



# Concentrated emulsions as novel fat replacers in reduced-fat and low-fat Cheddar cheeses. Part 2. Large amplitude oscillatory shear behavior

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## ABSTRACT

Lower-fat cheeses with desirable texture can be difficult to produce. The objective of this study was to characterize the effects of concentrated emulsions as a fat replacer on the viscoelastic properties of reduced-fat (15% fat) and low-fat (6% fat) Cheddar cheeses. Concentrated emulsions were prepared by adding a fish gelatin–gum arabic mixture at pH 5.0 and 3.6 to olive oil at a water:oil ratio of 30:70 (w/w). Cheddar cheeses containing emulsions were made by adding the emulsions to skim milk after adding starter culture and before renneting and subsequent cheesemaking. Two control cheeses at each fat level were produced using either olive oil or cream. Cheeses containing emulsions showed greater nonlinearity under large amplitude oscillatory shear, and smaller critical stress and moduli values compared with controls at all storage timepoints. These results were ascribed to greater casein network discontinuity and more open spaces created by aggregated emulsion droplets.

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## 1. Introduction

Given the prevalence of obesity in the United States, consumers are adopting healthier eating strategies, such as reducing portion size and substituting lower-fat foods for full-fat foods (Amelia, Drake, Nelson, & Barbano, 2013). Among the low-fat foods available worldwide, low-fat dairy products are in high demand and the demand for low- and non-fat cheese has increased significantly (Mohamed, 2015; TMR, 2018). A recent study by DMI (2009) found that 16% of adults ages 20 to 54 are restricting cheese in their diet. The same study also noted that 29% of these individuals would be willing to incorporate cheese into their diet if low-fat cheeses with comparable flavor and texture to full-fat cheese were available (DMI, 2009). Thus, there is great interest in developing low-fat dairy products to satisfy this demand.

Cheese consists of water, fat, protein (mainly caseins), and minerals. The cheese matrix comprises coagulated casein micelles forming the basic matrix structure with water and fat entrapped in the matrix (Walstra, Wouters, & Geurts, 2006). Fat content affects different aspects of cheese including composition, yield, flavor, and microstructure. It also affects cheese biochemical, textural,

functional, and rheological properties (Collins, McSweeney & Wilkinson, 2003). As a filler and plasticizing agent, fat can increase the fluidity and reduce the density and continuity of the casein matrix (Rajah, 2002). Accordingly, production of reduced- and low-fat cheeses, especially Cheddar and mozzarella, poses a significant challenge to the cheese industry. Low-fat cheeses are usually identified as bland, firm, rubbery, and defective in color (Rahimi, Khosrowshahi, Madadlou, & Aziznia, 2007). Increasing moisture content is the most common method used to overcome the usual textural defects of low-fat cheeses (Rahimi et al., 2007). In this regard, two main strategies have been developed to ultimately increase the moisture content and improve the flavor and texture of low fat cheeses: (i) cheesemaking process modifications to retain more moisture in the final product, and (ii) use of hydrocolloids as fat replacers and water-binders (Liu, Xu, & Gou, 2008). These strategies may be used alone or in combination. Although the current Code of Federal Regulations (21 CFR 133) does not permit polysaccharide hydrocolloids as an additive in most cheeses (CFR, 2017), there is still ongoing research into polysaccharide and non-dairy protein fat replacers in cheese systems.

Reducing cook temperature, pre-acidification of milk prior to renneting, increasing curd size, and rennet concentration are different production modifications that can be used to achieve a low-fat cheese with a softer body and higher moisture content

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(Madadlou, Khosroshahi, & Mousavi, 2005; Metzger, Barbanò, Kindstedt, & Gou, 2001; Nair, Mistry, & Oommen, 2000). However, because of the sensitivity of enzymes, starter cultures, and protein structures to environmental conditions, such as pH and temperature, there may be limitations to how far processing parameters can be adjusted. These limitations can be mitigated by using different protein and polysaccharide hydrocolloids as fat replacers to mimic the sensory and physical functions of fat in low-fat cheese products. A key purpose of these ingredients is to weaken and reduce the continuity and density of cheese matrix by binding to water molecules and forming colloidal clumps or networks throughout the protein matrix. In other words, these fat replacers act as casein matrix-breakers (Everett & Auty, 2008). However, some studies have revealed a synergistic effect of some hydrocolloids on casein matrix formation and consequently enhancement of cheese firmness. For instance, Hosseini-Parvar, Matia-Merino, and Golding (2015) reported that addition of basil seed gum as a fat replacer in model process cheese led to increased firmness, particularly at higher gum concentrations, because the polysaccharide chains created a network throughout the protein matrix of the process cheese, strengthening the casein network.

Selection of fat replacers in cheese requires a fundamental understanding of how the fat replacer interacts with the cheese microstructure and the impact of those interactions on cheese mechanical behaviors. Fish gelatin and gum arabic can form complex coacervates (Li, Zhang, Zhao, Ding, & Lin, 2018) that can be used to stabilize emulsions. These coacervates can be used to produce emulsions with a range of droplet sizes (Bai, Huan, Li, & McClements, 2017; Piacentini, Giorno, Dragosavac, Vladisavljević, & Holdich, 2013) and did not show separation over several months [Anvari & Joyner (Melito), 2017]. Therefore, these emulsions show promise as a viable fat replacer in cheese.

In Part 1 of this study, we evaluated the effect of concentrated emulsions, prepared using fish gelatin and gum arabic as emulsifiers in a water:oil (W:O) emulsion at pH 3.6 and 5.0, as a novel fat replacer on microstructural and rheological features of low-fat and reduced-fat Cheddar cheeses during 7 months' storage at 6 °C [Anvari & Joyner (Melito), 2018]. We found that the concentrated emulsions induced significant changes on cheese rheological and microstructural properties, acting as casein matrix breakers by creating large cavities occupied by aggregated emulsion droplets. Furthermore, cheeses containing emulsions showed lower firmness under compression compared to control cheeses made with cream or olive oil. However, aging and emulsion addition had no significant influence on cheese mechanical spectra under small amplitude oscillatory shear (SAOS) rheometry. Because large shear strains are applied to Cheddar cheese during processing operations such as slicing and shredding, as well as during oral processing, characterization of nonlinear viscoelastic behavior is needed to provide a better understanding and a more comprehensive evaluation of structure–function relationships under large-strain conditions in reduced- and low-fat Cheddar cheeses containing concentrated emulsions. Accordingly, the objective of this study was to determine the effects of concentrated emulsions as a fat replacer on the large amplitude oscillatory shear (LAOS) behaviors of low-fat and reduced-fat Cheddar cheese.

## 2. Materials and methods

### 2.1. Materials

Fish gelatin (Type B; pI 4.81) and gum arabic were purchased from Sigma Chemical Co. (St. Louis, MO, USA). Skim milk and olive oil were purchased from a local supermarket (Logan, UT, USA) and cream was obtained from the Utah State University Aggie Creamery

(Logan, UT, USA). Starter cultures (*Lactococcus lactis*, DVS 850) were purchased from Chr. Hansen Inc. (Milwaukee, WI, USA) and double-strength chymosin (Maxiren) was purchased from DSM Food Specialties (Parsippany, NJ, USA).

### 2.2. Preparation of fish gelatin–gum Arabic aqueous mixtures

Fish gelatin–gum arabic aqueous mixtures were prepared at a total biopolymer concentration of 2% (w/w), biopolymer ratio of 1:1 w/w, and pH of 5.0 or 3.6 (adjusted using 1.0 M acetic acid or 1.0 M sodium hydroxide). These pH values were chosen because they yielded emulsions stabilized by either soluble (pH 5.0) or insoluble (pH 3.6) fish gelatin–gum arabic complexes [Anvari & Joyner (Melito), 2017]. Mixtures were held at 25 °C for 24 h before emulsion preparation to ensure complete dispersion (Yang, Anvari, Pan, & Chung, 2012).

### 2.3. Preparation of concentrated emulsions

To prepare the concentrated emulsions, the fish gelatin–gum arabic aqueous mixtures were added to olive oil at a W:O of 30:70 (w/w) and homogenized using a Polytron stand homogenizer (Kinematica AG, Lucerne, Switzerland) at 10,000 rpm at room temperature ( $22 \pm 2$  °C) for 60 s. Emulsions were used for cheesemaking directly after homogenization.

### 2.4. Cheddar cheesemaking process

All cheeses were prepared in triplicate in the manner of Anvari and Joyner (Melito) (2018). Cheeses were made at three different fat levels based on FDA regulations for Cheddar cheese (FDA 2017a,b): full-fat (35%, w/w), reduced-fat (15%, w/w), and low-fat (6%, w/w) cheeses (treatments shown in Table 1). Briefly, after adding 5.0 g starter cultures to 16 kg skim milk (32 °C) and 20 min ripening, concentrated emulsions (pH 3.6 or 5.0) were added to the milk vats for reduced-fat or low-fat cheese production. After emulsion addition, 3.8 mL rennet was added to each vat; the vats were then set for 30 min and cut using 6.35 mm wire knives. The curd was healed for 5 min, cooked to 36 °C under continuous stirring by hand for 70 min, drained, and washed to cool it to 27 °C. Curds were drained again and rested, then dry stirred to a pH of 5.8, salted, packed into stainless-steel Wilson hoops, and pressed for ~18 h at room temperature ( $20 \pm 2$  °C) and 35 psig. After de-hooping, cheeses were vacuum-packaged and stored at 6 °C until tested.

Two control samples were made with olive oil and cream at each fat level. Full-fat Cheddar cheese (35% fat, w/w) made with cream was also produced as a control. All analyses were conducted 1, 2, and 5 mo after production. Since we observed microbial spoilage (holes in the microstructure likely caused by gas-producing bacteria) in all samples after 7 mo storage, cheeses were not evaluated past 5 mo of production.

### 2.5. Rheological analysis

All rheological measurements were conducted using a Discovery Hybrid Rheometer (DHR3, TA Instruments Inc., New Castle, DE, USA) equipped with 20 mm diameter cross-hatched parallel plates. Strain sweep tests were performed (0.01–100%, 1 Hz) to determine critical strain ( $\gamma_c$ ), and critical stress ( $\sigma_c$ ), as well as the following linear viscoelastic region (LVR) parameters: viscoelastic moduli  $G'_{LVR}$  and  $G''_{LVR}$ , damping factor ( $\tan \delta_{LVR}$ ), and complex viscosity ( $\eta^*_{LVR}$ ). Critical strain for each sample was determined to be the strain at which the storage modulus ( $G'$ ) deviated by more than 3% from the previous value. LAOS testing was performed by collecting

raw waveform data at 0.05, 50, and 100% strains at a frequency of  $10 \text{ rad s}^{-1}$ . All rheological measurements were conducted at  $4 \text{ }^\circ\text{C}$  (with a 10 s equilibration time) and each cheese replicate was tested in triplicate.

## 2.6. Data analysis

LAOS data were analyzed using the MITlaos program (MITlaos beta) created by Ewoldt, Clasen, Hosoi, and Mckinley (2007) designed for MATLAB (MathWorks; Natick, MA, USA). Strain sweep data were analyzed using ANOVA followed by Tukey's test using SAS 9.3 (SAS Institute; Cary, NC, USA).

## 3. Results and discussion

It should be noted that data on cheese microstructures, peak force under compression, and small-strain viscoelastic behaviors are presented in the Part 1 companion paper [Anvari & Joyner (Melito), 2018]. Briefly, we found that microstructures and mechanical properties were impacted by fat level. Microstructures and large-strain compression behaviors were also affected by fat type and storage time. Few significant differences were found for proximate composition and final pH within each fat level, implying that fat type did not impact cheese composition or final pH. No emulsion stability issues were noted in the cheeses during cheesemaking or over the duration of the study based on visual observation and fat retention values (Table 1). Please also note that the data discussed below are for cheeses stored up to 5 months. Additional data from the 7 months storage time point are presented in Supplementary material Tables S1–S4 and Figs. S1 and S2.

### 3.1. Viscoelastic behavior of cheeses

Dynamic strain sweep data for low-fat and reduced-fat Cheddar cheeses are shown in Fig. 1 and Table 2, and Fig. 2 and Table 3, respectively. Critical strain is a criterion of structural strength and shape retention factor against mechanical deformation. Control cheeses made with cream showed critical strain values in the order of low-fat > reduced-fat > full-fat at all storage timepoints, indicating that the structure of the low-fat control cheese made with cream was more resistant to deformation at higher strains compared with its full-fat and reduced-fat counterparts. A similar trend has been reported by Rogers et al. (2009). Additionally, critical stress values (the stress value at critical strain) increased with decreased fat content in the control cheeses containing cream, suggesting the low-fat cheese had the most strain-stable structure, probably due to higher development of the casein matrix with decreased fat content.

The  $\eta_{LVR}^*$  values for full-fat cheeses were unexpectedly higher than those of their reduced-fat and low-fat counterparts at all

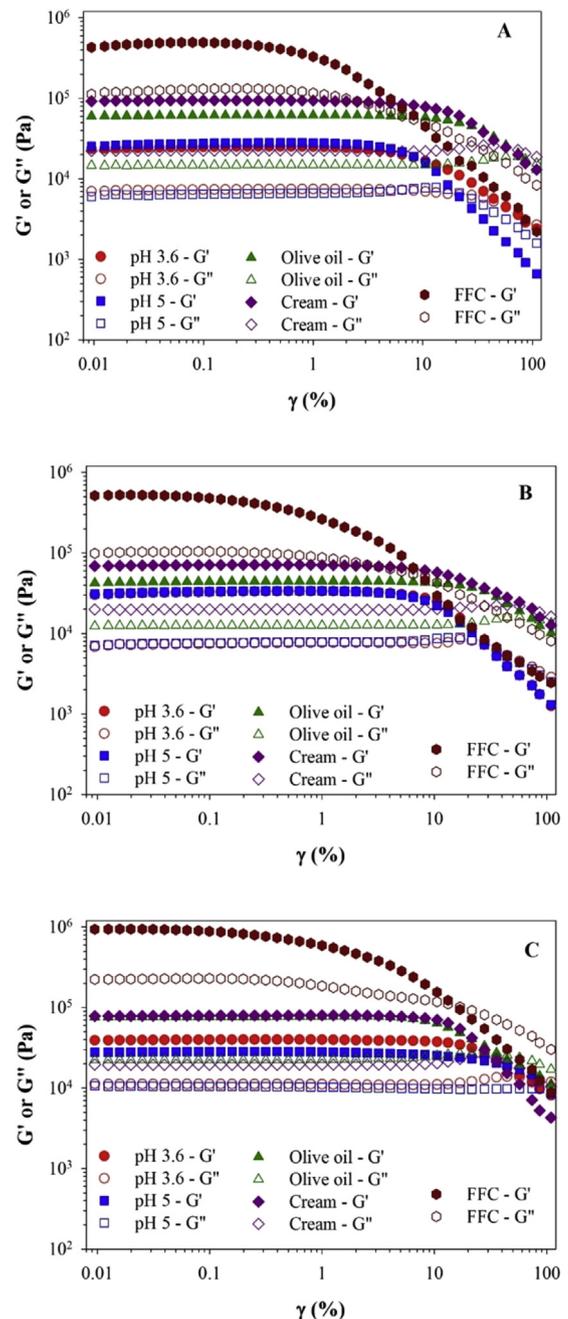


Fig. 1. Strain sweep results for low-fat Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses after A) 1 month, B) 2 months, and C) 5 months of storage at  $6 \text{ }^\circ\text{C}$ .

Table 1  
Cheese formulation and proximate composition.<sup>a</sup>

Samples	Added emulsion or lipid (g)	Total amount of added lipid (g)	Cheese yield (%)	Fat yield (%)	pH	Fat (%)	Moisture (%)	Protein (%)	Salt (%)
LF-Emulsion pH 3.6	142	99.4	8.33 ± 0.37 <sup>a</sup>	86.1 ± 7.58 <sup>a</sup>	5.46 ± 0.17 <sup>cd</sup>	6.33 ± 0.28 <sup>c</sup>	56.1 ± 0.98 <sup>a</sup>	30.7 ± 0.07 <sup>a</sup>	3.04 ± 0.15 <sup>a</sup>
LF-Emulsion pH 5.0	142	99.4	8.49 ± 0.36 <sup>a</sup>	90.3 ± 13.6 <sup>a</sup>	5.41 ± 0.11 <sup>d</sup>	6.50 ± 0.70 <sup>c</sup>	56.5 ± 0.45 <sup>a</sup>	29.5 ± 0.67 <sup>a</sup>	3.09 ± 0.11 <sup>a</sup>
LF- Olive Oil	100	100	8.68 ± 0.33 <sup>a</sup>	88.6 ± 12.3 <sup>a</sup>	5.51 ± 0.12 <sup>bcd</sup>	6.33 ± 1.04 <sup>c</sup>	51.9 ± 1.83 <sup>a</sup>	30.5 ± 1.38 <sup>a</sup>	3.00 ± 0.06 <sup>a</sup>
LF- Cream	290	101.5	8.25 ± 0.43 <sup>a</sup>	82.6 ± 10.1 <sup>a</sup>	5.74 ± 0.03 <sup>ab</sup>	6.25 ± 1.06 <sup>c</sup>	52.2 ± 7.07 <sup>a</sup>	30.6 ± 2.21 <sup>a</sup>	2.99 ± 0.19 <sup>a</sup>
RF-Emulsion pH 3.6	365	255.5	8.65 ± 0.15 <sup>a</sup>	85.2 ± 1.70 <sup>a</sup>	5.50 ± 0.01 <sup>cd</sup>	15.3 ± 0.57 <sup>b</sup>	52.0 ± 0.58 <sup>a</sup>	26.4 ± 0.85 <sup>b</sup>	2.58 ± 0.10 <sup>b</sup>
RF-Emulsion pH 5.0	365	255.5	8.69 ± 0.46 <sup>a</sup>	83.5 ± 4.22 <sup>a</sup>	5.58 ± 0.05 <sup>abcd</sup>	15.0 ± 1.32 <sup>b</sup>	52.3 ± 1.07 <sup>a</sup>	26.6 ± 1.20 <sup>b</sup>	2.61 ± 0.11 <sup>b</sup>
RF- Olive Oil	256	256	8.51 ± 0.50 <sup>a</sup>	81.3 ± 4.82 <sup>a</sup>	5.69 ± 0.02 <sup>abc</sup>	15.0 ± 0.00 <sup>b</sup>	50.5 ± 0.98 <sup>a</sup>	25.8 ± 0.91 <sup>b</sup>	2.50 ± 0.00 <sup>b</sup>
RF- Cream	735	257.3	8.76 ± 0.51 <sup>a</sup>	85.7 ± 0.80 <sup>a</sup>	5.76 ± 0.02 <sup>a</sup>	15.0 ± 1.00 <sup>b</sup>	49.9 ± 0.90 <sup>a</sup>	22.2 ± 0.11 <sup>b</sup>	2.48 ± 0.08 <sup>b</sup>
Full-Fat	1900	665	7.99 ± 0.07 <sup>a</sup>	90.9 ± 0.78 <sup>a</sup>	5.35 ± 0.04 <sup>d</sup>	34.0 ± 0.00 <sup>a</sup>	36.6 ± 1.03 <sup>b</sup>	23.0 ± 0.45 <sup>c</sup>	1.30 ± 0.10 <sup>c</sup>

<sup>a</sup> Abbreviations are: LF, low fat; RF, reduced fat. Each batch of cheese was prepared from 16 kg skim milk, 5 g starter culture, 3.8 mL chymosin, and the specified weight of emulsion, olive oil, or cream. Different superscript letters within a column indicate significant differences.

**Table 2**  
Viscoelastic parameters for low-fat (LF) Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses during 5 months storage at 6 °C.<sup>a</sup>

Storage time	Samples	$G'_{LVR}$ (kPa)	$G''_{LVR}$ (kPa)	Tan ( $\delta$ ) <sub>LVR</sub>	$\gamma_c$ (%)	$\sigma_c$ (kPa)	$\eta^*_{LVR}$ (kPa s)
1 month	LF-Emulsion pH 3.6	24.0 ± 0.67 <sup>cB</sup>	7.46 ± 0.56 <sup>cB</sup>	0.31 ± 0.00 <sup>aA</sup>	3.25 ± 0.25 <sup>cC</sup>	0.79 ± 0.02 <sup>bC</sup>	4.00 ± 0.20 <sup>bC</sup>
	LF-Emulsion pH 5.0	26.8 ± 0.71 <sup>cB</sup>	6.77 ± 0.71 <sup>cC</sup>	0.25 ± 0.00 <sup>aB</sup>	3.61 ± 0.41 <sup>cB</sup>	0.90 ± 0.03 <sup>bC</sup>	4.40 ± 0.41 <sup>bB</sup>
	LF-Olive oil control	59.5 ± 0.27 <sup>bB</sup>	14.9 ± 0.56 <sup>bB</sup>	0.25 ± 0.01 <sup>aB</sup>	13.1 ± 2.91 <sup>aA</sup>	7.65 ± 0.43 <sup>aA</sup>	9.76 ± 0.12 <sup>bB</sup>
	LF-Cream control	83.4 ± 0.56 <sup>aA</sup>	22.0 ± 0.18 <sup>aA</sup>	0.25 ± 0.01 <sup>aB</sup>	7.22 ± 0.82 <sup>bA</sup>	6.28 ± 0.11 <sup>aA</sup>	13.7 ± 0.94 <sup>aA</sup>
	Full-fat control	451.7 ± 2.90 <sup>B</sup>	131.3 ± 1.23 <sup>B</sup>	0.29 ± 0.01 <sup>A</sup>	0.31 ± 0.01 <sup>A</sup>	1.50 ± 0.10 <sup>A</sup>	74.9 ± 4.98 <sup>B</sup>
2 months	LF-Emulsion pH 3.6	34.3 ± 0.69 <sup>cA</sup>	7.76 ± 0.25 <sup>cB</sup>	0.30 ± 0.00 <sup>aA</sup>	8.06 ± 1.45 <sup>bB</sup>	1.12 ± 0.15 <sup>bB</sup>	5.36 ± 0.12 <sup>cB</sup>
	LF-Emulsion pH 5.0	31.9 ± 0.05 <sup>cA</sup>	7.86 ± 0.18 <sup>cB</sup>	0.24 ± 0.00 <sup>aB</sup>	8.01 ± 0.41 <sup>bB</sup>	1.18 ± 0.13 <sup>bB</sup>	5.23 ± 0.02 <sup>cA</sup>
	LF-Olive oil control	42.1 ± 2.87 <sup>bC</sup>	12.8 ± 0.81 <sup>bC</sup>	0.30 ± 0.00 <sup>aA</sup>	11.4 ± 1.32 <sup>aB</sup>	4.98 ± 0.24 <sup>aB</sup>	7.00 ± 0.47 <sup>bC</sup>
	LF-Cream control	65.1 ± 1.13 <sup>aC</sup>	19.6 ± 3.52 <sup>aB</sup>	0.30 ± 0.00 <sup>aA</sup>	10.7 ± 0.66 <sup>aB</sup>	3.82 ± 0.23 <sup>aB</sup>	10.8 ± 1.88 <sup>aC</sup>
	Full-fat control	47.5 ± 0.50 <sup>B</sup>	104 ± 7.00 <sup>C</sup>	0.27 ± 0.00 <sup>B</sup>	0.17 ± 0.02 <sup>B</sup>	0.57 ± 0.01 <sup>B</sup>	77.3 ± 6.46 <sup>B</sup>
5 months	LF-Emulsion pH 3.6	37.2 ± 2.77 <sup>bA</sup>	11.1 ± 0.61 <sup>cA</sup>	0.29 ± 0.00 <sup>aA</sup>	9.41 ± 1.31 <sup>aA</sup>	2.40 ± 0.29 <sup>cA</sup>	6.18 ± 0.44 <sup>bA</sup>
	LF-Emulsion pH 5.0	25.7 ± 2.34 <sup>cB</sup>	8.43 ± 6.58 <sup>dA</sup>	0.32 ± 0.00 <sup>aA</sup>	9.05 ± 1.05 <sup>aA</sup>	2.47 ± 0.45 <sup>cA</sup>	4.30 ± 0.29 <sup>bB</sup>
	LF-Olive oil control	74.8 ± 4.00 <sup>aA</sup>	23.1 ± 1.40 <sup>aA</sup>	0.31 ± 0.00 <sup>aA</sup>	10.1 ± 0.01 <sup>aC</sup>	3.96 ± 2.05 <sup>bC</sup>	12.5 ± 1.43 <sup>aA</sup>
	LF-Cream control	74.4 ± 4.31 <sup>aB</sup>	19.8 ± 1.87 <sup>bB</sup>	0.26 ± 0.00 <sup>aB</sup>	8.25 ± 1.87 <sup>aA</sup>	6.43 ± 2.36 <sup>aA</sup>	12.3 ± 0.60 <sup>aB</sup>
	Full-fat control	834.8 ± 1.04 <sup>A</sup>	22.7 ± 2.76 <sup>A</sup>	0.21 ± 0.01 <sup>A</sup>	0.05 ± 0.01 <sup>C</sup>	1.51 ± 0.00 <sup>A</sup>	137 ± 1.71 <sup>A</sup>

<sup>a</sup> Data are presented as mean ± standard deviation; different superscript lowercase letters show significant differences ( $P < 0.05$ ) among the low-fat samples at each storage timepoint while different superscript uppercase letters show significant differences ( $P < 0.05$ ) for each sample individually at different storage times. For full-fat cheese, only significant differences ( $P < 0.05$ ) between values during storage are shown.

storage timepoints. A similar trend was observed for LVR moduli values; they increased with increased fat content. These results can be explained by increased distribution of fat globules and their crystallization in microstructure of the full-fat cheese at 6 °C [Anvari & Joyner (Melito), 2018]; the crystallized fat strengthens the microstructure (Rogers, McMahon, Daubert, Berry, & Foegeding, 2010). Hence, the cream content played an important role on Cheddar cheese viscoelastic behavior: higher fat content induced higher rigidity. However, the crystallized (solid) fat structure was likely more sensitive to shear strain-induced deformation compared to the casein matrix, resulting in a shorter LVR in the full-fat cheeses. Interestingly, the tan  $\delta_{LVR}$  values were generally similar for all fat contents at each storage timepoint. This result indicated that the extent of viscous versus elastic behavior was not impacted by cheese microstructural features, at least under small shear strains.

Generally, low-fat Cheddar cheeses containing emulsions showed similar values of  $\gamma_c$  for the first two months of storage, significantly lower critical strain values at 5 mo storage and significantly lower critical stress values for all storage timepoints compared with those of the controls at all storage timepoints, indicating reduced structural strength and stability against mechanical deformation (Tables 2 and 3). Reduced-fat cheese samples containing emulsions, on the other hand, had similar or higher critical strain values and no discernable trend for critical stress values until 5 mo storage, after which cheeses containing emulsions had lower critical stress values. These results can be explained by differences in structural development of the cheeses containing concentrated emulsions. In Part 1 of this study, we observed distinct differences in cheese microstructures based on fat type and age [Anvari & Joyner (Melito), 2018]. These microstructural differences increased with increased time, in agreement with the strain sweep results in this study. Also in agreement with this study, cheeses containing emulsions showed lower peak force under compression [Anvari & Joyner (Melito), 2018], and peak compression force generally decreased with increased storage time.

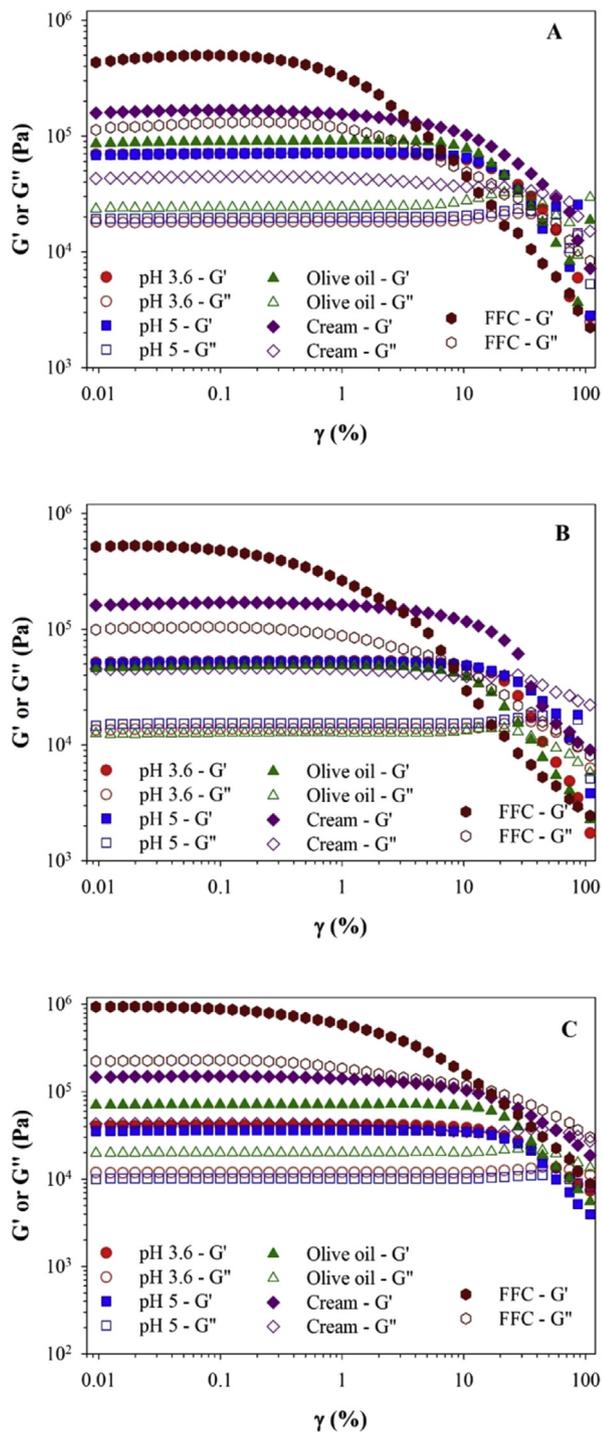
All samples had distinctly higher  $G'$  values than  $G''$  values in the LVR, denoting a predominantly elastic response. At higher shear strains,  $G'$  decreased as strain increased from critical strain to 100% strain (Figs. 1 and 2) for all cheeses, indicating structural disruption and weakening. Furthermore,  $G''$  exhibited a maximum at higher strains and a crossover point with  $G'$  for most samples, indicating a shift from viscoelastic solid to viscoelastic fluid behavior. The

presence of a pronounced maximum in  $G''$  has been classified as type III (weak strain overshoot) behavior by Hyun, Kim, Ahn, and Lee (2002) which has been reported in soft glassy systems, emulsions, suspensions, highly entangled polymer solutions, block copolymer solutions, and associative polymer solutions (Hyun et al., 2011). However, in the case of the cheese samples, the dominance of  $G''$  at higher strains was likely due to severe structural disruption, although samples were not visibly fractured at the end of testing.

Comparison of moduli values in the LVR at each fat level showed significant differences ( $P < 0.05$ ) among cheeses containing emulsions and control cheeses at each storage timepoint, where controls had larger  $G'$  and  $G''$  and the gap between the moduli was higher than those of cheeses containing emulsions, suggesting higher elasticity and stability of control cheese microstructures within the LVR. However, there were no significant differences ( $P > 0.05$ ) in  $G'$  and  $G''$  values between cheeses containing emulsions at pH 3.6 or 5.0 at each fat level. In control cheeses, casein molecules interacted directly with the cream or olive oil droplets during the cheese-making process, but in cheeses containing concentrated emulsions, the negatively charged or neutralized interface of the concentrated emulsions at pH 5.0 or 3.6, respectively, prevented casein–oil phase interactions. Hence, addition of concentrated emulsions likely reduced the casein network strength, which manifested as lower moduli values.

### 3.2. LAOS behavior of cheeses

LAOS testing can be used to classify material behaviors and provide valuable information on a material's complex microstructure that cannot be attained by traditional rheological measurements, such as flow curves and small amplitude oscillatory shear (Hyun et al., 2002). Complex materials with similar linear viscoelastic properties may display considerably different nonlinear viscoelastic behaviors. Hence, LAOS measurements can provide increased insight for characterizing structural differences (Hyun et al., 2011). Multiple analysis techniques have been used to obtain quantitative information from LAOS testing to describe and compare food systems. Information on microstructures within these systems can also be indirectly obtained from Lissajous–Bowditch plots, or plots of stress versus strain generated from oscillatory testing. In particular, Lissajous–Bowditch plots give useful information regarding structural transitions under large



**Fig. 2.** Strain sweep results for reduced-fat Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses after A) 1 month, B) 2 months, and C) 5 months of storage at 6 °C.

deformation, which can be used to predict material behavior during processing and utilization (Fuongfuchat et al., 2012).

Lissajous–Bowditch plots of cheeses at different fat contents and storage timepoints are depicted in Figs. 3 and 4. The shape of the Lissajous–Bowditch plots for all samples were elliptical at 0.05% strain (i.e., within the LVR), indicating ideal viscoelastic behavior, as expected. Under higher strains, nonlinearities were observed as distortion from the elliptical shape. Specific distortions of the shapes have been reported to relate to different

microstructural features, shear-induced structures, and other structural responses under large deformations (Fuongfuchat et al., 2012; Klein, Spiess, Calin, Balan, & Wilhelm, 2007; Rogers, Erwin, Vlassopoulos, & Cloitre, 2011). The shape of the Lissajous–Bowditch plots changed from an ellipse to a parallelogram (Figs. 3 and 4) under increased strain, indicating increased nonlinear behavior. The increase in area encompassed by the ellipse and the specific shape change to a parallelogram indicated increased viscous dissipation and a shift from elastic-dominated to viscous-dominated behavior [Fuongfuchat et al., 2012; Joyner (Melito) & Meldrum, 2016]. The observed increase in nonlinearity at higher strains was likely caused by microstructural deformations, leading to permanent deformation and flow, and manifesting in the Lissajous as viscous-dominated behavior.

Comparison of the plots at each fat level and storage timepoint showed that the reduced-fat cheeses containing concentrated emulsions generally had lower maximum stress and greater distortion from their elliptical shapes than the control cheeses. This trend was also apparent for the low-fat cheeses after 5 mo of storage. As differences in maximum stress were particularly noticeable at higher strains, these results suggest that the cheeses containing emulsions had weaker microstructures that were more likely to rupture. In cheeses containing concentrated emulsions, the flocculated droplets created more and larger voids in the microstructure and disrupted the continuity of the casein matrix [Anvari & Joyner (Melito), 2018]. Increasing the number of flocculated droplets therefore increased the number of weak points in the microstructure, leading to a softer cheese with a greater extent of nonlinear behavior compared to the control cheeses.

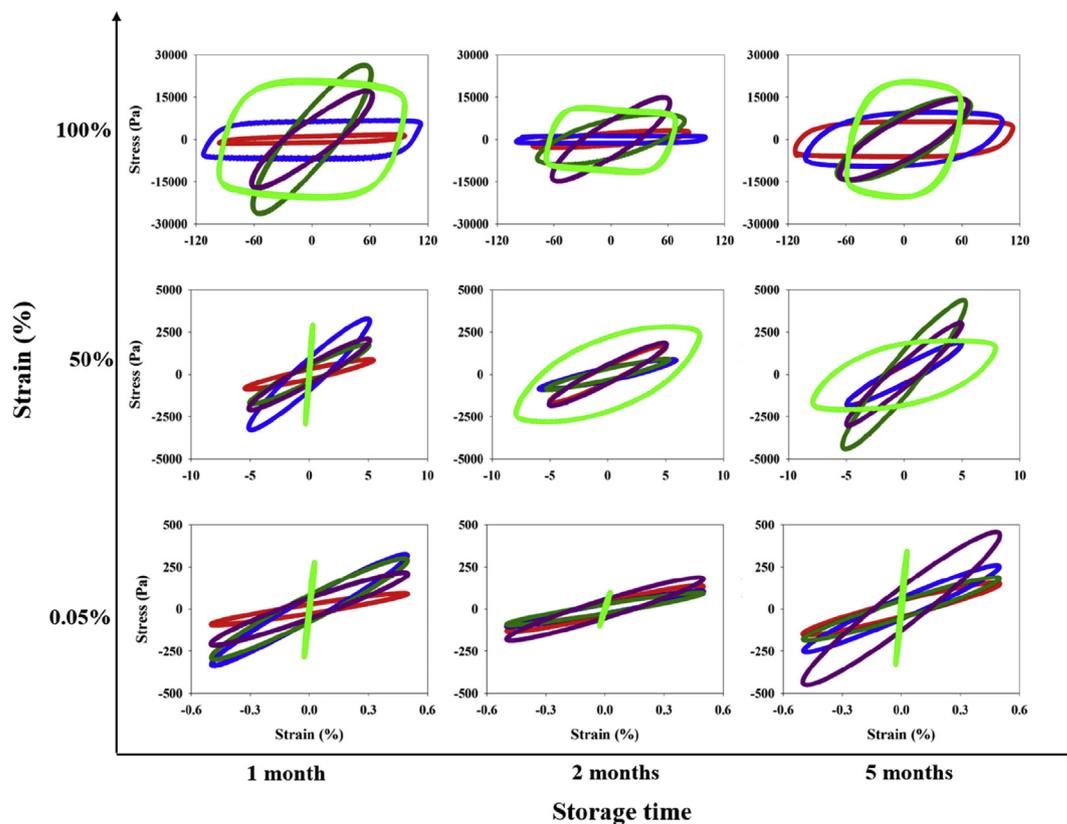
The shift from elastic-to viscous-dominated behavior during LAOS testing can be shown by the phase angle values at different strains (Tables 4 and 5). Phase angle increased with increased strain for all samples at each fat level. However, the magnitude of the increase was highly dependent on the type of fat used in the cheese. Control cheeses containing olive oil or cream had the lowest phase angle values of all cheeses at 100% strain for all timepoints; this behavior extended to lower strains at longer storage times. This result indicated that the control cheeses had structures with more elastic-dominant behavior and higher resistance to disruption. This agreed with the frequency sweep and uniaxial compression results reported in Part 1 of this study, where the controls showed higher firmness and larger dynamic moduli within the LVR [Anvari & Joyner (Melito), 2018]. There were no significant differences among the phase angle values of cheeses containing emulsions at each strain, fat level, and timepoint. In general, phase angle values increased for all samples during storage, indicating weakening of the cheese structure with age, probably due to proteolysis of the casein matrix over time.

To compare the nonlinear behaviors of different materials quantitatively, Ewoldt, Hosoi, and McKinley (2008) developed a mathematical model in which the third-order harmonic data are used to determine both extent and type of nonlinear behavior. The extent of nonlinear behavior can be measured using the ratio of the third harmonic viscoelastic moduli,  $G'_3$  and  $G''_3$  to the first harmonic viscoelastic moduli,  $G'_1$  and  $G''_1$ . A value of  $G'_3/G'_1 \geq 0.01$  (or  $G''_3/G''_1 \geq 0.01$ ) indicates nonlinear viscoelastic behavior (Melito, Daubert, & Foegeding, 2013); the greater the value, the greater the extent of nonlinear behavior. Furthermore, the type of nonlinear behavior can be characterized by using two viscoelastic moduli and two instantaneous viscosities defined by Ewoldt et al. (2008). The ratio between the large-strain elastic modulus ( $G'_L$ ) and the minimum-strain elastic modulus ( $G'_M$ ) is a measure of elastic-related nonlinear behavior;  $G'_L/G'_M < 0.90$  indicates strain-softening behavior and  $G'_L/G'_M > 1.10$  indicates strain-hardening behavior. The ratio of the instantaneous viscosities at maximum

**Table 3**  
Viscoelastic parameters for reduced-fat (RF) Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses during 5 months storage at 6 °C.<sup>a</sup>

Storage time	Samples	$G'_{LVR}$ (kPa)	$G''_{LVR}$ (kPa)	$\tan(\delta)_{LVR}$	$\gamma_c$ (%)	$\sigma_c$ (kPa)	$\eta^*_{LVR}$ (Pa s)
1 month	RF-Emulsion pH 3.6	66.6 ± 0.25 <sup>c,A</sup>	18.5 ± 0.56 <sup>c,A</sup>	0.27 ± 0.01 <sup>a,A</sup>	7.20 ± 0.82 <sup>a,C</sup>	4.96 ± 0.40 <sup>b,C,A</sup>	11,002 ± 366 <sup>c,A</sup>
	RF-Emulsion pH 5.0	69.3 ± 2.06 <sup>c,A</sup>	20.1 ± 0.12 <sup>c,A</sup>	0.29 ± 0.01 <sup>a,A</sup>	8.23 ± 1.89 <sup>a,C</sup>	5.90 ± 0.66 <sup>b,A</sup>	11,478 ± 365 <sup>c,A</sup>
	RF-Olive oil control	86.3 ± 0.57 <sup>b,A</sup>	25.6 ± 0.79 <sup>b,A</sup>	0.29 ± 0.01 <sup>a,A</sup>	7.21 ± 0.81 <sup>a,B</sup>	6.41 ± 0.00 <sup>a,B</sup>	14,330 ± 133 <sup>b,A</sup>
	RF-Cream control	138.4 ± 0.99 <sup>a,B</sup>	40.9 ± 0.23 <sup>a,B</sup>	0.29 ± 0.00 <sup>a,A</sup>	2.87 ± 0.32 <sup>b,A</sup>	4.16 ± 0.54 <sup>c,B</sup>	22,965 ± 111 <sup>a,B</sup>
	Full-fat control	451.7 ± 2.90 <sup>B</sup>	131.3 ± 1.23 <sup>B</sup>	0.29 ± 0.01 <sup>A</sup>	0.31 ± 0.01 <sup>A</sup>	1.50 ± 0.10 <sup>A</sup>	74,868 ± 4,979 <sup>B</sup>
2 months	RF-Emulsion pH 3.6	48.5 ± 0.89 <sup>b,B</sup>	13.9 ± 0.19 <sup>c,B</sup>	0.27 ± 0.00 <sup>b,A</sup>	9.07 ± 1.03 <sup>a,B</sup>	4.65 ± 0.38 <sup>b,B</sup>	8186 ± 268 <sup>b,B</sup>
	RF-Emulsion pH 5.0	49.5 ± 0.11 <sup>b,B</sup>	15.4 ± 0.11 <sup>b,B</sup>	0.31 ± 0.00 <sup>a,A</sup>	10.11 ± 0.01 <sup>a,B</sup>	5.15 ± 0.00 <sup>a,B</sup>	8194 ± 11 <sup>b,B</sup>
	RF-Olive oil control	45.1 ± 0.44 <sup>b,C</sup>	12.7 ± 0.89 <sup>c,C</sup>	0.27 ± 0.01 <sup>b,A</sup>	5.73 ± 0.63 <sup>b,B</sup>	2.72 ± 0.03 <sup>c,C</sup>	7456 ± 110 <sup>b,C</sup>
	RF-Cream control	145.3 ± 0.13 <sup>a,A</sup>	42.4 ± 1.20 <sup>a,A</sup>	0.29 ± 0.00 <sup>ab,A</sup>	3.61 ± 0.41 <sup>c,A</sup>	5.48 ± 0.08 <sup>a,A</sup>	24,090 ± 100 <sup>a,A</sup>
	Full-fat control	474.6 ± 0.50 <sup>B</sup>	104.3 ± 7.00 <sup>C</sup>	0.21 ± 0.00 <sup>B</sup>	0.17 ± 0.02 <sup>B</sup>	0.57 ± 0.01 <sup>B</sup>	77,337 ± 6,463 <sup>B</sup>
5 months	RF-Emulsion pH 3.6	38.9 ± 1.10 <sup>c,C</sup>	11.9 ± 0.78 <sup>c,C</sup>	0.30 ± 0.00 <sup>a,A</sup>	10.09 ± 0.01 <sup>b,A</sup>	4.10 ± 0.17 <sup>d,C</sup>	6466 ± 333 <sup>c,C</sup>
	RF-Emulsion pH 5.0	33.8 ± 0.98 <sup>c,C</sup>	10.1 ± 0.23 <sup>c,C</sup>	0.29 ± 0.01 <sup>a,A</sup>	13.11 ± 2.96 <sup>a,A</sup>	4.70 ± 1.88 <sup>c,C</sup>	5610 ± 407 <sup>c,C</sup>
	RF-Olive oil control	67.3 ± 2.77 <sup>b,B</sup>	20.0 ± 0.57 <sup>b,B</sup>	0.30 ± 0.00 <sup>a,A</sup>	11.42 ± 1.32 <sup>ab,A</sup>	8.00 ± 0.10 <sup>a,A</sup>	11,174 ± 99 <sup>b,B</sup>
	RF-Cream control	125.1 ± 3.88 <sup>a,C</sup>	38.4 ± 1.29 <sup>a,C</sup>	0.30 ± 0.00 <sup>a,A</sup>	4.03 ± 0.00 <sup>c,A</sup>	5.29 ± 0.33 <sup>b,A</sup>	20,835 ± 729 <sup>a,C</sup>
	Full-fat control	834.9 ± 1.04 <sup>A</sup>	227.0 ± 2.76 <sup>A</sup>	0.27 ± 0.01 <sup>A</sup>	0.05 ± 0.01 <sup>C</sup>	1.51 ± 0.01 <sup>A</sup>	137,692 ± 1,709 <sup>A</sup>

<sup>a</sup> Data are presented as mean ± standard deviation; different superscript lowercase letters show significant differences ( $P < 0.05$ ) among the reduced-fat samples at each storage timepoint while different superscript uppercase letters show significant differences ( $P < 0.05$ ) for each sample individually at different storage times. For full-fat cheese, only significant differences ( $P < 0.05$ ) between values during storage are shown.

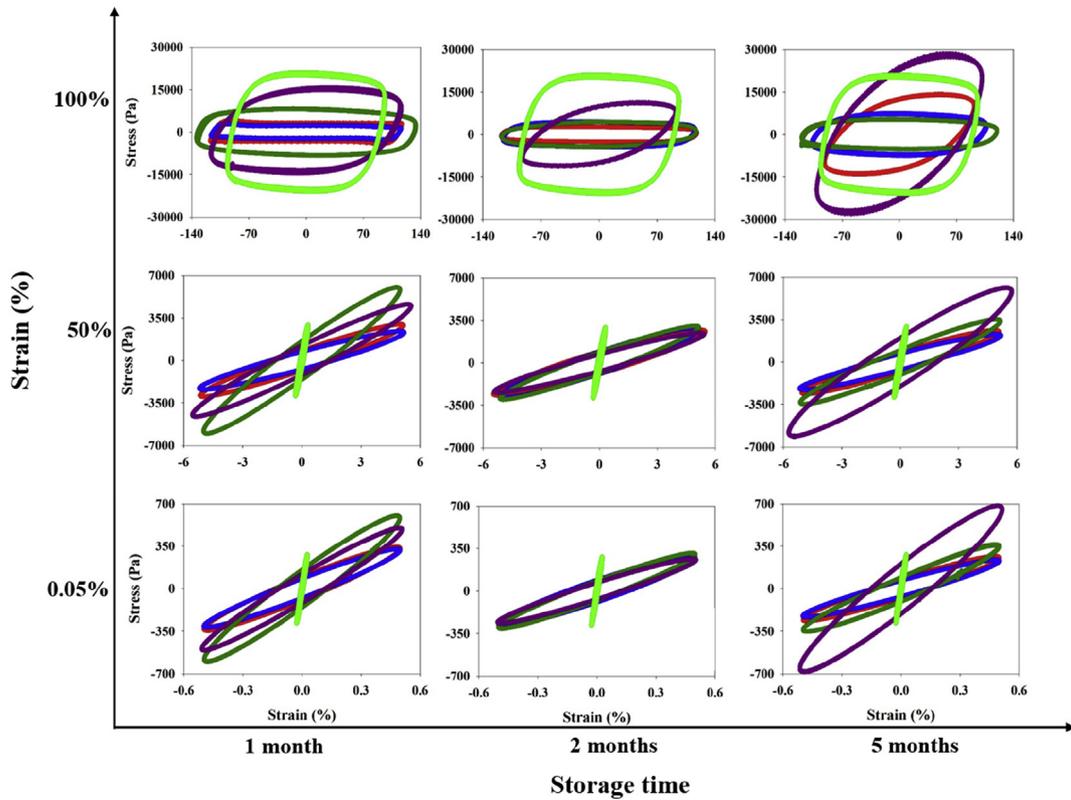


**Fig. 3.** Lissajous–Bowditch plots for low-fat cheeses at various storage timepoints: purple, control low-fat cheese made with cream; olive green, control low-fat cheese made with olive oil; bright green, full-fat control cheese; red, low-fat cheese containing emulsions at pH 3.6; blue, low-fat cheese containing emulsions at pH 5.0. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

shear rate ( $\eta'_L$ ) and minimum shear rate ( $\eta'_M$ ) can be used in a similar way to determine the extent of shear-thinning ( $\eta'_L/\eta'_M < 0.9$ ) and shear thickening behaviors ( $\eta'_L/\eta'_M > 1.10$ ) (Melito, Daubert, & Foegeding, 2012).

The LAOS parameters for cheeses at different fat contents and storage timepoints are shown in Tables 6–9. All cheeses generally showed linear viscoelastic behavior ( $G'_3/G'_1 < 0.01$ ,  $0.90 < G'_L/G'_M < 1.10$ ) at 0.05% strain and an increasing trend of  $G'_3/G'_1$ ,  $G'_3/$

$G'_1$ , and  $G'_L/G'_M$  with increased strain for all samples, in agreement with the Lissajous–Bowditch plots (Figs. 3 and 4). For all timepoints, full-fat control cheeses showed a notably greater extent of nonlinear behavior at 100% strain than any other cheese, indicating that they were easier to permanently deform. This result was likely due to their higher fat content, which would weaken the protein structure, decreasing its ability to respond to deformation without breaking. At each fat level, Cheddar cheeses containing emulsions



**Fig. 4.** Lissajous–Bowditch plots for reduced-fat cheeses at various storage timepoints: purple, control reduced-fat cheese made with cream; olive green, control reduced-fat cheese made with olive oil; bright green, full-fat control cheese; red, reduced-fat cheese containing emulsions at pH 3.6; blue, reduced-fat cheese containing emulsions at pH 5.0. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

**Table 4**

Phase angles under LAOS for low-fat (LF) Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses during 5 months storage at 6 °C.<sup>a</sup>

Storage time	Samples	Strain		
		0.05%	50%	100%
1 month	LF-Emulsion pH 3.6	13.0 ± 0.20	15.5 ± 0.44	49.0 ± 1.51
	LF-Emulsion pH 5.0	14.2 ± 1.66	15.5 ± 1.28	60.2 ± 4.99
	LF-Olive oil control	15.5 ± 0.16	15.6 ± 0.16	26.4 ± 1.25
	LF-Cream control	15.8 ± 0.30	16.3 ± 0.24	25.5 ± 0.59
	Full-fat control	14.0 ± 0.71	16.4 ± 0.15	73.2 ± 2.55
2 months	LF-Emulsion pH 3.6	16.3 ± 0.50	16.9 ± 0.45	52.1 ± 2.77
	LF-Emulsion pH 5.0	14.9 ± 0.45	23.3 ± 1.50	71.7 ± 1.13
	LF-Olive oil control	16.5 ± 0.20	18.7 ± 1.90	46.4 ± 1.23
	LF-Cream control	17.1 ± 0.11	17.6 ± 0.04	28.4 ± 1.71
	Full-fat control	12.8 ± 0.44	31.0 ± 0.17	70.4 ± 1.80
5 months	LF-Emulsion pH 3.6	16.7 ± 0.08	18.9 ± 0.19	54.0 ± 0.42
	LF-Emulsion pH 5.0	16.8 ± 0.21	24.2 ± 0.27	75.7 ± 2.09
	LF-Olive oil control	15.8 ± 0.21	16.1 ± 0.08	49.6 ± 1.85
	LF-Cream control	17.7 ± 0.11	18.2 ± 0.16	30.9 ± 0.82
	Full-fat control	13.5 ± 0.07	37.4 ± 5.77	76.3 ± 1.30

<sup>a</sup> Data are presented as mean ± standard deviation.

**Table 5**

Phase angles under LAOS for reduced-fat (RF) Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses during 5 months storage at 6 °C.<sup>a</sup>

Storage time	Samples	Strain		
		0.05%	50%	100%
1 month	RF-Emulsion pH 3.6	14.8 ± 1.00	16.0 ± 0.51	81.7 ± 7.84
	RF-Emulsion pH 5.0	14.8 ± 0.57	16.0 ± 1.19	83.1 ± 1.66
	RF-Olive oil control	14.2 ± 0.39	14.5 ± 0.42	75.3 ± 1.29
	RF-Cream control	14.1 ± 1.08	16.0 ± 1.21	54.6 ± 3.13
	Full-fat control	14.0 ± 0.71	16.4 ± 0.15	73.2 ± 2.55
2 months	RF-Emulsion pH 3.6	16.0 ± 0.10	17.3 ± 1.38	83.5 ± 2.28
	RF-Emulsion pH 5.0	17.2 ± 0.83	17.9 ± 0.41	81.1 ± 8.37
	RF-Olive oil control	14.4 ± 0.08	16.0 ± 1.20	78.7 ± 0.25
	RF-Cream control	14.7 ± 0.68	19.0 ± 1.25	69.6 ± 0.66
	Full-fat control	12.8 ± 0.44	31.0 ± 0.17	70.4 ± 1.80
5 months	RF-Emulsion pH 3.6	16.2 ± 0.14	17.7 ± 0.14	85.8 ± 4.06
	RF-Emulsion pH 5.0	18.2 ± 0.20	18.6 ± 0.03	88.1 ± 8.36
	RF-Olive oil control	15.5 ± 0.24	16.8 ± 0.12	80.4 ± 3.57
	RF-Cream control	16.9 ± 0.18	19.5 ± 0.25	72.8 ± 1.73
	Full-fat control	13.5 ± 0.07	37.4 ± 5.77	76.3 ± 1.30

<sup>a</sup> Data are presented as mean ± standard deviation.

showed less strain-hardening at higher strains according to the  $G'_L/G'_M$  values (Tables 6 and 8), suggesting that they would have less of the rubbery texture commonly associated with lower-fat cheeses. With the exception of low-fat cheeses at 1 mo storage, cheeses containing emulsions at pH 3.6 had a lower extent of nonlinear behavior and reduced strain hardening as compared to cheeses containing emulsions at pH 5.0. These results indicated that emulsion structure, which was impacted by pH [Anvari & Joyner (Melito), 2017], affected the nonlinear behavior of the cheese. They also suggest that cheeses prepared with emulsions at pH 5.0

would have textures more like full-fat cheese, although additional study is needed to confirm this. Increased strain generally resulted in a greater extent of nonlinear viscous behavior for all samples based on increasing  $G''_3/G''_1$  values (Tables 7 and 9). This was expected, as it indicated disruption of the protein network of cheese under higher strains. Overall, increased strain did not noticeably impact the extent of shear-thinning or -thickening behavior, which was not surprising as elastic-type behaviors are typically dominant in Cheddar cheese at the testing temperature (4 °C). Storage time had no definite effect on the extent or type of elastic or viscous

**Table 6**  
Elastic parameters for low-fat (LF) Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses during 5 months storage at 6 °C.<sup>a</sup>

Samples	$\gamma$ (%)	Storage time					
		1 month		2 months		5 months	
		$G'_L/G'_M$	$G'_3/G'_1$	$G'_L/G'_M$	$G'_3/G'_1$	$G'_L/G'_M$	$G'_3/G'_1$
LF-Emulsion pH 3.6	0.05	0.99 ± 0.00	0.000 ± 0.000	0.99 ± 0.01	0.000 ± 0.000	0.99 ± 0.00	0.000 ± 0.000
	50	1.01 ± 0.00	0.003 ± 0.001	0.99 ± 0.02	0.003 ± 0.000	0.98 ± 0.01	0.004 ± 0.000
	100	1.50 ± 0.56	0.221 ± 0.105	1.00 ± 0.02	0.007 ± 0.001	1.11 ± 0.01	0.004 ± 0.001
LF-Emulsion pH 5.0	0.05	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.002 ± 0.010	0.99 ± 0.00	0.022 ± 0.005
	50	1.00 ± 0.01	0.001 ± 0.000	0.99 ± 0.00	0.006 ± 0.001	0.98 ± 0.00	0.012 ± 0.001
	100	1.28 ± 0.20	0.452 ± 0.013	1.81 ± 0.04	0.072 ± 0.009	1.28 ± 0.87	0.031 ± 0.009
LF-Olive oil control	0.05	0.99 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.009 ± 0.020	1.00 ± 0.01	0.030 ± 0.010
	50	0.99 ± 0.01	0.003 ± 0.000	0.99 ± 0.03	0.007 ± 0.000	0.99 ± 0.01	0.008 ± 0.000
	100	2.89 ± 0.87	0.096 ± 0.008	1.99 ± 0.01	0.033 ± 0.000	1.31 ± 0.02	0.049 ± 0.001
LF-Cream control	0.05	0.99 ± 0.01	0.000 ± 0.000	0.99 ± 0.00	0.000 ± 0.000	0.99 ± 0.00	0.000 ± 0.000
	50	1.00 ± 0.00	0.001 ± 0.000	0.99 ± 0.00	0.000 ± 0.000	1.02 ± 0.01	0.004 ± 0.000
	100	2.15 ± 0.00	0.011 ± 0.002	2.12 ± 0.01	0.007 ± 0.002	1.34 ± 0.00	0.021 ± 0.001
Full-fat control	0.05	1.00 ± 0.00	0.001 ± 0.000	1.00 ± 0.01	0.000 ± 0.000	1.00 ± 0.00	0.000 ± 0.000
	50	1.02 ± 0.00	0.009 ± 0.000	1.08 ± 0.00	0.022 ± 0.002	1.22 ± 0.01	0.094 ± 0.006
	100	5.24 ± 0.25	0.038 ± 0.018	3.40 ± 0.90	0.495 ± 0.204	1.42 ± 0.00	0.714 ± 0.004

<sup>a</sup> Absolute values of  $G'_3/G'_1$  values were used; data are presented as mean ± standard deviation.

**Table 7**  
Viscous parameters for low-fat (LF) Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses during 5 months storage at 6 °C.<sup>a</sup>

Samples	$\gamma$ (%)	Storage time					
		1 month		2 months		5 months	
		$\eta'_L/\eta'_M$	$G''_3/G''_1$	$\eta'_L/\eta'_M$	$G''_3/G''_1$	$\eta'_L/\eta'_M$	$G''_3/G''_1$
LF-Emulsion pH 3.6	0.05	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.001 ± 0.000	1.00 ± 0.00	0.000 ± 0.000
	50	1.04 ± 0.02	0.008 ± 0.004	0.99 ± 0.02	0.008 ± 0.000	0.94 ± 0.01	0.002 ± 0.008
	100	0.98 ± 0.06	0.013 ± 0.000	0.97 ± 0.02	0.005 ± 0.000	0.93 ± 0.01	0.004 ± 0.001
LF-Emulsion pH 5.0	0.05	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.01	0.013 ± 0.010	0.99 ± 0.00	0.000 ± 0.000
	50	1.03 ± 0.00	0.006 ± 0.001	1.00 ± 0.02	0.006 ± 0.002	0.97 ± 0.00	0.004 ± 0.000
	100	1.00 ± 0.04	0.036 ± 0.008	0.98 ± 0.11	0.032 ± 0.002	0.92 ± 0.02	0.028 ± 0.007
LF-Olive oil control	0.05	0.99 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.000 ± 0.000
	50	1.06 ± 0.04	0.014 ± 0.009	0.99 ± 0.03	0.006 ± 0.000	0.99 ± 0.01	0.002 ± 0.000
	100	1.01 ± 0.03	0.046 ± 0.010	0.99 ± 0.06	0.028 ± 0.010	1.07 ± 0.03	0.014 ± 0.005
LF-Cream control	0.05	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.02	0.000 ± 0.000	1.00 ± 0.01	0.002 ± 0.001
	50	1.00 ± 0.01	0.001 ± 0.000	0.99 ± 0.00	0.001 ± 0.000	0.99 ± 0.01	0.002 ± 0.000
	100	0.96 ± 0.00	0.013 ± 0.001	0.95 ± 0.00	0.012 ± 0.005	0.96 ± 0.01	0.012 ± 0.005
Full-fat control	0.05	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.01	0.003 ± 0.000	1.01 ± 0.00	0.003 ± 0.000
	50	1.02 ± 0.02	0.009 ± 0.000	1.12 ± 0.02	0.020 ± 0.006	1.29 ± 0.03	0.058 ± 0.008
	100	1.01 ± 0.05	0.035 ± 0.003	1.05 ± 0.06	0.023 ± 0.006	0.90 ± 0.01	0.064 ± 0.009

<sup>a</sup> Absolute values of  $G''_3/G''_1$  values were used; data are presented as mean ± standard deviation.

**Table 8**  
Elastic parameters for reduced-fat (RF) Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses during 5 months storage at 6 °C.<sup>a</sup>

Samples	$\gamma$ (%)	Storage time					
		1 month		2 months		5 months	
		$G'_L/G'_M$	$G'_3/G'_1$	$G'_L/G'_M$	$G'_3/G'_1$	$G'_L/G'_M$	$G'_3/G'_1$
RF-Emulsion pH 3.6	0.05	1.00 ± 0.00	0.000 ± 0.000	0.99 ± 0.01	0.000 ± 0.000	0.99 ± 0.00	0.000 ± 0.000
	50	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.02	0.001 ± 0.000	0.99 ± 0.01	0.002 ± 0.001
	100	1.29 ± 0.11	0.005 ± 0.000	2.00 ± 0.02	0.007 ± 0.000	1.01 ± 0.01	0.012 ± 0.002
RF-Emulsion pH 5.0	0.05	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.003 ± 0.000	0.99 ± 0.00	0.000 ± 0.000
	50	1.00 ± 0.00	0.000 ± 0.000	0.99 ± 0.00	0.003 ± 0.000	0.98 ± 0.00	0.005 ± 0.000
	100	2.00 ± 1.00	0.058 ± 0.007	2.71 ± 0.11	0.072 ± 0.009	1.32 ± 0.01	0.411 ± 0.099
RF-Olive oil control	0.05	0.99 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.001 ± 0.000	0.99 ± 0.00	0.000 ± 0.000
	50	0.99 ± 0.01	0.003 ± 0.000	0.99 ± 0.03	0.007 ± 0.000	0.98 ± 0.01	0.009 ± 0.000
	100	2.12 ± 0.34	0.878 ± 0.023	2.99 ± 0.01	0.933 ± 0.060	1.53 ± 0.08	2.035 ± 0.054
RF-Cream control	0.05	1.00 ± 0.01	0.000 ± 0.000	0.99 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.000 ± 0.000
	50	1.00 ± 0.00	0.002 ± 0.000	0.99 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.001 ± 0.000
	100	2.31 ± 0.22	0.327 ± 0.009	3.57 ± 0.21	0.010 ± 0.031	1.18 ± 0.08	0.041 ± 0.001
Full-fat control	0.05	1.00 ± 0.00	0.001 ± 0.000	1.00 ± 0.01	0.000 ± 0.000	1.00 ± 0.00	0.000 ± 0.000
	50	1.02 ± 0.00	0.009 ± 0.000	1.08 ± 0.00	0.022 ± 0.002	1.22 ± 0.01	0.094 ± 0.006
	100	5.24 ± 0.25	0.038 ± 0.018	3.40 ± 0.90	0.495 ± 0.204	1.42 ± 0.00	0.714 ± 0.004

<sup>a</sup> Absolute values of  $G'_3/G'_1$  were used; data are presented as mean ± standard deviation.

**Table 9**

Viscous parameters for reduced-fat (RF) Cheddar cheeses containing concentrated emulsions, controls (containing olive oil or cream), and full-fat cheeses during 5 months storage at 6 °C.<sup>a</sup>

Samples	$\gamma$ (%)	Storage time					
		1 month		2 months		5 months	
		$\eta'_{L}/\eta'_{M}$	$G''_{3}/G''_{1}$	$\eta'_{L}/\eta'_{M}$	$G''_{3}/G''_{1}$	$\eta'_{L}/\eta'_{M}$	$G''_{3}/G''_{1}$
RF-Emulsion pH 3.6	0.05	0.99 ± 0.00	0.000 ± 0.000	0.99 ± 0.00	0.000 ± 0.000	0.99 ± 0.00	0.000 ± 0.000
	50	1.00 ± 0.02	0.001 ± 0.000	1.01 ± 0.00	0.002 ± 0.000	1.00 ± 0.00	0.002 ± 0.000
	100	1.00 ± 0.00	0.340 ± 0.054	1.03 ± 0.01	0.130 ± 0.081	1.15 ± 0.01	0.031 ± 0.001
RF-Emulsion pH 5.0	0.05	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.001 ± 0.010	0.99 ± 0.01	0.000 ± 0.000
	50	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.006 ± 0.002	1.00 ± 0.01	0.004 ± 0.000
	100	0.77 ± 0.00	0.126 ± 0.034	0.99 ± 0.00	0.032 ± 0.002	1.25 ± 0.07	0.052 ± 0.012
RF-Olive oil control	0.05	0.99 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.000 ± 0.000
	50	1.01 ± 0.00	0.003 ± 0.000	0.99 ± 0.01	0.003 ± 0.000	1.01 ± 0.01	0.004 ± 0.002
	100	0.91 ± 0.00	0.209 ± 0.077	1.00 ± 0.01	0.126 ± 0.022	0.98 ± 0.05	0.085 ± 0.009
RF-Cream control	0.05	1.00 ± 0.00	0.001 ± 0.000	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.00	0.000 ± 0.000
	50	1.02 ± 0.00	0.002 ± 0.000	1.01 ± 0.00	0.002 ± 0.000	1.00 ± 0.00	0.001 ± 0.000
	100	1.22 ± 0.02	0.028 ± 0.014	1.25 ± 0.01	0.042 ± 0.005	1.17 ± 0.05	0.026 ± 0.010
Full-fat control	0.05	1.00 ± 0.00	0.000 ± 0.000	1.00 ± 0.01	0.003 ± 0.000	1.01 ± 0.00	0.003 ± 0.000
	50	1.02 ± 0.02	0.009 ± 0.000	1.12 ± 0.02	0.020 ± 0.006	1.29 ± 0.03	0.058 ± 0.008
	100	1.01 ± 0.05	0.035 ± 0.003	1.05 ± 0.06	0.023 ± 0.006	0.90 ± 0.01	0.064 ± 0.009

<sup>a</sup> Absolute values of  $G''_{3}/G''_{1}$  were used; data are presented as mean ± standard deviation.

nonlinearity, which was unexpected based on the strain sweep results and the findings in Part 1 of this study [Anvari & Joyner (Melito), 2018]. Thus, the structural changes during storage impacted the overall strength of the casein matrix, but not its behavior under large shear strains. Overall, cheese nonlinear viscoelastic behavior appeared to be more affected by the original structure rather than the changes to the structure over time.

#### 4. Conclusions

In this study, we considered the effect of adding concentrated emulsions as novel fat replacers on the viscoelastic linear and nonlinear behaviors of reduced-fat and low-fat Cheddar cheeses during 5 mo storage at 6 °C. Cheeses made with concentrated emulsions, regardless of aqueous phase pH, showed less resistance and stability to large shear strain deformation, and lower moduli and critical stress values compared with the controls. This was attributed to greater discontinuity of the casein network and more open spaces created by aggregated emulsion droplets. Viscoelastic linear behaviors of all cheese samples changed with storage time, implying a greater degree of the casein matrix proteolysis with longer storage times. However, the viscoelastic nonlinear behavior was more affected by fat type and applied strain than storage time, indicating that the manner in which the cheese structure deformed under large shear strain more highly impacted by structural organization rather than changes to the structure over time. The results of this study can be used for development of low-fat or reduced-fat cheeses with textures similar to full-fat cheese. They can also be extended to other food products with similar structures to create solid foods with a softer, less rubbery texture.

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#### Appendix A. Supplementary data

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