was appropriate, Tukey's test was used in order to determine differences between the means. The relationship between the consumer panel overall acceptability data and the dynamic rheological properties of the experimental cheeses was determined using stepwise multiple linear regression analysis. The significance was determined at $P \leq 0.05$. Data analysis was performed using Statgraphics Plus software (Statistical Graphics Corp., Manugistics, Inc., Cambridge, MA, USA).

3 Results and discussion

3.1 Turbidity analysis of the WPI–LMP interaction

For the different WPI/LMP weight ratios, the absorbance versus the pH profiles are shown in Fig. 1. All the profiles showed similar trends and were characterized by three regions observed from high to low pH values as follows: (A) a region at relatively high pH values (>5.0) where the individual biopolymers co-exist without interacting due to strong electrostatic repulsion between the negatively charged WPI and LMP chains, and where the absorbance readings are relatively low and remain almost constant; (B) an intermediate pH region where complexes begin to form at a

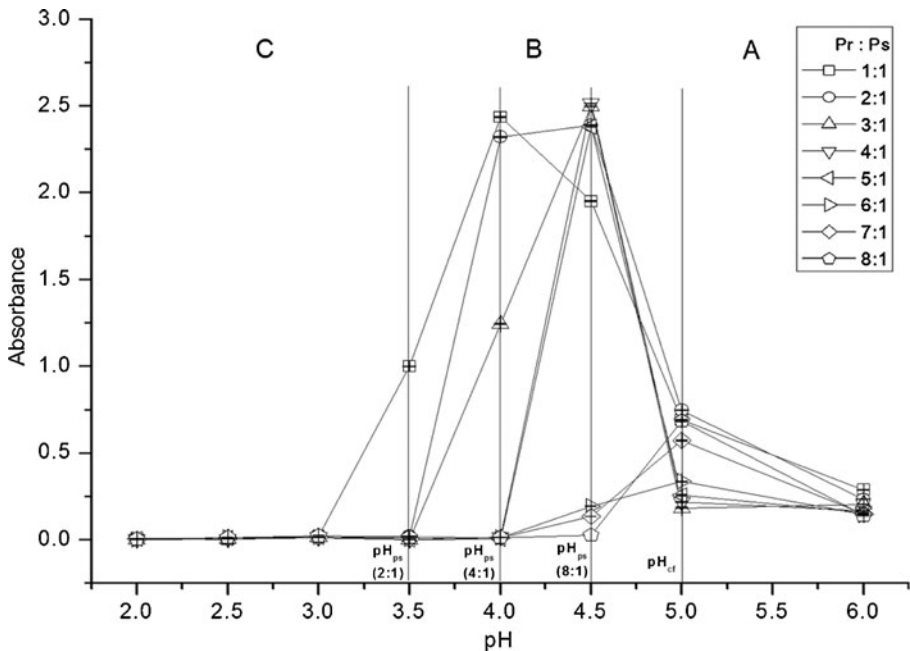


Fig. 1 Absorbance of whey protein isolate (WPI)-low-methoxyl pectin (LMP) dispersions (1 wt%) at different protein/polysaccharide (Pr/Ps) ratios in function of pH. pH_{cf} critical pH at which WPI-LMP complexes begin to form, pH_{ps} maximum phase separation pH at which coacervation between WPI-LMP was highest

critical pH (pH_{cf}) (~4.75) by the binding of protein molecules to the polysaccharide chains, which remain soluble due to an incomplete neutralization of the negatively charged pectin moieties and the positively charged protein moieties (Park et al. 1992) and where the absorbance readings increased to a maximum value as biopolymer soluble complex formation proceeded; and (C) a region at relatively low pH values (≤ 4.5), where the WPI-LMP soluble complexes begin to aggregate into insoluble complexes characterized by a gradual decrease in the absorbance readings, until a critical pH value (pH_{ps}) is reached where maximum phase separation is achieved. In this region, a more balanced distribution between the positively charged WPI molecules and the negatively charged LMP molecules develop and charge neutralization occurs. While the onset of the pH_{cf} value was independent of the Pr/Ps ratio used, the pH_{ps} values were dependent on the Pr/Ps ratio (Fig. 1). As the Pr/Ps ratio increased, the pH_{ps} values shifted towards higher pH values, e.g., for Pr/Ps ratios of 2:1, 4:1, 6:1, and 8:1, the pH_{ps} values were 3.5, 4.0, 4.25, and 4.5, respectively. Weinbreck et al. (2004) reported that higher Pr/Ps ratios led to increased pH_{ps} values.

In the remainder of the paper, when referring to CC, it is meant that it was obtained at a pH_{ps} of 4.5 and a Pr/Ps ratio of 8:1. Under these conditions, the CC yield was 63.1% having a protein content of 76% on dry basis.

3.2 Rheological behavior of the WPI-LMP coacervate

Given that the objective of this work was to develop reduced-fat Petit-Suisse cheeses by partially or totally substituting MC by CC, the viscoelastic properties of both

materials were determined and compared. G' -strain% data indicated that the LVR, in which the moduli are constant regardless of strain amplitude, occurred in the range from 0.002 to 0.3 strain % for the CC and between 0.002 and 0.01 strain % for the MC at 1 Hz of frequency (Fig. 2). Both materials displayed higher G' than G'' values indicating that they behave predominantly as gel-like elastic networks. Nevertheless, G' and G'' values were higher for the CC than for the MC suggesting a higher interconnected gel-like network in the former than in the latter. It has been demonstrated that aggregation of pectin molecules bound with β -lactoglobulin molecules confer the elastic character to β -lactoglobulin–pectin coacervates, while β -lactoglobulin molecules contribute to its viscous behavior and act as junction points of the network (Wang et al. 2007). On the other hand, MC basically consists of a semisolid oil-in-water emulsion, formed by milk components and a high concentration of milk fat globules surrounded by a thin protein–phospholipid membrane (Kaláb 1993).

MC and CC showed different G' and G'' behavior at strain % higher than those corresponding to the LVR. MC was characterized by a downward inflexion in G' and G'' , while CC was characterized by a downward inflexion for G' , but an upward inflexion followed by a downward inflexion for G'' as strain % increased (Fig. 2). The behavior shown in the non-linear viscoelastic region (NLVR) by MC is known as strain thinning, while that of CC as weak strain overshoot. Strain thinning is characteristic of many emulsions, and in the case of MC, it may be attributed to the state of entanglement of milk protein chains interconnecting with the fat globules at low strain values (where G' and G'' are constant), but as the strain increases, the protein chains disentangle and align themselves with the flow field. Weak strain overshoot is characteristic of inter-molecular association (mostly through hydrogen bonding and electrostatic interactions) between polyelectrolyte molecules presenting an extended structure due to the electrostatic repulsion from the charged groups in the side chains. When an external strain is imposed, the complex structure resists a finite strain, where G'' increases. Once the finite strain is superseded, the structure commences rupturing,

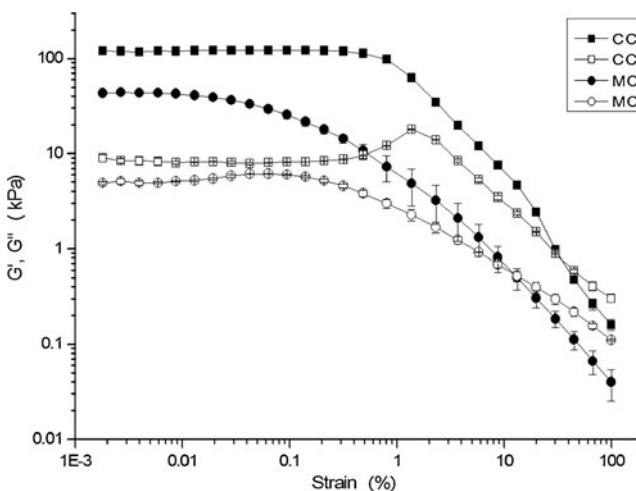


Fig. 2 Amplitude sweep of milk cream (MC) and complex coacervate (CC) obtained at pH of 4.5, when protein isolate–low-methoxyl pectin ratio of 8:1 and total biopolymers concentration of 1 wt%. Values of G' (filled symbols) and G'' (empty symbols)

and the broken elements align with the flow field, with G'' decreasing (Hyun et al. 2002). At high strains, both materials showed a crossover between G' and G'' , indicating that their structure was characterized by a predominantly viscous behavior.

3.3 Cheese composition

The FFC cheese had a fat content that was significantly higher ($P \leq 0.05$) than that of the RFC cheeses (Table 1), which was expected, as it was manufactured using milk cream containing 36% fat w/w, whereas in the RFC cheeses the MC was partially or totally replaced with different percentages of CC. The fat content in the RFC cheeses decreased from 3.3 to 0.2 g per 100 g as the MC was replaced with the CC. In contrast, the protein content in the cheeses was inversely proportional to their fat content. Thus, the FFC had significant lower protein content than the RFC cheeses, with the exception of RFC₂₅ cheese which had no significant differences in protein content. The protein content of the RFC cheeses increased as the degree of substitution of MC by CC increased. No significant differences were detected in the moisture content and in the pH values of the cheeses, which ranged from 4.67 to 4.73.

3.4 Cheese rheology

Cheese exhibits both solid and liquid characteristics, so its mechanical behavior can be described by the storage modulus (G'), which is a measure of its elastic character, and the loss modulus (G''), which is a measure of its viscous character (Lobato-Calleros et al. 2006). The G' data (Figs. 3a and 4a) showed that the LVR occurred in the strain % interval of 0.01–0.2 for all the cheeses at 1 Hz of frequency, whether at 1 or 7 days of storage. The G' - and G'' -strain % curves of the FFC and RFC cheeses showed similar trends and shapes (Figs. 3 and 4). After 1 day of storage, the cheeses showed G' values corresponding to the LVR as follows: RFC₇₅>RFC₅₀=FFC=RFC₁₀₀>RFC₂₅ (Table 2). The different experimental cheeses showed that the G'' values (Table 2) followed similar relative order as G' values.

G' and G'' values of the experimental cheeses aged 7 days (Fig. 4) were higher than those exhibited after 1 day of storage (Fig. 3). The increases in the moduli values were dependent on the experimental cheese composition (Table 2). The G' value of the cheeses after 7 days of storage varied as follows: RFC₇₅>FFC>RFC₅₀>RFC₂₅=RFC₁₀₀, and for G'' as follows: RFC₇₅>RFC₅₀=FFC>RFC₁₀₀=RFC₂₅ (Table 2). At

Table 1 Chemical composition and overall acceptability (means±SD) of Petit-Suisse cheeses

Cheese code	Protein (%)	Fat (%)	Moisture (%)	Overall acceptability
FFC	13.7±0.1 ^c	3.9±0.1 ^a	62.5±0.2 ^a	4.4±0.7 ^a
RFC ₂₅	14.3±0.6 ^{bc}	3.3±0.1 ^b	63.0±0.4 ^a	3.3±0.6 ^b
RFC ₅₀	15.5±0.1 ^{ab}	2.1±0.1 ^c	62.8±0.4 ^a	4.0±0.9 ^{ab}
RFC ₇₅	15.2±0.5 ^{ab}	1.2±0.1 ^d	63.0±0.2 ^a	3.8±0.8 ^{ab}
RFC ₁₀₀	16.3±0.0 ^a	0.2±0.6 ^c	63.1±0.6 ^a	2.8±0.9 ^c

Different letters within the same column indicate that the means differ significantly ($P \leq 0.05$)

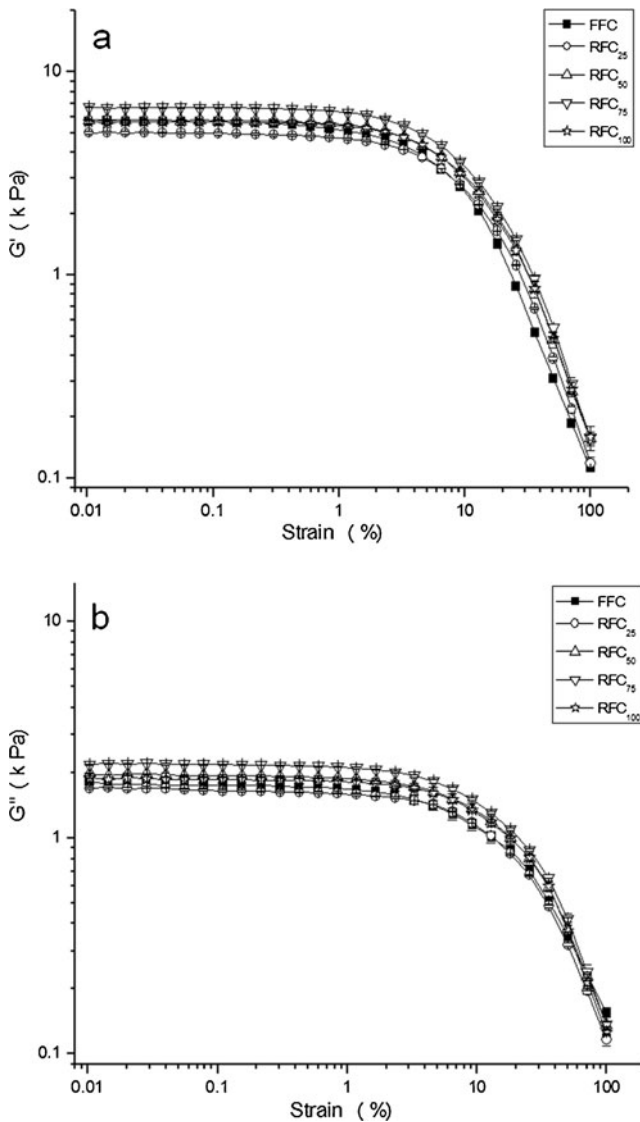


Fig. 3 Rheological properties of Petit-Suisse cheeses as a function of strain % after 1 day of storage: **a** storage modulus G' and **b** loss modulus G''

this point, it is important to mention that during Petit-Suisse cheese manufacturing the quark gel is broken down and incorporated with the MC and the CC using severe shearing conditions. As a consequence, a buildup and rebodilying of the gel network occurs during quiescent storage, influencing the mechanical properties of the experimental cheeses (Arshad et al. 1993). The descending order in the magnitude of the increase in G' with storage time ($\Delta G'$) was as follows: RFC₇₅ (4.7 kPa) > FFC (3.9 kPa) > RFC₅₀ (2.9 kPa) > RFC₂₅ (1.3 kPa) > RFC₁₀₀ (0.5 kPa), while that of $\Delta G''$ was RFC₇₅ (1.3 kPa) > FFC (1.1 kPa) > RFC₅₀ (0.8 kPa) > RFC₂₅ (0.3 kPa) >

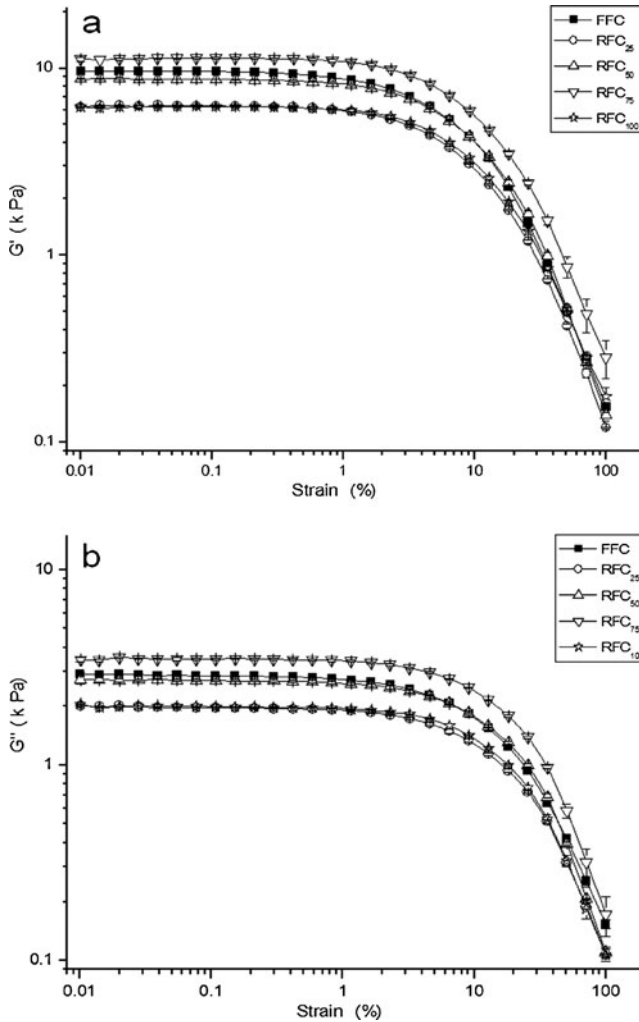


Fig. 4 Rheological properties of Petit-Suisse cheeses as a function of strain % after 7 days of storage: **a** storage modulus G' and **b** loss modulus G''

Table 2 Values of the storage (G') and loss (G'') moduli of Petit-Suisse cheeses (means \pm SD) in the linear viscoelastic region

Cheese code	G' (1 day) (kPa)	G'' (1 day) (kPa)	G' (7 days) (kPa)	G'' (7 days) (kPa)
FFC	5.7 \pm 0.3 ^b	1.8 \pm 0.1 ^{bc}	9.6 \pm 0.3 ^b	2.9 \pm 0.2 ^b
RFC ₂₅	5.0 \pm 0.4 ^c	1.7 \pm 0.0 ^c	6.3 \pm 0.4 ^d	2.0 \pm 0.2 ^c
RFC ₅₀	5.8 \pm 0.3 ^b	1.9 \pm 0.0 ^b	8.7 \pm 0.3 ^c	2.7 \pm 0.1 ^b
RFC ₇₅	6.7 \pm 0.3 ^a	2.2 \pm 0.0 ^a	11.4 \pm 0.4 ^a	3.5 \pm 0.3 ^a
RFC ₁₀₀	5.7 \pm 0.2 ^b	1.9 \pm 0.1 ^{bc}	6.2 \pm 0.7 ^d	2.0 \pm 0.3 ^c

Different letters within the same column indicate that the means differ significantly ($P < 0.05$)

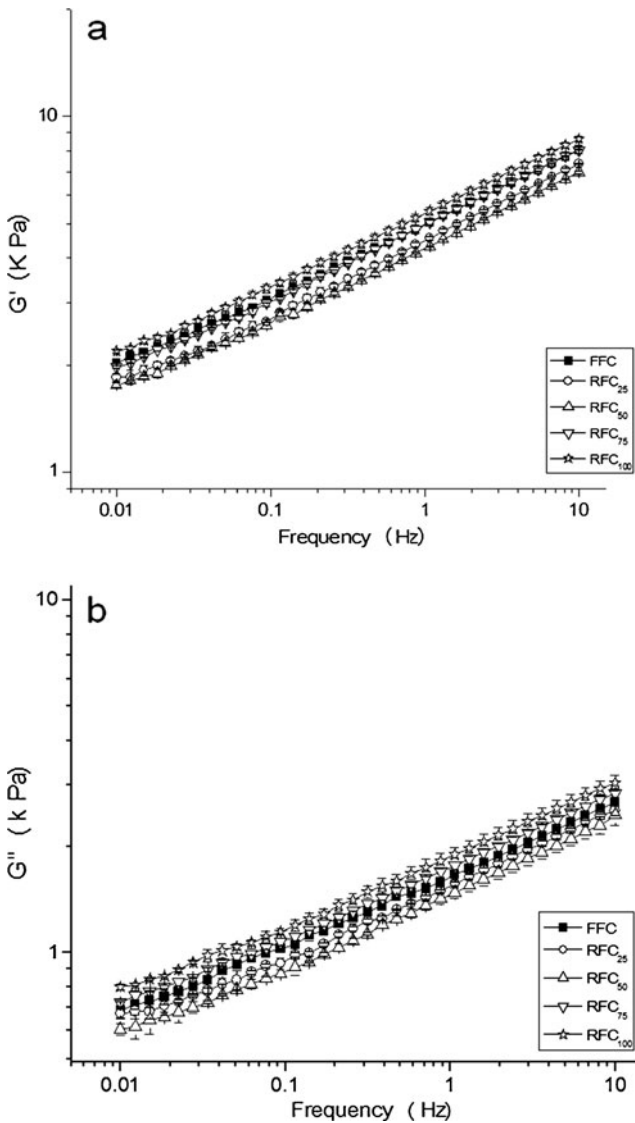


Fig. 5 Rheological properties of Petit-Suisse cheeses as a function of frequency after 1 day of storage: **a** storage modulus G' and **b** loss modulus G''

RFC₁₀₀ (0.1 kPa). $\Delta G'$ and $\Delta G''$ values may serve as a good indicator of the extent to which buildup and rebodding proceeds in response to the composition of the experimental cheeses. Even though no direct observation of the microstructure of the experimental cheeses was performed, according to the literature, the FFC protein matrix originates from small casein particles (held together by various physical forces) throughout which are dispersed moisture and milk fat globules (Kaláb 1993). The buildup and rebodding of the FFC structure may be attributed to the progressive bonding of casein molecules at the boundary of adjacent quark gel particles and to their aggregation around the milk fat globules entrapped in the protein

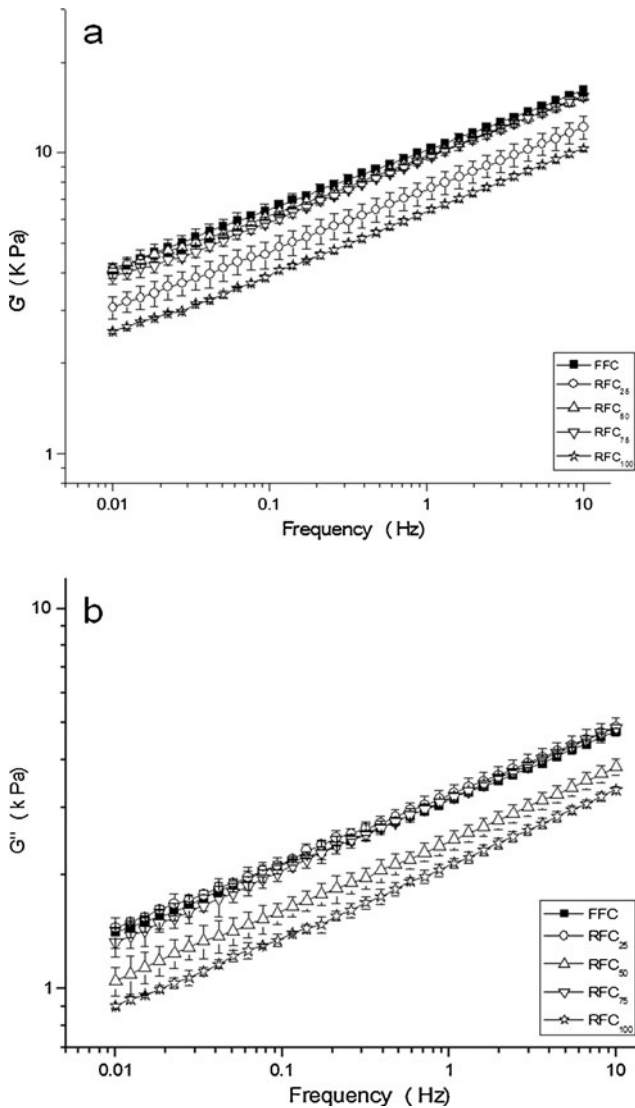


Fig. 6 Rheological properties of Petit-Suisse cheeses as a function of frequency after 7 days of storage: **a** storage modulus G' and **b** loss modulus G''

network. In contrast, in the reduced fat experimental cheeses, the building blocks contributing to structure are increased by three elements by the partial substitution of MC by CC. The spatial distribution of the three components, i.e., casein gel particles, milk fat globules from MC, and CC hydrocolloid gel particles, and their relative concentrations determined the extent to which they interacted among themselves. The $\Delta G'$ and $\Delta G''$ results pinpoint that the ratio between MC and CC played a very important role in the buildup and rebodding of the RFC cheeses. When the MC to CC ratio was 0.50:0.50 or 0.25:0.75, i.e., RFC₅₀ or RFC₇₅, cheeses tended to exhibit a viscoelastic behavior that was very close to that displayed by the FFC cheese. In contrast, when this ratio was 0.75:0.25 or 1.0:0.0 when CC was completely

substituted by MC, i.e., RFC₂₅ or RFC₁₀₀, the experimental cheeses tended to show markedly lower viscoelastic behavior than the FFC cheese. Thus, it would seem that an appropriate balance between MC and CC is required for the secondary hydrocolloid gel particles and milk fat globules to act as active texturizer fillers and contribute to the development of a more closely packed structural arrangement, resulting in experimental cheeses with higher viscoelastic properties. Guinee and Hickey (2009) reported that one of the main roles of hydrocolloids in cream cheese was to form weak gels binding to the protein–protein–fat particles and thereby creating a particle network, and that a blend of hydrocolloids was best suited because of synergistic effects contributing to the elastic character of the final product.

To effectively characterize the rheological behavior of cheese, the viscoelastic properties should be determined over a wide range of frequencies (Steffe 1996). Both the G' (Figs. 5a and 6a) and G'' (Figs. 5b and 6b) of all the experimental cheeses in the considered frequency window were almost linear in a log-log plot, with G' greater than G'' . Differences in both G' and G'' were identified among most of the experimental cheeses. As the storage time increased from 1 to 7 days, all the experimental cheeses suffered a significant increase in G' and G'' values. The observed difference in $\Delta G'$ and $\Delta G''$ was dependent on the composition of the experimental cheese. Table 3 shows the values of G' and G'' at 1 Hz for the experimental cheeses aged 1 and 7 days. The increase in $\Delta G'$ was lowest for RFC₁₀₀ (1.1 kPa) followed in increasing order by RFC₂₅ (3.8 kPa) < RFC₇₅ (4.7 kPa) < RFC₅₀ (5.3 kPa) = FFC (5.3 kPa). The increase in $\Delta G''$ was as follows: RFC₁₀₀ (0.2 kPa) < RFC₂₅ (1.0 kPa) < RFC₇₅ (1.4 kPa) < FFC (1.5 kPa) < RFC₅₀ (1.7 kPa). These results confirm the assumption made from the analysis of the G' values exhibited by the cheeses in the LVR, in that structure buildup and rebodding proceeds to a larger extent in the RFC which possessed a suitable balance between MC and CC, and that this restructuring is very close to that undergone by the FFC.

3.5 Sensory evaluation

The mean overall acceptability scores of the experimental cheeses by the consumer panel are shown in Table 1. The FFC had the highest overall acceptability score (4.4) which was not significantly different from those of RFC₅₀ (4.0) and RFC₇₅ (3.8), meaning that these experimental cheeses were moderately to extremely liked. In contrast, the RFC₂₅ and RFC₁₀₀ cheeses showed significantly lower overall

Table 3 Values of the storage (G') and loss (G'') moduli of the Petit-Suisse cheeses (means \pm SD) determined at 1 Hz by frequency sweep test

Cheese code	G' (1 day) (kPa)	G'' (1 day) (kPa)	G' (7 days) (kPa)	G'' (7 days) (kPa)
FFC	5.0 \pm 0.1 ^{ab}	1.7 \pm 0.1 ^{ab}	10.3 \pm 0.5 ^a	3.2 \pm 0.1 ^a
RFC ₂₅	4.3 \pm 0.0 ^c	1.5 \pm 0.1 ^c	8.2 \pm 0.2 ^b	2.5 \pm 0.2 ^b
RFC ₅₀	4.6 \pm 0.1 ^{bc}	1.6 \pm 0.0 ^{bc}	9.9 \pm 0.6 ^a	3.3 \pm 0.2 ^a
RFC ₇₅	5.0 \pm 0.1 ^{ab}	1.7 \pm 0.1 ^{ab}	9.7 \pm 0.2 ^a	3.2 \pm 0.1 ^a
RFC ₁₀₀	5.4 \pm 0.2 ^a	1.9 \pm 0.1 ^a	6.5 \pm 0.2 ^c	2.1 \pm 0.1 ^b

Different letters within the same column indicate that the means differ significantly ($P \leq 0.05$)

acceptability scores (3.3 and 2.8, respectively) in comparison to the FFC cheese, meaning that they were neither liked nor disliked by the consumer panel. The sensory evaluation results were closely interrelated to the changes undergone in $\Delta G'$ and $\Delta G''$ with aging time. A linear regression model ($P \leq 0.01$) was obtained which estimates the overall acceptability scores of the experimental cheeses as a function of $\Delta G'$ and $\Delta G''$ occurring either under strain or frequency sweeps:

$$\begin{aligned} \text{Cheese overall acceptability} = & 0.88\Delta G'(\text{strain}) + 6.27\Delta G'(\text{frequency}) \\ & - 21.36\Delta G''(\text{frequency}) \end{aligned}$$

This model fitted well the experimental data explaining 99.79% of the variability in acceptability.

4 Conclusions

This work established that it is possible to formulate reduced-fat Petit-Suisse cheeses where milk cream (i.e., milk fat globules) was partially substituted by a whey protein isolate–low-methoxyl pectin complex coacervate, displaying dynamic rheological properties and overall sensory acceptability similar to that of a full-fat Petit-Suisse cheese. An adequate balance between the milk cream and the complex coacervate was required for the secondary hydrocolloid gel particles and milk fat globules to develop a more closely packed structural arrangement, leading to a mechanical–sensory response resembling that of the full-fat cheese counterpart.

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