



Tomas Bata University in Zlín  
Library

## Furcellaran as a substitute for emulsifying salts in processed cheese spread and the resultant storage changes

---

### Citation

KŮROVÁ, Vendula, Richardos-Nicolaos SALEK, Michaela ČERNÍKOVÁ, Eva LORENCOVÁ, Ludmila ZÁLEŠÁKOVÁ, and František BUŇKA. Furcellaran as a substitute for emulsifying salts in processed cheese spread and the resultant storage changes. *International Journal of Dairy Technology* [online]. vol. 75, iss. 3, John Wiley and Sons Inc, 2022, p. 679 - 689 [cit. 2023-11-09]. ISSN 1364-727X. Available at <https://onlinelibrary.wiley.com/doi/10.1111/1471-0307.12871>

### DOI

<https://doi.org/10.1111/1471-0307.12871>

### Permanent link

<https://publikace.k.utb.cz/handle/10563/1010957>

---

This document is the Accepted Manuscript version of the article that can be shared via institutional repository.



**TBU Publications**

Repository of TBU Publications

[publikace.k.utb.cz](https://publikace.k.utb.cz)

# Furcellaran as a substitute for emulsifying salts in processed cheese spread and the resultant storage changes

Vendula Kůrová<sup>1</sup>, Richardos Nikolaos Salek,<sup>1,\*</sup> Michaela Černíková,<sup>1</sup> Eva Lorencová,<sup>1</sup> Ludmila Zálešáková<sup>1</sup> and František Buňka<sup>2</sup>

<sup>1</sup>*Department of Food Technology, Faculty of Technology, Tomas Bata University in Zlín, T.G. Masaryka 5555, Zlín 76001*

<sup>2</sup>*Department of Logistics, Faculty of Military Leadership, Food Research Laboratory, University of Defence, Kounicova 65, Brno 66210 Czech Republic*

*\*Author for correspondence: E-mail: rsalek@utb.cz*

The viscoelastic properties of processed cheese spread (PCS; dry matter 40% w/w, fat in dry matter 55% w/w) produced with various levels (0.10, 0.25, 0.50, 0.75 and 1.00% w/w) of two types of furcellaran (FA or FB), with and without the use of emulsifying salts (ES), were evaluated. The incremental higher levels of furcellaran application, irrespective of its type, increased the values of viscoelastic moduli. Processed cheese spread samples produced without the addition of ES showed higher rigidity. The type and concentration of furcellaran, the presence/absence of ES and storage time had a significant effect on the viscoelastic properties of PCS.

**Keywords:** Processed cheese, furcellaran, emulsifying salts, rheology, storage period

## INTRODUCTION

Processed cheese (PC) and processed cheese spread (PCS) are cheese-based food products manufactured by mixing, shearing and emulsifying natural cheese(s), of varying ages, in the presence of suitable emulsifying salts (ES). Furthermore, dairy (e.g. cream, butter, anhydrous milk fat and various milk powder mixtures) and nondairy (e.g. stabilisers, preservatives, acidifying agents and NaCl) ingredients are used according to the final product property requirements (**Kapoor and Metzger 2008; Guinee 2017; Solowiej et al. 2020**). Emulsifying salts, such as sodium salts of phosphates and citrates (or their combination), are an essential part of 'conventional' PC products, since they allow the formation of a smooth and homogeneous consistency of cheese through (i) calcium sequestration from the calcium paracaseinate phosphate matrix present in natural cheese (displacing  $\text{Ca}^{2+}$  with  $\text{Na}^+$ ) and (ii) pH adjustment.

In addition, the functions of ES mentioned above (in conjunction with heating and mixing) lead to peptisation, hydration and dispersion of the proteins present in the cheese matrix. This allows casein to exert its emulsifying ability, and hence, a stable oil-in-water emulsion is formed (**Gupta et al. 1984; Dimitreli and Tho-mareis 2009; Weiserova et al. 2011**). Furthermore, many factors are known to influence the consistency of PC products, which are as follows: (i) raw material composition (inclusive of the presence of hydrocolloids and/or ES), (ii) production parameters and (iii) storage conditions (e.g. storage temperature and period) (**Kapoor and Metzger 2008; Černíková et al. 2017**).

Hydrocolloids are long-chain biopolymers (polysaccharides or proteins) able to form viscous dispersions and gels. Therefore, they are applied as gelling or thickening agents and emulsion (oil-in-water) stabilisers during food processing (**Dickinson 2009; Saha and Bhattacharya 2010**). Furcellaran (so-called 'Danish agar' or 'under-sulphated K-carrageenan') derived from *Furcellaria lumbicalis* belongs to the red algae galactans, which are basically sulphated polysaccharides that usually have a linear backbone built up of alternating 3-linked  $\beta$ -D-galactopyranose and 4-linked  $\alpha$ -galactopyranose residues. Furthermore, a substantial part of a-galactose is present in the form of a 3,6-anhydro derivative and various hydroxyl groups may be substituted by ester sulphate or methyl groups (Tuvikene et al. 2008). In particular, furcellaran is structurally very similar to K-carrageenan (contains only 16-20% ester sulphate compared with 22% for k-carrageenan). However, the individual types of carrageenan and furcellaran vary in their 3,6-anhydrogalactose and sulphate contents. Nevertheless, although skeletal changes are minor, they can lead to changes in the polysaccharide gel properties (e.g. the solubility, gel strength, texture, melting and setting temperatures; **Imeson 2009**). On the contrary, all of these red algae galactans are widely used in the dairy industry in order to stabilise, thicken and gel a wide range of dairy products (e.g. PCS, puddings, milkshakes, ice cream mixes and ready-to-eat desserts; **Imeson 2009; Saha and Bhattacharya 2010**).

Although ES are applied in relatively low amounts (up to 3% w/w) during the production of PC-like products (**Kapoor and Metzger 2008**), their addition causes the calcium-to-phosphorus ratio to decrease from 1.0:1.2 to 1.0:1.5–3.0. Thus, the latter may impair the absorption and physiological activity of calcium incorporated in PC-like products (**Schäffer et al. 1999; Micmski et al. 2013**). The possible substitution of ES (partial or total) could also provide an opportunity to reduce sodium and phosphorus content (**Schäffer et al. 2001; Johnson et al. 2009; Černíková et al. 2010**). Consumption of a high amount of sodium (>4000 mg/d; especially the elderly) in human nutrition is considered a risk factor for numerous diseases (hypertension and cardiovascular ailments; **Mente et al. 2021**). Moreover, excessive consumption (>4000 mg/day for all age groups) of phosphorus in individuals with chronic kidney disease has been associated with hyperphosphataemia (occurrence of elevated concentration of phosphate in the blood). Hyper-phosphataemia is generally associated with complications of bone mineral metabolism and, in some cases, with mortality (Uribarri and Calvo 2013; Abdo et al. 2021). Therefore, for some individuals (from a consumer point of view), ES could be considered an 'unsuitable/undesirable' ingredient of PC or PCS-like products (if applied at levels higher than 2.5% w/w); however, the reduction in ES concentration could result in an unstable final product having a nonhomogeneous matrix (Hoffmann and Schrader 2015). Very few studies have dealt with partial (Ahmad et al. 2016) or total (**Schäffer et al. 1999, 2001; Černíková et al. 2010**) replacement of ES using hydrocolloids in PC products. In addition, a recent study also dealt with the application of hydrocolloids as stabilisers for a new spreadable processed whey cheese (**Chatziantoniou et al. 2019**). However, no study describing the application of furcellaran in PCS or its use as an ES replacement has yet been reported in literature.

Therefore, the objective of the current study was to evaluate the effect of furcellaran (of two types) used at varying levels (0.10 to 1.00% w/w; a total of 5 levels) on the viscoelastic properties of PCS produced with or without the use of traditional phosphate-based ES just after production and during a storage period of 60 days (at  $6 \pm 2^\circ\text{C}$ ).

## MATERIALS AND METHODS

### *Materials*

In this experiment, two types of furcellaran (supplied by Est-agar a.s., Karla village, Estonia) with different properties were tested: Estgel 8500 [FA;  $M_w$   $2.95 \times 10^3$  Da; water gel strength of Bloom 420 g (2.5% furcellaran; trigger 4.5 g, deformation 15.0 mm and speed  $0.4 \text{ mm} \times \text{s}^{-1}$ ); pH 8.18 (1.0% aqueous solution at 25°C); and 6.0% moisture] and Estgel 1000 [FB;  $M_w$   $2.55 \times 10^3$  Da; water gel strength of Bloom 480 g (test parameters same as for Bloom 420 g); pH 8.30 (1.0% aqueous solution at 25°C); and 9.7% moisture]. Furthermore, for PCS sample preparation, Edam cheese blocks [50% dry matter (DM); 30% fat in DM (FDM); and 7-week maturity] from the same batch were used (Kromilk, a.s., Kroměříž, Czech Republic). Table butter (84% w/w DM, 82% w/w fat content) was provided by Madeta a.s. (České Budějovice, Czech Republic). Finally, all applied ES [monosodium phosphate ( $\text{NaH}_2\text{PO}_4$ ; MSP), disodium hydrogen phosphate ( $\text{Na}_2\text{HPO}_4$ ; DSP), tetrasodium diphosphate ( $\text{Na}_4\text{P}_2\text{O}_7$ ; TSPP) and sodium salt of polyphosphate having the chain length  $n \approx 20$  (P20)] were purchased from Fosfa a.s. (Břeclav, Czech Republic).

### *Manufacture of processed cheese spread samples*

Two model groups of PCS were produced: (i) with the addition of ES blend (MSP:DSP:TSPP:P20 at a ratio of 1.9:1.6:1.4:1.4; used at a rate of 3.0% w/w of the total weight of the melt) and furcellaran (FA or FB; levels of each were 0.10, 0.25, 0.50, 0.75 and 1.00% w/w), and (ii) without the use of ES, but applying FA or FB at the same rates as specified for (i). A control sample (CS) was prepared as for (i) utilising ES at the same rate and avoiding the use of hydrocolloid. All model samples were designed to have DM 40.0% w/w and FDM 55.0% w/w. Furthermore, Edam cheese (7-week maturity) and table butter were cut into small pieces (20 x 20 x 20 mm) and disintegrated (at 2750 g) in Stephan UMC-5 equipment with an indirect heating system (Stephan Machinery GmbH, Hamelin, Germany). Subsequently, the remaining ingredients (water, ES and/or hydrocolloids) were added into the Stephan cooker. The quantity of PCS produced ranged between 1188.6 and 1196.7 g per batch. The PCS samples were processed at the melting temperature of 90°C for 1 min (at 3000 rpm, under partial vacuum of 20 kPa); the total processing period was 8-10 min. The hot molten mass ( $90 \pm 2^\circ\text{C}$ ) was transferred into polypropylene pots (thickness of 0.82 mm) with sealable aluminium lids. The samples were left to cool down and then stored at  $6 \pm 2^\circ\text{C}$  for a period of 60 days. Basic chemical analysis and viscoelastic property determination of the PCS samples were performed on the 1st, 7th, 14th, 30th and 60th day of storage.

### *Basic chemical analysis*

The DM content and the fat content of PCS were determined according to ISO 5534 (ISO 2004a; 2004b). The results are the mean value of three measurements ( $n = 3$ ). For the pH determination, a pH meter (pHspear, Eutech Instruments, Oakton, Malaysia) with a tip glass electrode was used. The pH evaluation was performed by direct insertion of the electrode into the sample at ambient temperature ( $22 \pm 1^\circ\text{C}$ ). Each PCS sample was measured at least six times ( $n = 6$ ).

### *Dynamic oscillatory rheology*

An oscillatory shear rheometer (HAAKE RheoStress 1, Thermo Scientific™, Bremen, Germany) with a parallel-plate geometry (diameter 35.0 mm, gap 1.0 mm) was employed to measure the viscoelastic properties of the model PCS samples. Before analysis, the apparatus and the PCS samples to be tested were tempered to  $20.0 \pm 0.1$  °C. Furthermore, in order to prevent sample dehydration, the exposed edge of the parallel-plate geometry was covered with a thin layer of silicone oil. The measurement was performed in the oscillating mode within the region of linear viscoelasticity with a shear stress amplitude value of 20 Pa and a frequency ranging from 0.1 to 100.0 Hz. The storage modulus ( $G'$ ; Pa) and loss modulus ( $G''$ ; Pa) were determined as a function of frequency  $f$  (Hz). In addition, the values of the phase-shift angle tangent ( $\tan \delta$ ; dimensionless) and the complex modulus ( $G^*$ , Pa) were determined as per the Eqns (1) and (2), respectively.

$$\tan \delta = G'' / G' \quad (1)$$

$$G^* = \sqrt{(G')^2 + (G'')^2} \quad (2)$$

The frequency of 1.0 Hz was selected as the reference value for the  $G'$ ,  $G''$ ,  $\tan \delta$ ,  $G^*$  data and complex viscosity ( $\eta^*$ ) presentation. All measurements were performed in triplicate for each model PCS sample ( $n = 3$ ).

### *Statistical analysis*

The data obtained were analysed using the Kruskal-Wallis and the Wilcoxon tests (Minitab® 16 software; Minitab Ltd., Coventry, UK) and evaluated at a significance level of 0.05.

## **RESULTS AND DISCUSSION**

### *Proximate composition of the processed cheese spread samples*

To allow comparison of the developed model samples developed in terms of furcellaran addition, it was necessary to maintain the basic chemical parameters (DM and FDM) of the PCS samples in close proximity to each other, since these factors can substantially affect their viscoelastic properties (Černíková et al. 2017). The fat content ranged (regardless of the presence of furcellaran and/or addition of ES) from 22.50 to 22.90% w/w, while the DM content of all samples ranged from 41.00 to 41.75% w/w during the entire experiment. The results of the pH measurements (**Table 1**) were comparable for the individual groups of samples on specified storage days, whereas the pH values of the model samples produced without ES were lower ( $P \leq 0.05$ ; compared with those produced utilising ES). The explanation for the above-mentioned difference in the pH values of PCS samples could manifest in the absence of ES, since the addition of a suitable combination of phosphate ES could lead to an increase (and stabilisation) in pH (to the optimal range; 5.6-6.1) from the original pH (5.0-5.5) of the natural cheese used as the predominant raw material (Marches-seau et al. 1997; Lee and Klostermeyer 2001; Guinee 2017). The obtained results of pH values of PCS in the current investigation are in accordance with those previously reported by Buňka et al. (2014).

Moreover, over the 60-day storage period, the pH of all model cheese samples decreased significantly ( $P \leq 0.05$ ; to pH of 5.35 for PCS with ES addition, and to pH of 5.22 for PCS without using ES; **Table 1**). In particular, a more intensive pH value decrease was recorded over the first 7 days of storage ( $P < 0.05$ ; **Table 1**). The decrease in the pH values of the 'conventional' PCS is primarily caused by the hydrolysis of phosphate ES (with two and more phosphorus atoms) during the processing and storage (**Gupta et al. 1984; Dimitreli and Thomareis 2009; Weiserová et al. 2011; Salek et al. 2015**). Hydrolysis of ES is mainly caused by the processing (at suitable temperature and pH conditions). Moreover, hydrolysis of phosphate-based ES occurs through the nucleophilic attack of water on the terminal phosphate unit, which results in the breaking of the P-O-P (phosphorus-oxygen-phosphorus) bond and the formation of monophosphates. The above-mentioned phenomenon continues during processed cheese storage. At lower pH ( $\approx 5.2$ ) of PC-like products, the hydrolysis of ES is promoted (**Barth et al. 2017**). However, the pH of PCS produced in the absence of ES was even lower than that with ES addition. Certain fluctuations in the pH values were observed in PCS made without using ES (**Table 1**), which might be due to the lack of the buffering capacity (particularly monophosphates) in PCS devoid of ES (**Guinee 2017**). According to **Marchesseau et al. (1997)** and **Lee and Klostermeyer (2001)**, a decrease in the pH values (beyond the optimal pH range determined, viz. 5.6–6.1) can lead to intense interactions in the PC protein matrix, and therefore, a firm and friable PCS product consistency might be expected.

#### *Dynamic oscillatory rheometry*

The results of dynamic oscillation rheometry measurements for the reference frequency of 1.0 Hz are illustrated in **Tables 2** and **3**. According to the data obtained ( $G'$ ,  $G''$ ,  $\tan \delta$  and  $\eta^*$ ), the addition of FA or FB at levels ranging from 0.10 to 1.00% w/w influenced the viscoelastic properties of the PCS samples significantly ( $P < 0.05$ ). The rising level of FA and FB (from 0.10 to 1.00% w/w; each type of hydrocolloid was individually applied in each PCS lot) led to the progressive increase in the  $G'$  and  $G''$  values (regardless of ES addition) due to furcellaran-milk protein (casein micelle) interactions leading to the formation of a three-dimensional network (**Imeson 2009**), which resulted in higher rigidity of the product. Moreover, 19 of 20 tested PCS samples produced with FA and FB addition displayed an elastic-like behaviour ( $G'' < G'$ ) typical for viscoelastic gels (**Saha and Bhattacharya 2010**). With an increasing level of FA and FB (individually applied in each PCS lot), more intensive interactions between the furcellaran chains and milk protein resulted in the creation of a more 'intensive' network in the PCS matrix (**Černíková et al. 2008; Ahmad et al. 2016**). When employing K-carrageenan in PC (most structurally similar to furcellaran), polysaccharide—milk protein interactions (namely the interaction between the sulphate groups of K-carrageenan and a positively charged region of K-casein) have been reported. However, the gel network in the presence of milk proteins appeared to be primarily developed by carrageenan interactions, so the K-carrageenan—milk protein interactions could be responsible for network strengthening (especially at low concentrations, viz. 0.03% of K-carrageenan; **Langendorff et al. 2000; Arltoft et al. 2007; Olivares et al. 2010**). A similar type of polysaccharide-casein interaction could also be expected when using furcellaran in the PCS system. These results were also confirmed by the increasing values of the  $G^*$  modulus in the PCS samples (data given as a function of the storage time; **Figures 1 and 2**) and  $\eta$  values, and a decreasing value of  $\tan \delta$  (**Tables 2 and 3**).

**Table 1** Changes in the pH values of processed cheese spread manufactured with different types (FA, FB) and levels of furcellaran, with and without the addition of emulsifying salts as influenced by storage ( $6 \pm 2^\circ\text{C}$ ) period.1

Furcellaran type/ concentration (% w/w)	Without emulsifying salts					With emulsifying salts				
	Storage time									
	1	7	14	30	60	1	7	14	30	60
CS	—	—	—	—	—	5.81 $\pm$ 0.02 <sup>AA</sup>	5.79 $\pm$ 0.01 <sup>AA</sup>	5.72 $\pm$ 0.02 <sup>AA</sup>	5.59 $\pm$ 0.01 <sup>AA</sup>	5.35 $\pm$ 0.02 <sup>AB</sup>
FA/0.10	5.84 $\pm$ 0.01 <sup>AAB</sup>	5.54 $\pm$ 0.01 <sup>AC</sup>	5.51 $\pm$ 0.01 <sup>AC</sup>	5.51 $\pm$ 0.01 <sup>AC</sup>	5.22 $\pm$ 0.01 <sup>AD</sup>	6.05 $\pm$ 0.01 <sup>AA</sup>	5.73 $\pm$ 0.01 <sup>ABC</sup>	5.71 $\pm$ 0.01 <sup>ABC</sup>	5.53 $\pm$ 0.01 <sup>AC</sup>	5.37 $\pm$ 0.01 <sup>ACD</sup>
FA/0.25	5.83 $\pm$ 0.01 <sup>AAB</sup>	5.52 $\pm$ 0.01 <sup>ACD</sup>	5.50 $\pm$ 0.01 <sup>ACD</sup>	5.50 $\pm$ 0.01 <sup>ACD</sup>	5.33 $\pm$ 0.02 <sup>AD</sup>	6.02 $\pm$ 0.01 <sup>AA</sup>	5.70 $\pm$ 0.01 <sup>ABC</sup>	5.70 $\pm$ 0.02 <sup>ABC</sup>	5.50 $\pm$ 0.01 <sup>ACD</sup>	5.38 $\pm$ 0.01 <sup>AD</sup>
FA/0.50	5.81 $\pm$ 0.01 <sup>AAB</sup>	5.51 $\pm$ 0.02 <sup>ACD</sup>	5.49 $\pm$ 0.02 <sup>ACD</sup>	5.49 $\pm$ 0.02 <sup>ACD</sup>	5.32 $\pm$ 0.01 <sup>AD</sup>	6.03 $\pm$ 0.01 <sup>AA</sup>	5.72 $\pm$ 0.00 <sup>ABC</sup>	5.66 $\pm$ 0.02 <sup>ABC</sup>	5.52 $\pm$ 0.00 <sup>ACD</sup>	5.39 $\pm$ 0.01 <sup>AD</sup>
FA/0.75	5.79 $\pm$ 0.02 <sup>AAB</sup>	5.53 $\pm$ 0.01 <sup>ABCD</sup>	5.50 $\pm$ 0.01 <sup>ABCD</sup>	5.50 $\pm$ 0.01 <sup>ABCD</sup>	5.33 $\pm$ 0.01 <sup>AC</sup>	6.02 $\pm$ 0.01 <sup>AA</sup>	5.72 $\pm$ 0.00 <sup>AB</sup>	5.68 $\pm$ 0.03 <sup>ABD</sup>	5.52 $\pm$ 0.00 <sup>ABD</sup>	5.39 $\pm$ 0.01 <sup>ACD</sup>
FA/1.00	5.73 $\pm$ 0.01 <sup>AAB</sup>	5.54 $\pm$ 0.01 <sup>ABD</sup>	5.50 $\pm$ 0.01 <sup>ABC</sup>	5.50 $\pm$ 0.01 <sup>ABC</sup>	5.23 $\pm$ 0.01 <sup>AC</sup>	6.02 $\pm$ 0.01 <sup>AA</sup>	5.71 $\pm$ 0.01 <sup>AB</sup>	5.68 $\pm$ 0.03 <sup>ABD</sup>	5.51 $\pm$ 0.01 <sup>ABC</sup>	5.38 $\pm$ 0.01 <sup>ACD</sup>
FB/0.10	5.78 $\pm$ 0.02 <sup>AA</sup>	5.61 $\pm$ 0.02 <sup>AAABC</sup>	5.50 $\pm$ 0.01 <sup>AAABC</sup>	5.50 $\pm$ 0.01 <sup>AAABC</sup>	5.27 $\pm$ 0.03 <sup>AC</sup>	5.83 $\pm$ 0.02 <sup>AA</sup>	5.76 $\pm$ 0.02 <sup>AA</sup>	5.68 $\pm$ 0.01 <sup>ABD</sup>	5.53 $\pm$ 0.02 <sup>ABC</sup>	5.39 $\pm$ 0.04 <sup>ACD</sup>
FB/0.25	5.68 $\pm$ 0.02 <sup>AAB</sup>	5.57 $\pm$ 0.01 <sup>ABD</sup>	5.52 $\pm$ 0.01 <sup>ABC</sup>	5.52 $\pm$ 0.01 <sup>ABC</sup>	5.27 $\pm$ 0.07 <sup>AC</sup>	5.85 $\pm$ 0.01 <sup>AA</sup>	5.74 $\pm$ 0.01 <sup>AAB</sup>	5.70 $\pm$ 0.02 <sup>AAB</sup>	5.57 $\pm$ 0.01 <sup>ABD</sup>	5.37 $\pm$ 0.02 <sup>ACD</sup>
FB/0.50	5.64 $\pm$ 0.01 <sup>AAB</sup>	5.55 $\pm$ 0.01 <sup>AABC</sup>	5.49 $\pm$ 0.01 <sup>ABC</sup>	5.49 $\pm$ 0.01 <sup>ABC</sup>	5.24 $\pm$ 0.07 <sup>AC</sup>	5.80 $\pm$ 0.01 <sup>AA</sup>	5.75 $\pm$ 0.01 <sup>AAB</sup>	5.62 $\pm$ 0.06 <sup>AABC</sup>	5.50 $\pm$ 0.01 <sup>ABC</sup>	5.35 $\pm$ 0.06 <sup>AC</sup>
FB/0.75	5.62 $\pm$ 0.01 <sup>AABD</sup>	5.56 $\pm$ 0.01 <sup>AABC</sup>	5.51 $\pm$ 0.01 <sup>ABC</sup>	5.51 $\pm$ 0.01 <sup>ABC</sup>	5.26 $\pm$ 0.06 <sup>AC</sup>	5.81 $\pm$ 0.01 <sup>AA</sup>	5.75 $\pm$ 0.01 <sup>AAB</sup>	5.64 $\pm$ 0.03 <sup>ABD</sup>	5.51 $\pm$ 0.01 <sup>ABC</sup>	5.36 $\pm$ 0.03 <sup>ACD</sup>
FB/1.00	5.62 $\pm$ 0.01 <sup>AABD</sup>	5.56 $\pm$ 0.01 <sup>AABC</sup>	5.50 $\pm$ 0.01 <sup>ABC</sup>	5.50 $\pm$ 0.01 <sup>ABC</sup>	5.29 $\pm$ 0.05 <sup>AC</sup>	5.82 $\pm$ 0.01 <sup>AA</sup>	5.77 $\pm$ 0.02 <sup>AAB</sup>	5.64 $\pm$ 0.02 <sup>ABD</sup>	5.54 $\pm$ 0.02 <sup>AABC</sup>	5.38 $\pm$ 0.04 <sup>ACD</sup>

CS, control sample; FA, furcellaran (Estgel 8500); FB, furcellaran (Estgel 1000).

<sup>1</sup>Values are expressed as the mean ( $n = 6$ )  $\pm$  standard deviation. Mean values followed by different superscript letters within the same column are statistically different ( $P < 0.05$ ). Mean values followed by different capital letter superscripts within the same row are statistically different ( $P < 0.05$ ).

However, PCS samples manufactured with FA at a 0.10% level presented higher viscosity-related properties ( $G'' > G'$ ;  $P < 0.05$ ; **Saha and Bhattacharya 2010**). The above-mentioned PCS sample was not significantly firmer when compared to CS (**Tables 2 and 3**;  $P < 0.05$ ). In addition, a similar effect has been reported for PC samples (with a DM content of 40% w/w, pH range of 5.88–5.95) made utilising 0.05% w/w of *K*-carrageenan and commercial ES (sodium salts of phosphates and polyphosphates; at a level of 2.0% w/w) where the effect on the rigidity was not clearly defined (Cernikova et al. 2008). Nevertheless, the required minimal concentration of such a hydrocolloid is probably affected by several factors including the pH and ionic environment in the cheese system (**Drohan et al. 1997; Bourriot et al. 1999; Schorsch et al. 2000; Černíková et al. 2008**), and therefore, it may be relatively difficult to precisely recommend the usage rate of hydrocolloid for PCS system. The viscoelastic properties of PCS were also affected by the type of furcellaran (viz. FA or FB;  $P < 0.05$ ) utilised, which corresponded to their inherent properties (mainly gel strength). FB usage led to increased firmness of the resultant PCS samples, even at the minimum level (i.e. 0.1% w/w) used. A firmer gel was obtained when utilising FB compared with FA (regardless of the presence of ES and length of storage) in most PCS samples (except PCS samples produced with 1.00% furcellaran addition on 1st storage day; **Tables 2 and 3**).

The current work additionally monitored the viscoelastic properties of PCS manufactured in the complete absence of ES, but utilising either FA or FB hydrocolloid as ES replacer. **Černíková et al. (2010)** previously reported that *K*-carrageenan and *l*-carrageenan could be possible substitutes for traditional ES in PC. The latter authors used sodium phosphate and polyphosphate ES (JOHA HBS, JOHA S9S and JOHA S4SS in a ratio 1:4:1) in their study. In all probability, the ability of carrageenans to replace the ES could be explained by the emulsifying properties of carrageenan-protein complexes (caused by hydrophilic carrageenans and hydrophobic casein fractions; **Černíková et al. 2010; Hladká et al. 2014**). In particular, a large increase in the viscosity of the aqueous phase or formation of gel structure can prevent the free movement of water and immobilisation of the emulsified fat globules (**Chatziantoniou et al. 2019**).

All the PCS samples manufactured in the absence of ES, but utilising the hydrocolloids (i.e. either FA or FB) at levels ranging from 0.10 to 1.00% w/w, appeared to be macroscopically homogeneous (there was no separation of any phase in any sample of PCS). Furthermore, according to **Tuvikene et al. (2008)** furcellaran gels present elastic properties and high gel strength. Generally, the PCS samples

manufactured without ES were found to be more rigid in comparison with those made utilising conventional ES (comparing samples with the same levels FA or FB, on the same storage day). The highest rigidity value was noted in PCS samples made using FB at 1.00% w/w rate, as noted at 60th day of storage (**Table 3; Figure 2b**). The latter finding is in accordance with the results previously reported by **Černíková et al. (2010)** and **Hladká et al. (2014)**, who used *K*-carrageenan as a total replacement for sodium phosphate and polyphosphate salts (JOHA HBS, JOHA S9S and JOHA S4SS in a ratio of 1:4:1; at levels of 2.00 and 2.50% w/w, respectively); however, the final products were characterised as 'very hard' and similar to PC blocks rather than spreadable products. In the case of a 'combination' of the emulsifying properties of casein (affected by the presence of ES) and polysaccharide-casein complexes (especially in the presence of FA and FB), finer dispersion of the milk fat in the protein matrix might have taken place leading to higher PC rigidity (**Shimp 1985; Lee et al. 2003; Kapoor and Metzger 2008; Černíková et al. 2017**) in the PCS samples made utilising both ES and polysaccharide. Moreover, it is construed that gel formation during the cooling period differs in PC with the addition of both traditional ES and hydrocolloid, as compared to PC samples in which the ES was totally replaced by the tested hydrocolloid (**Černíková et al. 2010**). However, an increase in the G values was observed in both of the examined sample groups; such an increase in G values was higher ( $P < 0.05$ ) for samples in which ES were replaced by the examined polysaccharide. Based on these results, some antagonistic effects of interaction between ES and furcellaran took place eventually during the formation of the PCS matrix.



**Table 2** Storage modulus ( $G'$ ), loss modulus ( $G''$ ), tangent of the phase-shift angle ( $\tan \delta$ ) and complex viscosity ( $\eta^*$ ) for the reference frequency of 1 Hz in processed cheese spread manufactured with various types (FA and FB) and levels (0.10, 0.25, 0.50, 0.75 and 1.00% w/w) of furcellaran in the presence of emulsifying salts as influenced by storage ( $6 \pm 2^\circ\text{C}$ ) period.1

Storage period (days)	Furcellaran type	Levels (% w/w)	$G'$ (Pa)	$G''$ (Pa)	$\tan \delta$ (-)	$\eta^*$ (Pa s)
1	None	CS	432 $\pm$ 92 <sup>a</sup>	452 $\pm$ 66 <sup>a</sup>	1.0463 <sup>a</sup>	100 $\pm$ 18 <sup>a</sup>
	FA	0.10	686 $\pm$ 25 <sup>b</sup>	646 $\pm$ 23 <sup>b</sup>	1.0292 <sup>a</sup>	150 $\pm$ 28 <sup>b</sup>
	FA	0.25	1214 $\pm$ 33 <sup>c</sup>	1019 $\pm$ 45 <sup>c</sup>	0.8390 <sup>b</sup>	252 $\pm$ 22 <sup>c</sup>
	FA	0.50	3452 $\pm$ 58 <sup>d</sup>	2150 $\pm$ 52 <sup>d</sup>	0.6228 <sup>c</sup>	647 $\pm$ 56 <sup>d</sup>
	FA	0.75	4021 $\pm$ 45 <sup>e</sup>	2309 $\pm$ 33 <sup>d</sup>	0.5742 <sup>d</sup>	738 $\pm$ 44 <sup>d</sup>
	FA	1.00	8140 $\pm$ 65 <sup>f</sup>	3770 $\pm$ 78 <sup>e</sup>	0.4633 <sup>e</sup>	1428 $\pm$ 64 <sup>e</sup>
	FB	0.10	760 $\pm$ 21 <sup>b</sup>	692 $\pm$ 36 <sup>b</sup>	0.9111 <sup>b</sup>	164 $\pm$ 45 <sup>b</sup>
	FB	0.25	1584 $\pm$ 35 <sup>g</sup>	1193 $\pm$ 41 <sup>f</sup>	0.7531 <sup>f</sup>	316 $\pm$ 65 <sup>c</sup>
	FB	0.50	2718 $\pm$ 68 <sup>h</sup>	1683 $\pm$ 25 <sup>g</sup>	0.6192 <sup>c</sup>	509 $\pm$ 45 <sup>f</sup>
	FB	0.75	5537 $\pm$ 47 <sup>i</sup>	2821 $\pm$ 45 <sup>h</sup>	0.5094 <sup>g</sup>	989 $\pm$ 68 <sup>g</sup>
7	None	CS	487 $\pm$ 25 <sup>a</sup>	503 $\pm$ 78 <sup>a</sup>	1.0337 <sup>a</sup>	111 $\pm$ 18 <sup>a</sup>
	FA	0.10	490 $\pm$ 21 <sup>a</sup>	476 $\pm$ 29 <sup>a</sup>	0.9721 <sup>b</sup>	129 $\pm$ 6 <sup>a</sup>
	FA	0.25	739 $\pm$ 28 <sup>b</sup>	639 $\pm$ 11 <sup>b</sup>	0.8647 <sup>c</sup>	156 $\pm$ 5 <sup>b</sup>
	FA	0.50	1670 $\pm$ 76 <sup>c</sup>	1132 $\pm$ 65 <sup>c</sup>	0.6779 <sup>d</sup>	321 $\pm$ 29 <sup>c</sup>
	FA	0.75	3400 $\pm$ 126 <sup>d</sup>	1860 $\pm$ 108 <sup>d</sup>	0.5470 <sup>e</sup>	617 $\pm$ 102 <sup>d</sup>
	FA	1.00	5826 $\pm$ 214 <sup>e</sup>	2699 $\pm$ 195 <sup>e</sup>	0.4632 <sup>f</sup>	1022 $\pm$ 141 <sup>e</sup>
	FB	0.10	813 $\pm$ 21 <sup>b</sup>	724 $\pm$ 18 <sup>f</sup>	0.8913 <sup>c</sup>	173 $\pm$ 5 <sup>f</sup>
	FB	0.25	2333 $\pm$ 148 <sup>f</sup>	1540 $\pm$ 87 <sup>g</sup>	0.6602 <sup>d</sup>	445 $\pm$ 12 <sup>g</sup>
	FB	0.50	4578 $\pm$ 235 <sup>g</sup>	2345 $\pm$ 145 <sup>e</sup>	0.5123 <sup>g</sup>	819 $\pm$ 21 <sup>h</sup>
	FB	0.75	5543 $\pm$ 256 <sup>e</sup>	2644 $\pm$ 189 <sup>e</sup>	0.4770 <sup>f</sup>	977 $\pm$ 18 <sup>e</sup>
14	None	CS	519 $\pm$ 18 <sup>a</sup>	508 $\pm$ 20 <sup>a</sup>	1.0937 <sup>a</sup>	123 $\pm$ 1 <sup>a</sup>
	FA	0.10	526 $\pm$ 17 <sup>a</sup>	500 $\pm$ 65 <sup>a</sup>	0.9492 <sup>b</sup>	136 $\pm$ 3 <sup>b</sup>
	FA	0.25	904 $\pm$ 38 <sup>b</sup>	737 $\pm$ 25 <sup>b</sup>	0.8149 <sup>c</sup>	186 $\pm$ 12 <sup>c</sup>
	FA	0.50	2161 $\pm$ 65 <sup>c</sup>	1314 $\pm$ 12 <sup>c</sup>	0.6080 <sup>d</sup>	403 $\pm$ 8 <sup>d</sup>
	FA	0.75	3455 $\pm$ 185 <sup>d</sup>	1750 $\pm$ 117 <sup>d</sup>	0.5065 <sup>e</sup>	617 $\pm$ 14 <sup>e</sup>
	FA	1.00	5917 $\pm$ 124 <sup>e</sup>	2584 $\pm$ 85 <sup>e</sup>	0.4367 <sup>f</sup>	1028 $\pm$ 74 <sup>f</sup>
	FB	0.10	1014 $\pm$ 85 <sup>b</sup>	844 $\pm$ 29 <sup>f</sup>	0.8329 <sup>c</sup>	210 $\pm$ 5 <sup>c</sup>
	FB	0.25	2809 $\pm$ 145 <sup>f</sup>	1750 $\pm$ 127 <sup>d</sup>	0.6230 <sup>d</sup>	527 $\pm$ 8 <sup>g</sup>
	FB	0.50	4915 $\pm$ 169 <sup>g</sup>	2430 $\pm$ 235 <sup>e</sup>	0.4943 <sup>e</sup>	873 $\pm$ 14 <sup>h</sup>
	FB	0.75	5426 $\pm$ 241 <sup>h</sup>	2315 $\pm$ 214 <sup>e</sup>	0.4266 <sup>f</sup>	939 $\pm$ 21 <sup>f</sup>
30	None	CS	8754 $\pm$ 347 <sup>i</sup>	3512 $\pm$ 285 <sup>f</sup>	0.4012 <sup>g</sup>	1501 $\pm$ 38 <sup>i</sup>
	FA	0.10	698 $\pm$ 17 <sup>a</sup>	681 $\pm$ 2 <sup>a</sup>	0.9794 <sup>a</sup>	138 $\pm$ 2 <sup>a</sup>
	FA	0.25	734 $\pm$ 12 <sup>a</sup>	756 $\pm$ 25 <sup>b</sup>	1.0657 <sup>b</sup>	162 $\pm$ 8 <sup>b</sup>
	FA	0.50	943 $\pm$ 21 <sup>b</sup>	830 $\pm$ 01 <sup>c</sup>	0.8475 <sup>c</sup>	175 $\pm$ 5 <sup>b</sup>
	FA	0.75	2563 $\pm$ 47 <sup>c</sup>	1529 $\pm$ 65 <sup>d</sup>	0.5966 <sup>d</sup>	475 $\pm$ 12 <sup>c</sup>
	FA	1.00	3543 $\pm$ 87 <sup>d</sup>	1855 $\pm$ 11 <sup>e</sup>	0.5235 <sup>e</sup>	637 $\pm$ 21 <sup>d</sup>
	FA	1.00	6816 $\pm$ 102 <sup>e</sup>	2841 $\pm$ 29 <sup>f</sup>	0.4167 <sup>f</sup>	1175 $\pm$ 23 <sup>e</sup>
	FB	0.10	913 $\pm$ 45 <sup>b</sup>	776 $\pm$ 56 <sup>b</sup>	0.8495 <sup>c</sup>	191 $\pm$ 2 <sup>b</sup>
	FB	0.25	2439 $\pm$ 78 <sup>c</sup>	1592 $\pm$ 87 <sup>d</sup>	0.6528 <sup>g</sup>	464 $\pm$ 12 <sup>c</sup>
	FB	0.50	3008 $\pm$ 145 <sup>f</sup>	1472 $\pm$ 174 <sup>d</sup>	0.4896 <sup>h</sup>	551 $\pm$ 18 <sup>f</sup>
60	None	CS	9766 $\pm$ 103 <sup>g</sup>	4021 $\pm$ 205 <sup>g</sup>	0.4117 <sup>f</sup>	1681 $\pm$ 7 <sup>g</sup>
	FA	0.10	11 632 $\pm$ 247 <sup>h</sup>	4570 $\pm$ 304 <sup>g</sup>	0.3928 <sup>i</sup>	1992 $\pm$ 32 <sup>h</sup>
	FA	0.25	804 $\pm$ 84 <sup>a</sup>	726 $\pm$ 55 <sup>a</sup>	0.9029 <sup>a</sup>	196 $\pm$ 9 <sup>a</sup>
	FA	0.50	863 $\pm$ 23 <sup>a</sup>	766 $\pm$ 21 <sup>a</sup>	0.8536 <sup>b</sup>	209 $\pm$ 2 <sup>a</sup>
	FA	0.75	1137 $\pm$ 53 <sup>b</sup>	849 $\pm$ 23 <sup>b</sup>	0.7467 <sup>c</sup>	226 $\pm$ 5 <sup>a</sup>
	FA	0.75	3947 $\pm$ 45 <sup>c</sup>	2197 $\pm$ 84 <sup>c</sup>	0.5565 <sup>d</sup>	719 $\pm$ 11 <sup>b</sup>
	FA	0.75	4469 $\pm$ 57 <sup>d</sup>	2146 $\pm$ 78 <sup>c</sup>	0.4802 <sup>e</sup>	789 $\pm$ 12 <sup>c</sup>
	FB	1.00	11 632 $\pm$ 247 <sup>h</sup>	4570 $\pm$ 304 <sup>g</sup>	0.3928 <sup>i</sup>	1992 $\pm$ 32 <sup>h</sup>
	FB	1.00	11 632 $\pm$ 247 <sup>h</sup>	4570 $\pm$ 304 <sup>g</sup>	0.3928 <sup>i</sup>	1992 $\pm$ 32 <sup>h</sup>
	FB	1.00	11 632 $\pm$ 247 <sup>h</sup>	4570 $\pm$ 304 <sup>g</sup>	0.3928 <sup>i</sup>	1992 $\pm$ 32 <sup>h</sup>

Table 2 (Continued).

Storage period (days)	Furcellaran type	Levels (% w/w)	$G'$ (Pa)	$G''$ (Pa)	$\tan \delta$ (–)	$\eta^*$ (Pa s)
	FA	1.00	6723 $\pm$ 147 <sup>c</sup>	2788 $\pm$ 89 <sup>d</sup>	0.4147 <sup>f</sup>	1158 $\pm$ 6 <sup>d</sup>
	FB	0.10	2071 $\pm$ 52 <sup>f</sup>	1452 $\pm$ 124 <sup>e</sup>	0.7013 <sup>g</sup>	402 $\pm$ 36 <sup>e</sup>
	FB	0.25	7150 $\pm$ 147 <sup>g</sup>	3477 $\pm$ 214 <sup>f</sup>	0.4862 <sup>e</sup>	1266 $\pm$ 23 <sup>f</sup>
	FB	0.50	7401 $\pm$ 258 <sup>g</sup>	3270 $\pm$ 202 <sup>f</sup>	0.4418 <sup>h</sup>	1288 $\pm$ 21 <sup>g</sup>
	FB	0.75	11 729 $\pm$ 324 <sup>h</sup>	4727 $\pm$ 324 <sup>g</sup>	0.4030 <sup>f</sup>	2013 $\pm$ 3 <sup>h</sup>
	FB	1.00	17 342 $\pm$ 412 <sup>i</sup>	5903 $\pm$ 174 <sup>h</sup>	0.3404 <sup>i</sup>	2916 $\pm$ 17 <sup>i</sup>

CS, control sample; FA, furcellaran (Estgel 8500); FB, furcellaran (Estgel 1000).

<sup>i</sup>Values are expressed as the mean ( $n = 3$ )  $\pm$  SD. The means within a column (the difference between samples with type and varying levels of furcellaran) shown with differing superscript letters differ ( $P < 0.05$ ) from each other.

**Table 3** Values of the storage modulus ( $G'$ ), loss modulus ( $G''$ ) tangent of the phase-shift angle ( $\tan \delta$ ) and complex viscosity ( $\eta^*$ ) for the reference frequency of 1 Hz in processed cheese spread manufactured with various types (FA and FB) and levels (0.10, 0.25, 0.50, 0.75 and 1.00% w/w) of furcellaran to entirely replace emulsifying salts as influenced by refrigerated storage ( $6 \pm 2^\circ\text{C}$ ) period.1

Storage period (days)	Furcellaran type	Concentration (% w/w)	$G'$ (Pa)	$G''$ (Pa)	$\tan \delta$ (–)	$\eta^*$ (Pa s)
1	None	CS	432 $\pm$ 92 <sup>a</sup>	452 $\pm$ 66 <sup>a</sup>	1.0463 <sup>a</sup>	100 $\pm$ 18 <sup>a</sup>
	FA	0.10	2844 $\pm$ 130 <sup>b</sup>	892 $\pm$ 53 <sup>b</sup>	0.3136 <sup>b</sup>	474 $\pm$ 77 <sup>b</sup>
	FA	0.25	11 401 $\pm$ 1489 <sup>c</sup>	2934 $\pm$ 121 <sup>c</sup>	0.2573 <sup>c</sup>	1874 $\pm$ 105 <sup>c</sup>
	FA	0.50	23 762 $\pm$ 3793 <sup>d</sup>	5365 $\pm$ 861 <sup>d</sup>	0.2258 <sup>d</sup>	3877 $\pm$ 619 <sup>d</sup>
	FA	0.75	28 806 $\pm$ 1553 <sup>d</sup>	6366 $\pm$ 258 <sup>d</sup>	0.2210 <sup>d</sup>	4695 $\pm$ 250 <sup>d</sup>
	FA	1.00	41 595 $\pm$ 2196 <sup>e</sup>	8879 $\pm$ 492 <sup>e</sup>	0.2135 <sup>d</sup>	6769 $\pm$ 358 <sup>e</sup>
	FB	0.10	6125 $\pm$ 31 <sup>g</sup>	1985 $\pm$ 75 <sup>f</sup>	0.3241 <sup>b</sup>	994 $\pm$ 54 <sup>f</sup>
	FB	0.25	10 587 $\pm$ 57 <sup>c</sup>	2984 $\pm$ 96 <sup>c</sup>	0.2819 <sup>e</sup>	1697 $\pm$ 47 <sup>c</sup>
	FB	0.50	33 148 $\pm$ 3163 <sup>d</sup>	7322 $\pm$ 704 <sup>e</sup>	0.2209 <sup>d</sup>	5403 $\pm$ 516 <sup>d</sup>
	FB	0.75	42 504 $\pm$ 792 <sup>e</sup>	9086 $\pm$ 129 <sup>g</sup>	0.2138 <sup>d</sup>	6918 $\pm$ 1295 <sup>e</sup>
	FB	1.00	46 149 $\pm$ 854 <sup>e</sup>	10 108 $\pm$ 189 <sup>g</sup>	0.2190 <sup>d</sup>	7519 $\pm$ 139 <sup>e</sup>
7	None	CS	487 $\pm$ 25 <sup>a</sup>	503 $\pm$ 78 <sup>a</sup>	1.0337 <sup>a</sup>	111 $\pm$ 18 <sup>a</sup>
	FA	0.10	4285 $\pm$ 145 <sup>b</sup>	1358 $\pm$ 54 <sup>b</sup>	0.3169 <sup>b</sup>	715 $\pm$ 25 <sup>b</sup>
	FA	0.25	9397 $\pm$ 1237 <sup>c</sup>	2590 $\pm$ 224 <sup>c</sup>	0.2756 <sup>c</sup>	1551 $\pm$ 199 <sup>c</sup>
	FA	0.50	18 896 $\pm$ 4784 <sup>d</sup>	4426 $\pm$ 879 <sup>d</sup>	0.2342 <sup>d</sup>	3089 $\pm$ 773 <sup>d</sup>
	FA	0.75	23 809 $\pm$ 1900 <sup>d</sup>	5583 $\pm$ 525 <sup>d</sup>	0.2345 <sup>d</sup>	3892 $\pm$ 314 <sup>d</sup>
	FA	1.00	35 108 $\pm$ 383 <sup>e</sup>	7977 $\pm$ 64 <sup>e</sup>	0.2272 <sup>d</sup>	5730 $\pm$ 64 <sup>e</sup>
	FB	0.10	6925 $\pm$ 25 <sup>f</sup>	2058 $\pm$ 58 <sup>f</sup>	0.2972 <sup>e</sup>	1058 $\pm$ 18 <sup>f</sup>
	FB	0.25	11 997 $\pm$ 842 <sup>c</sup>	3152 $\pm$ 227 <sup>c</sup>	0.2627 <sup>c</sup>	1974 $\pm$ 139 <sup>g</sup>
	FB	0.50	20 118 $\pm$ 1726 <sup>d</sup>	4768 $\pm$ 442 <sup>d</sup>	0.2370 <sup>d</sup>	3291 $\pm$ 284 <sup>d</sup>
	FB	0.75	30 894 $\pm$ 19 <sup>g</sup>	7082 $\pm$ 61 <sup>f</sup>	0.2292 <sup>d</sup>	5044 $\pm$ 1 <sup>h</sup>
	FB	1.00	43 290 $\pm$ 622 <sup>h</sup>	7974 $\pm$ 46 <sup>f</sup>	0.2326 <sup>d</sup>	5603 $\pm$ 95 <sup>e</sup>
14	None	CS	519 $\pm$ 18 <sup>a</sup>	508 $\pm$ 20 <sup>a</sup>	1.0937 <sup>a</sup>	123 $\pm$ 1 <sup>a</sup>
	FA	0.10	3241 $\pm$ 250 <sup>b</sup>	1159 $\pm$ 79 <sup>b</sup>	0.3575 <sup>b</sup>	548 $\pm$ 42 <sup>b</sup>
	FA	0.25	9652 $\pm$ 578 <sup>c</sup>	2851 $\pm$ 111 <sup>c</sup>	0.2953 <sup>c</sup>	1602 $\pm$ 93 <sup>c</sup>
	FA	0.50	14 676 $\pm$ 379 <sup>d</sup>	3661 $\pm$ 63 <sup>d</sup>	0.2494 <sup>d</sup>	2407 $\pm$ 61 <sup>d</sup>
	FA	0.75	18 994 $\pm$ 435 <sup>e</sup>	4647 $\pm$ 68 <sup>e</sup>	0.2446 <sup>d</sup>	3112 $\pm$ 70 <sup>e</sup>
	FA	1.00	28 323 $\pm$ 124 <sup>f</sup>	6604 $\pm$ 12 <sup>f</sup>	0.2332 <sup>e</sup>	4629 $\pm$ 20 <sup>f</sup>
	FB	0.10	7386 $\pm$ 3097 <sup>c</sup>	2353 $\pm$ 793 <sup>c</sup>	0.3185 <sup>f</sup>	1234 $\pm$ 508 <sup>g</sup>
	FB	0.25	11 404 $\pm$ 1187 <sup>c</sup>	3148 $\pm$ 276 <sup>c</sup>	0.2760 <sup>g</sup>	1883 $\pm$ 194 <sup>c</sup>
	FB	0.50	19 176 $\pm$ 1764 <sup>e</sup>	4734 $\pm$ 200 <sup>e</sup>	0.2469 <sup>d</sup>	3144 $\pm$ 280 <sup>e</sup>
	FB	0.75	33 456 $\pm$ 2323 <sup>g</sup>	7520 $\pm$ 400 <sup>g</sup>	0.2248 <sup>e</sup>	5458 $\pm$ 375 <sup>h</sup>

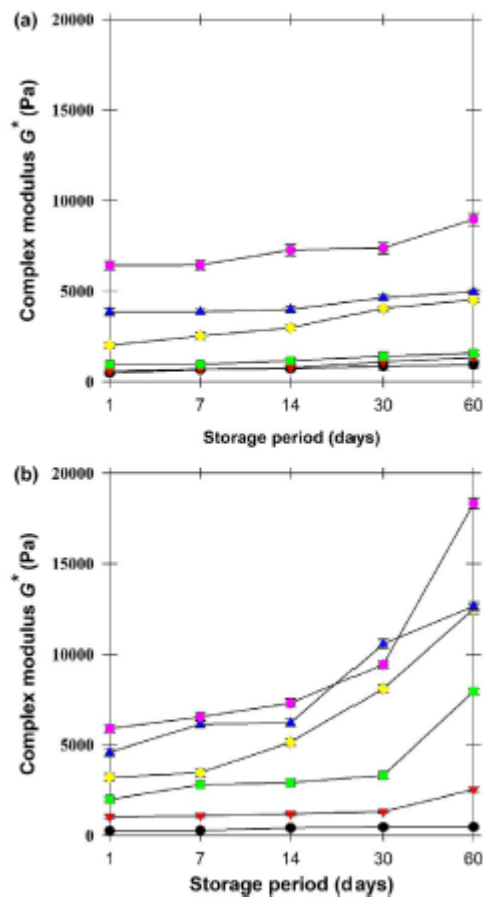
Table 3 (Continued).

Storage period (days)	Furcellaran type	Concentration (% w/w)	$G'$ (Pa)	$G''$ (Pa)	$\tan \delta$ (—)	$\eta^*$ (Pa s)
30	FB	1.00	38 170 $\pm$ 621 <sup>h</sup>	8535 $\pm$ 71 <sup>h</sup>	0.2236 <sup>e</sup>	6225 $\pm$ 94 <sup>i</sup>
	None	CS	698 $\pm$ 17 <sup>a</sup>	681 $\pm$ 2 <sup>a</sup>	0.9794 <sup>a</sup>	138 $\pm$ 2 <sup>a</sup>
	FA	0.10	4555 $\pm$ 595 <sup>b</sup>	1807 $\pm$ 205 <sup>b</sup>	0.3966 <sup>b</sup>	780 $\pm$ 100 <sup>b</sup>
	FA	0.25	6172 $\pm$ 269 <sup>c</sup>	2076 $\pm$ 36 <sup>c</sup>	0.3364 <sup>c</sup>	1036 $\pm$ 42 <sup>c</sup>
	FA	0.50	14 374 $\pm$ 79 <sup>d</sup>	3839 $\pm$ 48 <sup>d</sup>	0.2671 <sup>d</sup>	2368 $\pm$ 14 <sup>d</sup>
	FA	0.75	19 140 $\pm$ 1272 <sup>e</sup>	4960 $\pm$ 239 <sup>e</sup>	0.2592 <sup>d</sup>	3147 $\pm$ 206 <sup>e</sup>
	FA	1.00	26 530 $\pm$ 2128 <sup>f</sup>	6423 $\pm$ 545 <sup>f</sup>	0.2421 <sup>e</sup>	4344 $\pm$ 450 <sup>f</sup>
	FB	0.10	15 565 $\pm$ 1850 <sup>d</sup>	4969 $\pm$ 3115 <sup>e</sup>	0.3192 <sup>f</sup>	2602 $\pm$ 1946 <sup>d</sup>
	FB	0.25	25 191 $\pm$ 2428 <sup>f</sup>	7345 $\pm$ 583 <sup>g</sup>	0.2916 <sup>g</sup>	4176 $\pm$ 406 <sup>f</sup>
	FB	0.50	21 955 $\pm$ 1165 <sup>f</sup>	5543 $\pm$ 399 <sup>e</sup>	0.2525 <sup>d</sup>	3604 $\pm$ 19 <sup>ts</sup>
	FB	0.75	33 175 $\pm$ 1103 <sup>g</sup>	7676 $\pm$ 235 <sup>g</sup>	0.2314 <sup>h</sup>	5419 $\pm$ 179 <sup>g</sup>
	FB	1.00	39 892 $\pm$ 748 <sup>h</sup>	9172 $\pm$ 535 <sup>h</sup>	0.2299 <sup>i</sup>	6515 $\pm$ 135 <sup>h</sup>
60	None	CS	804 $\pm$ 84 <sup>a</sup>	726 $\pm$ 55 <sup>a</sup>	0.9029 <sup>a</sup>	196 $\pm$ 9 <sup>a</sup>
	FA	0.10	2041 $\pm$ 6 <sup>b</sup>	1014 $\pm$ 43 <sup>b</sup>	0.4966 <sup>b</sup>	636 $\pm$ 4 <sup>b</sup>
	FA	0.25	4137 $\pm$ 149 <sup>c</sup>	1752 $\pm$ 33 <sup>c</sup>	0.4236 <sup>c</sup>	715 $\pm$ 24 <sup>c</sup>
	FA	0.50	9729 $\pm$ 57 <sup>d</sup>	3017 $\pm$ 6 <sup>d</sup>	0.3101 <sup>d</sup>	1621 $\pm$ 9 <sup>d</sup>
	FA	0.75	13 776 $\pm$ 814 <sup>e</sup>	3661 $\pm$ 206 <sup>e</sup>	0.2658 <sup>e</sup>	2269 $\pm$ 134 <sup>e</sup>
	FA	1.00	26 082 $\pm$ 2366 <sup>f</sup>	6068 $\pm$ 415 <sup>f</sup>	0.2326 <sup>f</sup>	4262 $\pm$ 382 <sup>f</sup>
	FB	0.10	12 700 $\pm$ 710 <sup>e</sup>	4761 $\pm$ 312 <sup>g</sup>	0.3748 <sup>g</sup>	2159 $\pm$ 123 <sup>e</sup>
	FB	0.25	13 370 $\pm$ 2832 <sup>e</sup>	4337 $\pm$ 735 <sup>g</sup>	0.3244 <sup>d</sup>	2237 $\pm$ 1471 <sup>e</sup>
	FB	0.50	25 676 $\pm$ 121 <sup>f</sup>	6829 $\pm$ 318 <sup>f</sup>	0.2660 <sup>e</sup>	4229 $\pm$ 32 <sup>f</sup>
	FB	0.75	30 491 $\pm$ 1394 <sup>g</sup>	7522 $\pm$ 287 <sup>f</sup>	0.2467 <sup>h</sup>	4998 $\pm$ 226 <sup>g</sup>
	FB	1.00	37 618 $\pm$ 88 <sup>h</sup>	9438 $\pm$ 2 <sup>h</sup>	0.2509 <sup>h</sup>	6173 $\pm$ 14 <sup>h</sup>

CS, control sample; FA, furcellaran (Estgel 8500); FB, furcellaran (Estgel 1000).

<sup>a</sup>Values are expressed as the mean ( $n = 3$ )  $\pm$  SD. The means within a column (samples using two types and varying levels of furcellaran) indicated by differing superscript letters ( $P < 0.05$ ) differ from one another.

In addition, as reported by several authors (Lee and Klostermeyer 2001; Dimitreli and Thomareis 2009; Weiserová et al. 2011; Salek et al. 2015; Guinee 2017), the 'conventional' PC rigidity depended on the pH value of cheese, structure of casein network in cheese, type and level of ES and length of storage (in the presence of ES). Actually, over the whole storage period, the PCS samples could be described as a gel ( $G' > G''$ , Tables 2 and 3; Saha and Bhattacharya 2010). The development of the complex modulus ( $G^*$ ) values (for the reference frequency of 1 Hz) of the PCS samples, with varying levels of either FA or FB with or without the addition of ES as a function of the 60-day storage period ( $6 \pm 2^\circ\text{C}$ ), is shown in Figures 1 and 2. In the PCS samples produced with ES and FA addition, a slight ( $P > 0.05$ ) increase in  $G^*$  was observed during the storage period (Figure 1a). On the contrary, the rigidity of PCS samples manufactured utilising FB (at a level  $\geq 0.10\%$  w/w) showed significant ( $P < 0.05$ ) enhancement of  $G'$ , especially at 14th and 30th day of storage (Figure 1b). Figure 2a illustrates a significant ( $P < 0.05$ ) increase in the  $G^*$  values between 7 and 60 days of storage period for samples manufactured in the absence of ES but containing FA (at all tested polysaccharide concentrations). In particular, the increasing level of FA resulted in increasing values of PCS rigidity. The same trend was also observed for samples prepared with FB (used at the same level as FA; Figure 2b); however, the stiffness of the PCS samples was significantly ( $P < 0.05$ ) increased even at 1st day of storage. Hladká et al. (2014) manufactured 'block-type' PC utilising 1% w/w carrageenan, without resorting to the use of ES. The authors suggested that an increased PC rigidity during storage (mainly during the first 7 days) might have been caused by the rearrangement of the developed carrageenan-protein complex, and therefore, more intensive water bonding (by the utilised polysaccharide) might have occurred during the development of the PC matrix (Hladká et al. 2014).

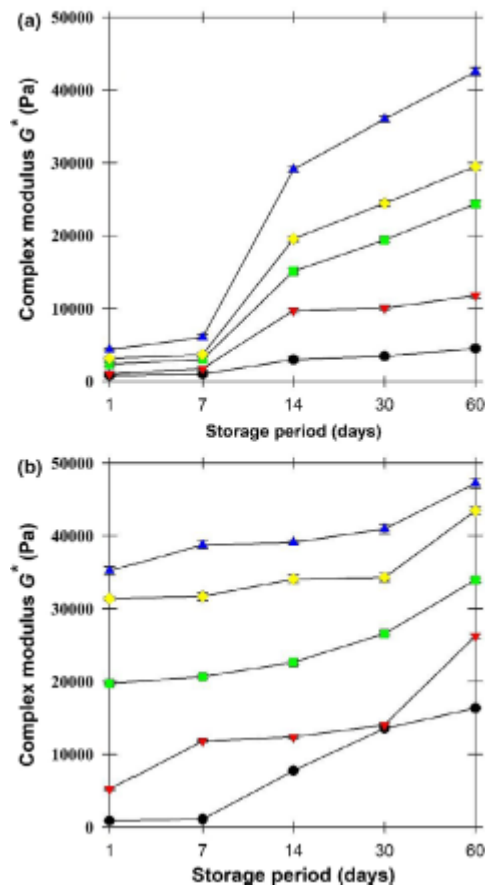


**Figure 1** Development of complex modulus  $G^*$  values (for the reference frequency of 1 Hz) for processed cheese spread samples manufactured with different types (FA - part a; FB - part b) and levels [0.10% (red triangle), 0.25% (green square), 0.50% (yellow rhombus), 0.75% (blue triangle), and 1.00% (purple circle) w/w; a control sample without furcellaran is included (black circle)] of furcellaran in the presence of emulsifying salts, during a 60-day storage period (at  $6 \pm 2^\circ\text{C}$ ).

Moreover, as previously mentioned, the relatively low pH values of the PCS samples obtained in the absence of ES (**Table 1**) affected the rigidity of PCS, especially towards the end of the storage period (**Marchesseau et al. 1997; Lee and Klostermeyer 2001**).

## CONCLUSIONS

This study dealt with the viscoelastic behaviour of PCS containing two types of furcellaran (FA or FB; applied individually in each lot) used at levels ranging from 0.10 to 1.00% w/w in PCS produced with ES addition and those made utilising furcellaran as a total replacement for ES. The data obtained revealed that the inclusion of each tested type of furcellaran (FA or FB) at all levels to the 'conventional PC led to an increase in the sample rigidity (except for the use of FA at a level of 0.10% w/w). The PCS manufactured with complete replacement of ES (especially with FB) was found to be significantly rigid. The current study thus shows that it is possible to replace ES in PCS with furcellaran; however, this replacement leads to a significant increase in the rigidity of such a product.



**Figure 2** Development of complex modulus  $G^*$  values (for the reference frequency of 1 Hz) for processed cheese spread samples manufactured with different types (FA - part a; FB - part b) and levels [0.10% (black circle), 0.25% (red triangle), 0.50% (green square), 0.75% (yellow rhombus) and 1.00% (blue triangle) w/w] of furcellaran, as complete replacement of emulsifying salts, during a 60-day storage period (at  $6 \pm 2^\circ\text{C}$ ).

## REFERENCES

- Abdo E, Yousef M I, Dakhkhny E E, Dabour N, Kheadr E and Elsaadany K (2021) Low-phosphate processed cheese diminishes diclofenac-induced hepato-renal injury in male rats. *Alexandria Journal of Food Science and Technology* **18** 1-15.
- Ahmad S, Butt M S, Pasha I and Sameen A (2016) Quality of processed Cheddar cheese as a function of emulsifying salt replaced by K-carrageenan. *International Journal of Food Properties* **19** 1874-1883.
- Arltoft D, Ipsen R, Madsen F and de Vries J (2007) Interactions between carrageenans and milk proteins: A microstructural and rheological study. *Biomacromolecules* **8** 729-736.
- Barth A P, Tormena C F and Viotto W H (2017) pH influences hydrolysis of sodium polyphosphate in dairy matrices and the structure of processed cheese. *Journal of Dairy Science* **100** 8735-8743.
- Bourriot S, Garnier C and Doublier J L (1999) Micellar-casein-K-carrageenan mixtures. I. Phase Separation and Ultrastructure. *Carbohydrate Polymers* **40** 145-157.
- Buňka F, Doudová L, Weiserová E, Černíková M, Kuchař D, Slavíková Š, Nagyová G, Ponížil P, Grüber T and Michálek J (2014) The effect of concentration and composition of ternary emulsifying salts on the textural properties of processed cheese spreads. *LWT - Food Science and Technology* **58** 247-255.

Černíková M, Buňka F, Pavlínek V, Březina P, Hrabě J and Valášek P (2008) Effect of carrageenan type on viscoelastic properties of processed cheese. *Food Hydrocolloids* **22** 1054-1061.

Černíková M, Buňka F, Pospiech M, Tremlová B, Hladká K, Pavlínek V and Březina P (2010) Replacement of traditional emulsifying salts by selected hydrocolloids in processed cheese production. *International Dairy Journal* **20** 336-343.

Černíková M, Nebesářová J, Salek R N, Řiháčková L and Buňka F (2017) Microstructure and textural and viscoelastic properties of model processed cheese with different dry matter and fat in dry matter content. *Journal of Dairy Science* **100** 4300-4307.

Chatziantoniou S E, Thomareis A S and Kontominas M G (2019) Effect of different stabilizers on rheological properties, fat globule size and sensory attributes of novel spreadable processed whey cheese. *European Food Research and Technology* **245** 2401-2412.

Dickinson E (2009) Hydrocolloids as emulsifiers and emulsion stabilizers. *Food Hydrocolloids* **23** 1473-1482.

Dimitreli G and Thomareis A S (2009) Instrumental textural and viscoelastic properties of processed cheese as affected by emulsifying salts and in relation to its apparent viscosity. *International Journal of Food Properties* **12** 261-275.

Drohan D D, Tziboula A, McNulty D and Horne D S (1997) Milk protein-carrageenan interactions. *Food Hydrocolloids* **11** 101-107.

Guinee T P (2017) Pasteurized processed and imitation cheese products. In *Cheese: Chemistry, Physics & Microbiology*, 4th edn, pp. 1133-1184. McSweeney P L H, Fox P F, Cotter P D and Everett D W, eds. Boston: Elsevier Academic Press.

Gupta S K, Karahadian C and Lindsay R C (1984) Effect of emulsifier salts on textural and flavor properties of processed cheeses. *Journal of Dairy Science* **67** 764-778.

Hladká K, Randulová Z, Tremlová B, Ponížil P, Mančík P, (Černíková M and Buňka F (2014) The effect of cheese maturity on selected properties of processed cheese without traditional emulsifying agents. *LWT - Food Science and Technology* **55** 650-656.

Hoffmann W and Schrader K (2015) Dispersion analysis of spreadable processed cheese with low content of emulsifying salts by photocentrifugation. *International Journal of Food Science and Technology* **50** 950-957.

Imeson A P (2009) Carrageenan and furcellaran. In *Handbook of Hydrocolloids*, 2nd edn, pp. 164-185. Phillips G O and Williams P A, eds. Cambridge: Woodhead Publishing Limited.

ISO (2004a) Cheese - Determination of Fat Content Van Gulik Method, 3rd edn, Geneva: International Organization for Standardization.

ISO (2004b) Cheese and Processed Cheese - Determination of the Total Solids Content (Reference Method), 2nd edn, Geneva: International Organization for Standardization.

Johnson M E, Kapoor R, McMahon D J, McCoy D R and Narasimmon R G (2009) Reduction of sodium and fat levels in natural and processed cheeses: Scientific and technological aspects. *Comprehensive Reviews in Food Science and Food Safety* **8** 252-268.

Kapoor R and Metzger L E (2008) Process cheese: Scientific and technological aspects. A review. *Comprehensive Reviews in Food Science and Food Safety* **7** 194-214.

Langendorff V, Cuvelier G, Launay B, Parker A and De Kruif C G (2000) Effects of carrageenan type on the behaviour of carrageenan/ milk mixtures. *Food Hydrocolloids* **14** 273-280.

Lee S K, Buwalda R J, Euston S R, Foegeding E A and McKenna A B (2003) Changes in the rheology and microstructure of processed cheese during cooking. *LWT - Food Science and Technology* **36** 339-345.

Lee S K and Klostermeyer H (2001) The effect of pH on the rheological properties of reduced-fat model processed cheese spreads. *LWT -Food Science and Technology* **34** 288-292.

Marchesseau S, Gastaldi E, Lagaude A and Cuq J L (1997) Influence of pH on protein interactions and microstructure of process cheese. *Journal of Dairy Science* **80** 1483-1489.

Mente A, O'Donnell M and Yusuf S (2021) Sodium intake and health: What should we recommend based on the current evidence? *Nutrients* **13** 3232.

Micinski J, Kowalski I, Szarek J and Zwierzchowski G (2013) Health-promoting properties of selected milk components. *Journal of Elementology* **18** 165-186.

Olivares M L, Passeggi M C G, Ferron J, Zorrilla S E and Rubiolo A C (2010) Study of milk/K-carrageenan mixtures by atomic force microscopy. *Food Hydrocolloids* **24** 776-782.

Saha D and Bhattacharya S (2010) Hydrocolloids as thickening and gelling agents in food: A critical review. *Journal of Food Science and Technology* **47** 587-597.

Salek R N, Cerníková M, Nagyová G, Kuchař D, Bacová H, Minardková L and Buňka F (2015) The effect of composition of ternary mixtures containing phosphate and citrate emulsifying salts on selected textural properties of spreadable processed cheese. *International Dairy Journal* **44** 37-43.

Schäffer B, Lorinczy D and Belagyi J (1999) DSC and electron microscopic investigation of dispersion-type processed cheeses made without peptization. *Journal of Thermal Analysis and Calorimetry* **56** 1211-1216.

Schäffer B, Szakaly S, Lorinczy D and Schaffer B (2001) Processed cheeses made with and without peptization. Submicroscopic structure and thermodynamic characteristics. *Journal of Thermal Analysis and Calorimetry* **64** 671-679.

Schorsch C, Jones M G and Norton I T (2000) Phase behaviour of pure micellar casein/K-carrageenan systems in milk salt ultrafiltrate. *Food Hydrocolloids* **14** 347-358.

Shimp L A (1985) Process cheese principles. *Food Technology* **39** 63-72.

Solowiej B G, Nastaj M, Szafráńska J O, Muszyński S, Gustaw W, Tomczyńska-Mleko M and Mleko S (2020) Effect of emulsifying salts replacement with polymerised whey protein isolate on textural, rheological and melting properties of acid casein model processed cheeses. *International Dairy Journal* **105** 104694.

Tuvikene R, Truus K, Kollist A, Volobujeva O, Mellikov E and Pehk T (2008) Gel-forming structures and stages of red algal galactans of different sulfation levels. *Journal of Applied Phycology* **20** 527-535.

Uribarri J and Calvo M S (2013) Dietary phosphorus excess: A risk factor in chronic bone, kidney, and cardiovascular disease? *Advances in Nutrition* **4** 542-544.

Weiserová E, Doudová L, Galiová L, Žák L, Michálek J, Janiš R and Buňka F (2011) The effect of combinations of sodium phosphates in binary mixtures on selected texture parameters of processed cheese spreads. *International Dairy Journal* **21** 979-986.