Abstract: The effect of carrageenan (κ-carrageenan, τ-carrageenan, and λ-carrageenan) on the physicochemical and functional properties of low-fat Colby cheese during ripening was investigated. Protein, fat, and moisture contents; the soluble fractions of the total nitrogen at pH 4.6; protein and fat recovery; and the actual yield and dry matter yield (DM yield) were monitored. Hardness, springiness, and the storage modulus were also evaluated to assess the functional properties of the cheese. Moreover, the behavior of water in the samples was investigated to ascertain the underlying mechanisms. The results indicated that 0.15 g/kg κ-carrageenan had no significant effect on the actual yield and DM yield, and physicochemical and functional properties of low-fat Colby cheese. The protein content increased in the low-fat cheese and low-fat cheese containing κ-carrageenan, and the moisture in the nonfat substance (MNFS) decreased in both samples, which contributed to the harder texture. The addition of 0.3 g/kg τ-carrageenan and 0.3 g/kg λ-carrageenan improved the textural and rheological properties of low-fat cheese by 2 ways: one is increasing the content of bound and expressible moisture due to their high water absorption capacity and the other is interfering with casein crosslinking, thereby further increasing MNFS and the actual yield.

Keywords: carrageenan, functional properties, low-fat cheese, yield, water partitioning

Practical Application: This study has proved that κ-carrageenan had no significant effect on the functional properties of low-fat Colby cheeses; τ-carrageenan and λ-carrageenan tend to interact with casein favorably, increasing the moisture content, and thus improving the functional properties of low-fat cheeses. The cheese producers can add 0.3 g/kg τ-carrageenan and 0.3 g/kg λ-carrageenan to raw milk and manufacture the low-fat cheeses with good functional properties.

Introduction
Consumers are becoming increasingly interested in low-fat foods, and this has led to a significant increase in the popularity of reduced and low-fat yogurts (LFC; Mistry and others 1996, Kavas and others 2004). However, because fat plays an important role in the development of the flavor, texture, and appearance of cheeses, the reduction or removal of fat from cheeses adversely affects their quality. LFC are usually considered to lack flavor and to be firm and rubbery, with poor meltability (Mistry 2001; Koca and Metin 2004; Madadiou and others 2005; Johnson and others 2009). Various approaches have been used to improve the functional properties of LFC, and the most common proposition is to increase the moisture content to create the same moisture in the nonfat substance (MNFS) as found in full-fat cheese (FFC). Carbohydrate-based fat replacers can mechanically entrap water, giving the cheese a sense of lubricity and creaminess, and therefore, have often been recommended for use in cheeses, including cellulose plus guar gum based Novagel NC200, β-glucan, and gum tragacanth (Haque and others 2007; Sahan and others 2008; Cooke and others 2013).

Among these types of ingredients, carrageenan can interact with milk protein, and thus, are widely used in the milk industry. Carrageenan is an anionic polysaccharide extracted from red seaweed, and the 3 basic types are κ-carrageenan, τ-carrageenan, and λ-carrageenan classified according to the number of sulfate groups per repeating disaccharide unit on the galactose/anhydrogalactose chain (1, 2, and 3, respectively; Imeson 2000). τ-carrageenan and λ-carrageenan have gel-formation capacity and are typically used in gelling applications, whereas κ-carrageenan is used as thickener (Yuguchi and others 2002). Bullens and others (1994) produced reduced-fat Cheddar cheese with microcrystalline cellulose and carrageenan, and found that these interfered with casein molecule interaction in cheese; the functional properties of this reduced fat cheese were similar to those of FFC. Totosaus and Guemes-Vera (2008) studied the effect of κ-carrageenan and λ-carrageenan on the composition and meltability of low-fat Oaxaca cheese, and found that κ-carrageenan improved the meltability of cheese, although λ-carrageenan increased the moisture content of cheese. However, to our knowledge, there are no studies on how carrageenan improves the functional properties of LFC. It was still unclear that carrageenan affected cheese quality by increasing the moisture content or by interrupting the interactions between casein molecules. Our previous study (Wang and others 2014) showed that κ-carrageenan, τ-carrageenan, and λ-carrageenan adsorb onto the surface of casein in different ways at low concentrations (for example, tail adsorption, flat adsorption, and ring adsorption for 0.2 g/kg κ-carrageenan, 0.25 g/kg τ-carrageenan, and 0.25 g/kg λ-carrageenan, respectively), thereby inhibiting the formation of the casein network to different degrees. Further, our finding suggested that τ-carrageenan and λ-carrageenan can...
improve the quality of LFC; however, this has still not been confirmed.

Therefore, the objective of this work was to evaluate the functionality of different types of carrageenan (κ-carrageenan, τ-carrageenan, and λ-carrageenan) as fat replacers in low-fat Colby cheese and to explore the underlying mechanism. The composition and the soluble fractions as a percentage of total nitrogen at pH 4.6 (pH 4.6 SN/TN) can provide information on the effect of carrageenan on the physiochemical properties of LFC. Textural analysis and dynamic rheological measurements have been used to assess the effect of carrageenan on the functional properties of LFC. Researchers have found that the functional properties of cheeses are related to their water distribution (McMahon and others 1999; Noronha and others 2008). Thus, we measured the behavior of water (bound moisture, expressible moisture, and entrapped moisture) using a differential scanning calorimeter to explain the differences in the functional properties of cheeses.

Materials and Methods

Materials

Fresh cow's milk (3.18% ± 0.06% protein, 3.97% ± 0.04% fat, 12.63% ± 0.39% total solids) and skim milk (3.21 ± 0.04% protein, 0.05% ± 0.02% fat, 8.82% ± 0.30% total solids) were obtained from a local farm (Sino-US Research & Development Center, China Agricultural Univ., Beijing, China). The milk was then standardized to 2.05% and 3.97% fat for making low-fat and full-fat Colby cheeses, respectively. Three types of carrageenan (κ-carrageenan, τ-carrageenan, and λ-carrageenan) were purchased from Sigma Chemical Co. (St. Louis, Mo., U.S.A.). Freeze-dried direct vat set starter culture R704 and rennet Stamix 1150 were supplied by Chr. Hansen Inc. (Beijing, China). All other chemicals were of analytical grade.

Cheese manufacture

Five different cheese making trials were carried out using 90 kg milk on 3 different days. The cheeses were produced in a randomized order in the experiment, including FFC, LFC, LFC made with 0.15 g/kg κ-carrageenan (KLF), LFC made with 0.3 g/kg τ-carrageenan (ILF), and low-fat cheese made with 0.3 g/kg λ-carrageenan (LLF). Carrageenan powder was added to raw standardized milk (2.05% fat) at 20 °C, and the samples were mixed vigorously until the carrageenan was completely dispersed.

Colby-like cheeses were made following the procedures of Olson and others (2007) with the following modifications: The prepared milks with carrageenan were pasteurized at 63 °C for 30 min, cooled to 32 °C, and inoculated with 0.04 g/kg (w/v) starter culture, which shifted the pH of the milk to 6.5. Then, 0.05 g/kg (w/w) rennet was added, and the milk was allowed to coagulate. The coagulation time for FFC, LFC, KLF, ILF, and LLF was 65 ± 5, 50 ± 3, 46 ± 3, 64 ± 2, and 69 ± 4 min, respectively. The formed coagulum was subsequently cut into approximately 1.5 × 1.5 × 1.5 cm³ cubes, left to heal for 15 min, heated to 39 °C for another 30 min, and held at this temperature until the pH dropped to 6.2. Approximately one-third of the total whey was drained, and cool water (pasteurized previously and then cooled to approximately 16 °C) was added until the original volume was reached. The curds were held in the cool water for 15 min without any stirring, and the whey–water mixture was then completely drained. Thereafter, the curds were dry stirred until the pH reached 5.8, dried salted at 30 g/kg (w/w of curds) over 15 min, packed into hoops, and pressed overnight at 2.46 kPa. After vacuum packaging, the cheese blocks were aged at 4 °C for 60 d, and samples were taken at 1, 15, 30, and 60 d for physicochemical and functional analysis.

Compositional analysis

The cheese samples were analyzed for moisture by an oven method (IDF 1982), total nitrogen by the Kjeldahl method (AOAC 2003), fat by the Röse–Gottlieb method (AOAC 2003), and pH 4.6 SN/TN by the method of Kuchroo and Fox (1982). All tests were performed in triplicate.

Analyses of protein, fat recovery, and cheese yield

The protein and fat recoveries (% w/w) were calculated as the amount of protein and fat retained in the cheese divided by the total amount of protein and fat in the milk, respectively (Johnson and others 2001; Madadalou and others 2005). The cheese yield was expressed as actual yield and dry matter yield (DM yield). The actual yield (kg cheese/100 kg milk) was calculated as the weight of cheese obtained in each vat divided by the weight of the milk (Hu and others 2013). DM yield was determined using the following formula (Fenelon and Guinee 1999): DM yield = actual yield × (100 − MD)/100, where MD is the moisture content of the cheese.

Water partitioning

The freezable water, defined as water freezeable at −40 °C, was measured using the method described by McMahon and others (1999). Bound water was defined as the water that did not freeze at −40 °C (Berlin 1981). The expressible water, which is the water that is not impeded by the protein matrix, was measured according to the method of Guo and Kindstedt (1995). The entrapped water was calculated as the difference between the freezable water and the expressible water. All measurements were repeated 3 times.

Analyses of functional properties

Textural analysis. Texture profile analysis was performed using a TMS-Pro Texture Analyzer (Food Technology Corp., Sterling, Va., U.S.A.) equipped with a 40-mm dia aluminum probe with a 2-mm gap. A frequency sweep was performed at 25 °C and a strain of 0.1 0% stress rheometer (TA Instruments Inc., New Castle, Del., U.S.A.) equipped with a 40-mm dia aluminum probe with a 2-mm gap. A frequency sweep was performed at 25 °C and a strain of 0.1 0%

Dynamic rheological measurements. After equilibration of the cheese samples to room temperature for 30 min, the rheological properties were studied using an AR2000 controlled-stress rheometer (TA Instruments Inc., New Castle, Del., U.S.A.) equipped with a 40-mm dia aluminum probe with a 2-mm gap. A frequency sweep was performed at 25 °C and a strain of 0.10%, which was within the linear viscoelastic region, with the frequency varied from 0.05 to 50 Hz. Three repetitions were performed for each cheese sample.

Statistical analysis

The experimental data were analyzed by analysis of variance using SPSS version 17.0 (SPSS Inc., Chicago, Ill., U.S.A.). Differences were compared at a significance level of P < 0.05.

Results and Discussion

Rennet-induced gelation is the crucial 1st step during cheese manufacture (Everett and Olson 2000; Zobrist and others 2005; Bönisch and others 2008). Previous studies have indicated that
carbohydrates improve the quality of LFC by increasing the moisture content (McMahon and Oberg 1998; Aryana and Haque 2001; Rahimi and others 2007). Therefore, in order to select the optimal concentration of carrageenan to produce high-quality low-fat cheese, we made curds with milk containing different kinds and concentrations of carrageenan in the preliminary experiment, measured their moisture content and the curd actual yield, and finally, determined that the optimal additive amounts of κ-carrageenan, λ-carrageenan, and β-carrageenan were 0.15, 0.3, and 0.3 g/kg, respectively.

Cheese composition, protein and fat recoveries, and cheese yield

The composition of the fresh cheeses is summarized in Table 1. FFC (26.17% fat), LFC (17.83% fat), KLF (18.04% fat), ILF (14.86% fat), and LLF (13.93% fat) referred to FFC, LFC, KLF, ILF, and LLF containing 0.3 g/kg (w/w) κ-carrageenan, respectively. Compared with FFC, LFC, and KLF had significantly higher protein and moisture contents, and lower fat content compared with the other samples. The protein contents of ILF and LLF were significantly higher than that of FFC, but were significantly lower than that of LFC and KLF (P < 0.05). The MNFS of ILF and LLF increased significantly (P < 0.05), and the highest MNFS was observed in KLF was inversely correlated with their fat content because the reduction of the fat content led to higher protein contents per unit weight of cheese (Rahimi and others 2002). Fat and moisture act as fillers in the protein matrix of cheese (Madadlou and others 2005), and when the fat content decreases, the moisture replaces the fat, but not on an equal basis, resulting in a decrease of the total filler volume, consequently decreasing the MNFS and the actual yield of the cheese, which is in agreement with other reports (Rudan and others 1999; Fenelon and Guinee 2000; Mistry 2000; Wang and others 2014).

Table 1—Compositional analysis of fresh cheese.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>FFC</th>
<th>LFC</th>
<th>KLF</th>
<th>ILF</th>
<th>LLF</th>
</tr>
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<tbody>
<tr>
<td>Protein (%)</td>
<td>18.91 ± 0.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>24.48 ± 0.61&lt;sup&gt;c&lt;/sup&gt;</td>
<td>24.46 ± 0.36&lt;sup&gt;c&lt;/sup&gt;</td>
<td>21.33 ± 0.45&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.35 ± 0.25&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>26.17 ± 0.29&lt;sup&gt;d&lt;/sup&gt;</td>
<td>17.83 ± 0.37&lt;sup&gt;c&lt;/sup&gt;</td>
<td>18.04 ± 0.16&lt;sup&gt;c&lt;/sup&gt;</td>
<td>14.86 ± 0.56&lt;sup&gt;b&lt;/sup&gt;</td>
<td>13.93 ± 0.19&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>46.11 ± 0.34&lt;sup&gt;a&lt;/sup&gt;</td>
<td>50.93 ± 0.33&lt;sup&gt;b&lt;/sup&gt;</td>
<td>51.61 ± 1.10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>55.91 ± 0.47&lt;sup&gt;c&lt;/sup&gt;</td>
<td>57.89 ± 1.76&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>MNFS%</td>
<td>68.88 ± 0.24&lt;sup&gt;a&lt;/sup&gt;</td>
<td>64.43 ± 0.51&lt;sup&gt;b&lt;/sup&gt;</td>
<td>64.85 ± 0.27&lt;sup&gt;a&lt;/sup&gt;</td>
<td>67.74 ± 0.28&lt;sup&gt;b&lt;/sup&gt;</td>
<td>69.25 ± 0.41&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Means with different letters (a to d) within the same row are significantly different (P < 0.05). FFC, full-fat cheese; LFC, low-fat cheese; KLF, low-fat cheese containing 0.15 g/kg (w/w) κ-carrageenan; ILF, low-fat cheese containing 0.3 g/kg (w/w) κ-carrageenan; LLF, low-fat cheese containing 0.3 g/kg (w/w) λ-carrageenan.

Table 2—Protein, fat recoveries and yield of cheese.

<table>
<thead>
<tr>
<th>Item</th>
<th>FFC</th>
<th>LFC</th>
<th>KLF</th>
<th>ILF</th>
<th>LLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein recovery (%)</td>
<td>76.72 ± 0.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.87 ± 1.87&lt;sup&gt;a&lt;/sup&gt;</td>
<td>77.99 ± 1.18&lt;sup&gt;a&lt;/sup&gt;</td>
<td>79.04 ± 1.67&lt;sup&gt;b&lt;/sup&gt;</td>
<td>82.10 ± 0.96&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Fat recovery (%)</td>
<td>87.65 ± 0.82&lt;sup&gt;b&lt;/sup&gt;</td>
<td>86.53 ± 1.58&lt;sup&gt;a&lt;/sup&gt;</td>
<td>87.87 ± 0.69&lt;sup&gt;b&lt;/sup&gt;</td>
<td>87.39 ± 2.80&lt;sup&gt;a&lt;/sup&gt;</td>
<td>85.19 ± 0.99&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Actual yield (kg cheese/100 kg milk)</td>
<td>12.98 ± 0.31&lt;sup&gt;c&lt;/sup&gt;</td>
<td>9.91 ± 0.17&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.33 ± 0.11&lt;sup&gt;c&lt;/sup&gt;</td>
<td>12.01 ± 0.13&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.46 ± 0.27&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>DM yield&lt;sup&gt;d&lt;/sup&gt; (%)</td>
<td>6.92 ± 0.17&lt;sup&gt;c&lt;/sup&gt;</td>
<td>4.90 ± 0.22&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.05 ± 0.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.41 ± 0.09&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.38 ± 0.13&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
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</table>

Means with different letters (a to c) within the same row are significantly different (P < 0.05). DM yield, dry matter yield.

Table 3—Changes in the soluble fractions as a percentage of total nitrogen at pH 4.6 of cheese ripened for 1, 15, 30, and 60 d at 4°C.

<table>
<thead>
<tr>
<th>Cheese age (d)</th>
<th>FFC</th>
<th>LFC</th>
<th>KLF</th>
<th>ILF</th>
<th>LLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.84 ± 0.34&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.77 ± 0.12&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4.32 ± 0.19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.38 ± 0.47&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.47 ± 0.42&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>15</td>
<td>12.32 ± 0.06&lt;sup&gt;b&lt;/sup&gt;</td>
<td>10.82 ± 0.34&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.58 ± 0.31&lt;sup&gt;c&lt;/sup&gt;</td>
<td>12.64 ± 1.59&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>13.46 ± 0.76&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>30</td>
<td>16.63 ± 0.67&lt;sup&gt;c&lt;/sup&gt;</td>
<td>15.18 ± 0.49&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.43 ± 0.46&lt;sup&gt;d&lt;/sup&gt;</td>
<td>18.94 ± 0.99&lt;sup&gt;d&lt;/sup&gt;</td>
<td>17.59 ± 0.09&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>60</td>
<td>19.08 ± 1.62&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15.38 ± 0.65&lt;sup&gt;a&lt;/sup&gt;</td>
<td>14.80 ± 1.01&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.10 ± 0.16&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.31 ± 1.29&lt;sup&gt;bc&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Means with different letters (a to d) within the same row are significantly different (P < 0.05). FFC, full-fat cheese; LFC, low-fat cheese; KLF, low-fat cheese containing 0.15 g/kg (w/w) κ-carrageenan; ILF, low-fat cheese containing 0.3 g/kg (w/w) κ-carrageenan; LLF, low-fat cheese containing 0.3 g/kg (w/w) λ-carrageenan.
The increased moisture amount in ILF and LLF was related to the increase in MNFS and the actual yield of the cheeses, and the reduction in the protein and fat content was likely related to their dilution effect (Drake and others 1996; Sipahioglu and others 1999). The differences between the actual yield and DM yield were due to the DM yield eliminating the contribution of moisture to cheese yield, and thus were especially significant in ILF and LLF.

Proteolysis

The proteolytic trends expressed as the pH 4.6 SN/TN of the cheeses during ripening are shown in Table 3. The pH 4.6 SN/TN of all cheeses continuously increased with aging, and the majority of the changes occurred in the first 30 d. Compared with FFC, the pH 4.6 SN/TN values of LFC and KLF were significantly lower (P < 0.05), and KLF had the lowest pH 4.6 SN/TN values. No significant differences were observed in the pH 4.6 SN/TN among FFC, ILF, and LFF, except for ILF on 30 d of ripening.

During ripening, protein is hydrolyzed to peptides and amino acids by residual coagulant enzymes, native milk proteases, and starter bacteria (Fox 1989; Romeih and others 2002). The degree of proteolysis of LFC and KLF was lower than that of FFC, which may be partly attributable to the low MNFS, because lower MNFS in LFC and KLF corresponds to decreased freedom of moisture and enzymatic and microbial activities (Lane and others 1997; Rudan and others 1999; Sahan and others 2008). The higher level of MNFS in the presence of t-carrageenan and k-carrageenan enhanced enzymatic activity and microbial growth, thus accelerating proteolysis (Mistry 2001; Zisu and Shah 2005; Cooke and others 2013).

Water partitioning

The amounts of the different moisture states of the cheeses are shown in Figure 1. No significant changes were observed in the amount of bound moisture in any of the cheeses during ripening (Figure 1A). Conversely, the amount of expressible moisture significantly decreased (P < 0.05; Figure 1B), and the amount of entrapped moisture significantly increased (P < 0.05) (Figure 1C); further, these changes mainly occurred during the first 30 d of ripening. Compared with FFC, the amount of bound moisture in LFC and KLF increased significantly (P < 0.05), and the values were higher in ILF and LLF than in the other cheeses. Further, the amount of expressible moisture in LFC and KLF decreased significantly (P < 0.05), whereas that in ILF and LLF increased significantly (P < 0.05); the highest values were observed in LLF. Moreover, the amount of entrapped moisture in LFC, KLF, and LLF increased significantly, especially in KLF (P < 0.05), but was not significantly different between ILF and FFC during the first 15 d, although the amount of entrapped moisture in ILF increased significantly later on.

The higher protein contents per unit weight of cheese enhanced the water-binding capacity of the protein matrix (Romeih and others 2002; Rahimi and others 2007), thus increasing the amount of bound and entrapped moisture in LFC and KLF. Similar results were reported in a study on Mozzarella cheese (McMahon and others 1999). Saldo and others (2002) indicated that the bound moisture content is mainly affected by the solute content in cheeses, including salt, fat, and protein and their hydrolysates. Our previous study (Wang and others 2014) showed that t-carrageenan and k-carrageenan adsorbed onto the surface of casein micelles via flat adsorption and ring adsorption, respectively. Therefore, t-carrageenan and k-carrageenan may become part of the protein matrix, increasing the amount of bound moisture due to their high water absorption capacity, and also increasing the protein recovery. Furthermore, our previous study (Wang and others 2014) showed that t-carrageenan and k-carrageenan covered the enzymatic action sites and interfered with the shrinkage of the casein micelles, which caused the formation of a loose network, thus providing more fat-serum channels, lowering the driving force involved in expelling water from the curds, and thereby increasing the amount of expressible moisture. Similar results were also reported by McMahon and others (1996) and Madadlou and others (2007). The inhibitory effect of k-carrageenan on the shrinkage of casein was higher than that of t-carrageenan (McMahon and others 1996; Koca and Metin 2004), which resulted in more fat-serum channels, further increasing the amount of expressible moisture. The hydrolysis of protein with aging increased the hydration effect of the cheeses. The moisture in the fat-serum

![Figure 1](image-url)
channels, along with the protein contained therein, can be absorbed into the protein matrix and become an integral part of the matrix, further increasing the entrapped moisture content and decreasing the expressible moisture content (Guo and Kindstedt 1995; McMahon and others 1999). During ripening, the content of bound moisture remained constant (Figure 1A), which is consistent with the results from previous reports (McMahon and others 1999; Saldo and others 2002).

**Textural and rheological analysis**

The hardness and springiness of the cheeses during ripening are shown in Figure 2A and B, respectively. The hardness values decreased significantly with aging for all cheeses, and the springiness values also decreased significantly during ripening for all the cheeses except for KLF, shown as the springiness of KLF did not change significantly; further, the majority of the decreases occurred in the 1st 30 d of ripening ($P < 0.05$). The hardness and

![Figure 2](image.png)

*Figure 2—Changes in hardness (A) and springiness (B) during ripening of cheese.*

![Figure 3](image.png)

*Figure 3—Changes in the storage modulus of cheese ( ■, FFC; □, LFC; ●, KLF; ▲, ILF; ●, LLF) ripened for 1 d (A), 15 d (B), 30 d (C), and 60 d (D), with the frequency from 0.05 to 50 Hz.*
springiness of LFC and KLF were higher than those of FFC; the hardness of ILF and LLF were lower than that of FFC; there were no significant differences in springiness among FFC, ILF and LLF. The G' values of the cheeses as a function of oscillatory frequency are shown in Figure 3, which shows that the G' values of all the cheeses increased with increasing frequency at any ripening time; the values significantly decreased with aging (P < 0.05), especially over the 1st 30 d. Compared with FFC, the G' values of LFC and KLF increased significantly (P < 0.05), and the highest values were found in LFC; moreover, the G' values of ILF and LLF decreased significantly (P < 0.05), and the least value of G' was associated with LLF.

Olson and Johnson (1990) indicated that the relative amounts of protein, fat, and moisture were the main factors affecting the hardness of cheese. In addition, Lelievre and Gills (2002) argued that MNFS is a principal factor affecting the quality of cheese, and the low degree of proteolysis in LFC and KLF led to lesser gradual retardation in the textural and rheological properties of resultant cheeses. The higher levels of MNFS in ILF and LLF accelerated the release of soluble protein, further improving their textural and rheological properties.

Acknowledgment

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References


Conclusion

This study assessed the effect of carrageenan on the functional properties of low-fat Colby cheese. The protein content of LFC and KLF was higher than that of FFC, and therefore, the amounts of bound and entrapped moisture increased; conversely, the MNFS, the actual yield and DM yield decreased, thus contributing to the increase in hardness, springiness, and storage modulus. The addition of 0.3 g/kg ι-carrageenan and 0.3 g/kg λ-carrageenan increased the content of bound moisture and expressive moisture, and interfered with the aggregation of casein micelles, thus increasing the MNFS and decreasing the hardness, springiness, and storage modulus of ILF and LLF. During ripening, the low degree of proteolysis in LFC and KLF led to lesser gradual retardation in the textural and rheological properties of resultant cheeses. The higher levels of MNFS in ILF and LLF accelerated the release of soluble protein, further improving their textural and rheological properties.
Carrageenan on functionality of cheese...


