Wear Behavior of Cheese as Affected by Varying Fat Contents

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Authorization to Submit Dissertation

This dissertation of Fariba Zad Bagher Seighalani, submitted for the degree of Doctor of Philosophy with a Major in Food Science and titled, "Wear behavior of cheese as affected by varying fat contents," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Cheese sliceability and shreddability are two main concerns for manufacturing palatable and functional cheese shreds and slices. However, processing behaviors may differ among cheeses with different fat contents because fat plays a crucial role in cheese texture. These differences may impact cheese processing behaviors. Wear testing and particularly mass loss measurements could be used as a quality control test to predict cheese processing behaviors as wear testing can imitate processing conditions which involve rubbing such as slicing and shredding. However, wear, a dimension of tribology, has been neglected in previous food tribology studies. Thus, the objectives of this project were to identify significant factors influencing cheese wear, determine the relationships among rheological, sensory, and wear behaviors, and develop a mathematical model to predict cheese mass loss. We started with preliminary work on two types of cheese: Monterey Jack and Cheddar. The two cheeses showed different wear and rheological behaviors, indicating relationships between cheese wear and rheological behaviors. In the formal study, cheeses with 40, 50, 52, and 54% fat (dw) at different aging times (15, 30, 45, and 60 d) were evaluated. Wear measurements were performed using a rheometer equipped with a steel twin ball-on-disc system using a range of normal forces (0.5 and 0.7 N), sliding speeds (30 and 50 mm/s), and temperatures (5, 15, and 25°C). Penetration depth (mm) and friction coefficient were recorded, and mass loss was measured by calculating differences between sample weights before and after testing. A box plot model was created based on mass loss and expert classification of cheese processing abilities. Rheological tests, including large amplitude oscillatory shear (LAOS), strain sweeps at different temperatures (5, 15, and 25ºC) and frequencies (0.5, 5, and 50 rad/s), and large-strain compression at room temperature (22±2ºC), were used to measure cheese viscoelastic

and fracture behaviors. Descriptive sensory analysis was used to evaluate cheese sensory texture attributes. To develop a wear model for cheese, mass loss and friction coefficient were used as the primary responses. Maximum strength derived from LAOS data was selected as a key rheological property for the model. Buckingham Pi theorem was used to find the relationship between the factors influencing wear behaviors and to construct the wear prediction model. Sensitivity analysis was conducted to determine the impact of each independent variable on mass loss. Mass loss was significantly affected by temperature, normal force, sliding speed, fat content, and aging time. Higher normal force resulted in significantly lower mass loss in all cheeses but C40 at 25°C, while penetration depth was higher at higher normal force. Mass loss values were significantly impacted at different temperatures at constant sliding speed and normal force. The highest mass loss was at 15ºC except for C40, mass loss was significantly lower at 5ºC and 25°C. However, penetration depth was significantly lower at 5ºC and increased at higher temperatures. Mass loss and penetration depth had lower p-values at higher sliding speed and also increased as cheeses aged up to 60 d. Fat content, temperature, and aging time also had significant impact on cheese viscoelastic parameters. Higher temperature, aging time, and fat content led to lower rigidity and a greater extent of nonlinear viscoelastic behaviors in the cheeses. Mass loss was negatively correlated with critical strain, critical stress, complex modulus, and fracture stress, but was positively correlated with phase angle and fracture strain. Sensory data showed that texture attributes were affected by cheese fat content and aging time and were significantly correlated to mass loss at high normal force and sliding speed. The developed model showed a mean absolute error (MAE) of 0.001g, which considered small compared to the average value of mass loss from the cheese samples (approximately 0.102 g for an approximately 30 g sample), indicating good fit. Sensitivity analysis showed that mass loss was most influenced by normal force, followed by sliding speed, friction coefficient, and maximum strength. The results of this study provided valuable information for understanding wear behavior of cheese and its relationships with rheology and sensory behaviors. The findings of this project can help manufacturers improve and predict processing behaviors of cheese or similar food products such as Deli meat.

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Dedication

I would love to dedicate this work to my dad who was my hero and left the world the week before my defense.

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Chapter 1: Introduction

Cheese consumption and popularity have been growing over time due to their nutritional values and palatability. Also, there is a growing demand for shredded and sliced cheese. Functionality of cheese, such as shreddability and sliceability, are important for successful processing. Moreover, low-fat cheese is becoming increasingly popular because of changes in people's diets to healthy options. Fat plays a vital role in the formation of desirable texture of cheese, and fat reduction can lead to firm, rubbery, and dry textures. Also, cheese functionality, such as shreddability and sliceability, might differ among cheeses with various fat contents due to structural differences. Some challenges that can occur during production of cheese products include sticking to processing surfaces and clogging of the slicer or shredder, which can lead to low-quality cheese shreds or slices. The determination of processing ability of newly formulated cheeses relies on experience of how similar cheeses processed; having a quantitative method for determining cheese processing behavior and a predictive model for behavior of novel cheese formulations can help cheese manufacturers to assess the processing ability of new products.

Tribology encompasses the lubrication, friction, and wear of materials. There are numerous studies on food tribology that have evaluated friction and lubrication behaviors of foods (Chen, Jianshe ; Stokes, 2012; Melito, Pernell, & Daubert, 2014; Selway & Stokes, 2013; Stokes, Boehm, & Baier, 2013). However, the wear behaviors of foods have been neglected. Wear is defined as a mass loss and deformation of materials when two contacting surfaces move on each other in relative motion (Axén, Hogmark, & Jacobson, 2000). It is an indicator of material resistance to damage and can be a result of mechanical or chemical changes in material structures (Kato & Adachi, 2001). Wear is an area of tribology that has been neglected in food tribology studies. Furthermore, wear phenomena in soft materials are complicated due to their low elasticity and elastic modulus, a high degree of deformation under normal loads, and significant internal energy dispassion during deformation compared to hard materials (Popov, 2019).

Both quantitative data and mathematical relationships are beneficial for better understanding the wear of materials. Experimental data can include information related to material components, surfaces, environmental conditions, and wear topography (Bayer, 2002). Hard (nondeformable), monophasic materials obey Archard's law, meaning that wear volume changes directly and proportionally with the applied normal load and sliding distance, and inversely with material hardness. However, soft materials do not obey Archard's law because they deform under pressure and typically have more than one phase. Additionally, phase separation may occur during the wear process, making the understanding of the wear mechanism(s) challenging. Thus, during wear analysis, many factors that impact on wear of soft systems are likely overlooked.

Because soft materials exhibit significant deformation under an applied force, permanent deformation at the contact points during the wear of soft materials is a primary factor in the formation of the wear track and wear particles. Therefore, rheology is an inseparable part of understanding wear behavior of soft materials. Oscillatory shear tests and large strain compressive tests are beneficial rheological techniques for a better understanding of mechanical behavior of cheese, and they are likely related to wear and processing behaviors.

In addition, some studies have showed correlations between textural sensory attributes, such as firmness, hardness, and degree of breakdown, with mechanical properties of cheese (Abson et al., 2014; Foegeding & Drake, 2007; Melito, Daubert, & Foegeding, 2013; Rogers et al., 2009). We hypothesize that textural properties evaluated by sensory analysis are also related to wear behaviors of cheese because oral processing involves rubbing of the food against oral surfaces and subsequent mass loss.

The amount of mass loss during wear depends on both environmental conditions and internal structure of the wearing materials. Studies of wear behavior of hydrogels and articular cartilages, which are soft solids with microstructures similar to those of hard cheeses, have provided valuable information for the durability of artificial cartilage by considering the materials and their lubrication properties (Yarimitsu, S., Sasaki, S., Murakami, T., & Suzuki, 2016). Also, a study on high-protein bars with different formulations showed a relation between wear rate with processing ability (Sparkman, Joyner, & Smith, 2019). Similarly, information on cheese wear behaviors could give valuable information about its processing ability.

Modeling of wear is an efficient tool for wear assessment. Wear models can be developed to investigate wear mechanisms, provide information for further experiments, and optimize system design. Accurate wear modeling is necessary for proper description of the wear process and industrial process design. Wear models are typically developed through empirical and mathematical observations and validated using experimentally representative processes or numerical simulations (Abdelgaied et al., 2011a; Sudheer, Prabhu, Raju, & Bhat, 2013; Tan &

Joyner, 2018b; Viswanath & Bellow, 1995a). Developing of mathematical modeling for cheese could be a cost-effective way for manufacturers to predict processing ability of cheeses.

The study of food wear is not a well-documented area in food science, and there are many dimensions that need to be discovered. It is also appeared to be a new method to understanding processing ability of food products (Sparkman et al., 2019). There is only one published study on cheese wear to date (Zad Bagher Seighalani, & Joyner, 2019). However, discovering and quantifying cheese wear mechanisms could provide useful information to cheese manufactures to assess the shreddability and sliceability of their new products and optimize processing abilities of their current products by considering cheese compositional properties and controlling processing parameters. Thus, the overall goal of this study is to understand the wear behaviors of hard cheeses with varying fat contents, which was achieved by designing three objectives: 1) develop a method for measuring cheese wear, 2) identify significant parameters influencing wear behaviors of cheese, 3) determine relationships between rheology and sensory with wear data, 4) develop a mathematical model for predicting cheese wear.

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Chapter 2: Literature Review

Cheese is one of the most popular value-added dairy products, and its demand has increased considerably over the past 50 years. Fat plays an important role in giving cheese good texture and flavor, although it is a concern to consumers, especially for those who are health-conscious (Amelia, Drake, Nelson, & Barbano, 2013; Mohamed, 2015). It has been established that a high-fat diet contributes to greater rates of many diseases like cancer and heart disease (Kuller, 1997). Thus, reduced-fat cheese as a healthier alternative has become popular among consumers, with dramatic changes in consumer eating patterns and development in cheese technology.

Cheese industries are also concerned about the quality of slices or shreds of different cheeses with various fat contents as sticking of cheese to slicer blades or wires is a potential obstacle that can lead to low-quality sliced or shredded cheeses. Understanding the wear behavior of cheese and its relationship with rheology and sensory behaviors, as well as developing a wear model, could provide useful information for solving cheese processing issues.

Cheese composition and structure

Cheese is composed of predominantly protein, fat, and moisture (Figure 2.1). The main component of cheese is the casein proteins, which are arranged as micelles. Caseins are a family of phosphoproteins consisting of four major members, αs1-, αs2-, β- and κ-casein, in the proportions of 4:1:4:1, respectively. Although all are casein molecules, they have different lengths and a different composition of the amino acids that give them slightly different functionalities. Caseins aggregate and form a structural network, called a micelle, with calcium phosphate acting as a glue to hold them together. Casein proteins are notably heat-stable but are sensitive to pH changes. During cheesemaking, the addition of rennet (rennin or chymosin) breaks the peptide bonds of κ-casein on the surface of the casein micelles, cleaving their C-termini or caseinomacropeptide (CMP) hairs as the pH decreases. When about 80% of κ-casein is hydrolyzed, the colloidal stability of the micelles is reduced, causing the casein micelles to coagulate in the presence of calcium ions. Fat globules and moisture are entrapped in the protein (casein) network that forms and form the main structure of cheese. About 95-99% of caseins are retained in cheese after whey drainage, while retention of fat is about 89-93% at the final product (Amenu & Deeth, 2007). Different ratios of fat, protein, and moisture in cheese lead to different mechanical properties and texture characteristics. Variation in cheese moisture content, fat, and protein can occur due to different raw milk quality and processing conditions during cheese production (Sahan, Yasar, Hayaloglu, Karaca, & Kaya, 2008).

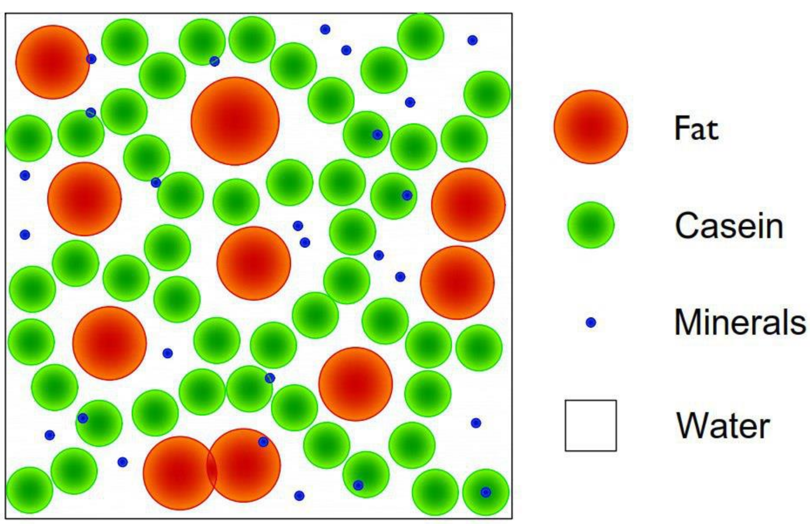

Figure 2.1. Cheese structure.

Cheese production

Commercial cheesemaking begins with similar processing steps regardless of the cheese variety (Bugaud et al., 2001). In the first step, whole milk is pasteurized in vats at 71ºC for 15 s. After cooling the milk to 31ºC, pasteurized milk may be pre-acidified by mixing with 0.5-1% starter cultures such as *Lactococcus lactis* subsp. *lactis*, *Lactococcus lactis* subsp. *cremoris*, and *Streptococcus salivaris* subsp. *thermophilus* at 30ºC for 40 min, resulting in a decrease in pH. Addition of starter cultures also plays an important role in texture and flavor development during storage (Lucey, Johnson, & Horne, 2003). Then, rennet and potentially salt (calcium chloride) are added to coagulate the milk. After formation of the coagulum, the curd is cut and cooked at 40ºC for 30 min to reach a pH between 6.1 and 6.4, then whey is drained while stirring the curd for maximum drainage. For Cheddar cheese, the curd is piled and milled to reach a pH 5.2-5.4, which is called "cheddaring". Cheddaring improves the quality of cheese because it promotes whey drainage and increased acid production (Amelia et al., 2013). Cheddaring is followed by milling the curd loaves and sprinkling salt over the curd to enhance flavor, control fermentation, and decrease the moisture content. After the salt is absorbed, the curd is hooped and pressed overnight at room temperature. The cheese is then vacuum-packed, stored at 5ºC in the dark, and ripened at 6 to 8ºC for various time periods depending on cheese type.

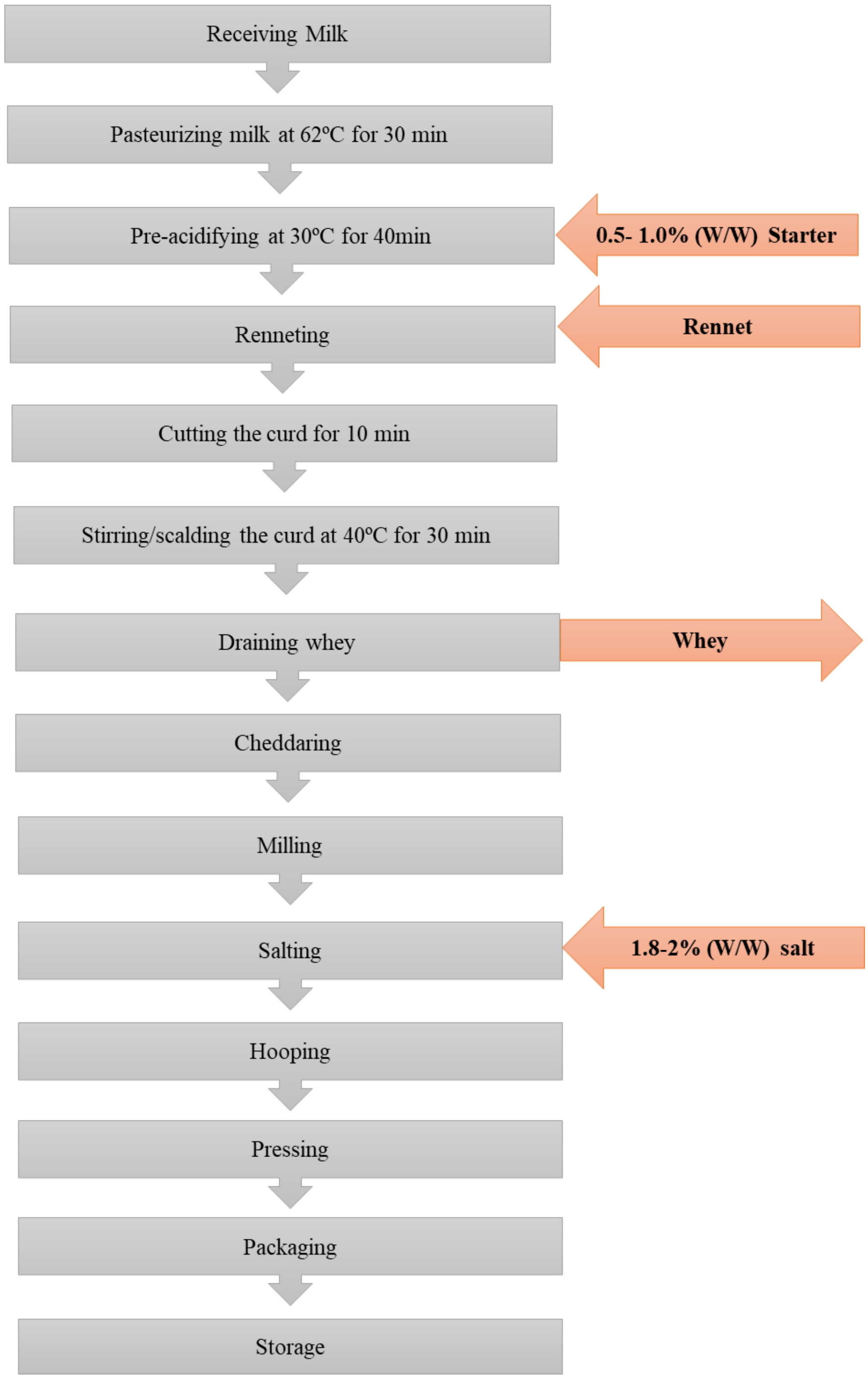

Figure 2.2. Cheese-making process.

Factors affecting cheese quality

Cheese quality relates to appearance, texture, flavor, nutritional value, and shelf-life. The parameters of the cheesemaking process and the type and quality of raw materials have a significant impact on the end product. The main factors impacting cheese quality include pH, heating, salt, and composition.

pH

pH measurement is a quality and safety control step during cheesemaking to ensure that the desired flavor and texture are met, and all batches are consistent (Everard et al., 2006). It is a critical factor in gelation, rennet activity, and syneresis of the cheese curd and ultimately the textural and functional properties of cheese (Choi et al., 2012). The pH of cheese curd is determined by the extent of acidification during production, buffering capacity of protein and fat in the curd and, in some cases, deacidification during ripening. However, titratable acidity measurements are more commonly used for quality assurance during cheese production because they are easier to perform and lower in cost compared to pH measurements.

The changes in pH are related to the chemical changes in the protein network. As pH decreases, the texture of cheese becomes shorter and more brittle. The desired pH differs among cheeses. Most cheeses have a pH between 5.1 and 5.9; a pH of 5.0 is considered too acidic for many cheeses. For example, the optimum pH for Cheddar cheese is between 5.2-5.25 (Amenu & Deeth, 2007). Hard-pressed cheese with pH of 4.9 to 5.0 has short and crumbly texture. However, pH of 4.2-4.8 is suitable in feta cheese (Rashidi & Razavi, 2015), which has a very brittle and crumbly texture. Some cheeses such as Brie and Camembert have a pH of 7.0, which gives a very soft texture. In terms of microbiological safety, acid development and reducing pH mitigates the growth of pathogenic bacteria. In addition, the growth of unappealing gas-forming organisms, such as coliforms, is gradually slowed as pH decreases below 5.4 (Amelia et al., 2013).

Temperature

Heating plays an important role during and after cheese production. During heating, cheese structure and functional properties undergo many changes (Muliawan, 2004; Tunick, 2010a, 2010b). The most recognized consequences of heat treatment are loss of coagulability by rennet, increase of gelation time, and a reduction in gel firmness (Broyard & Gaucheron, 2015). If the heat treatment is lower than 95ºC for 10 minutes, protein conformational changes are reversible are reversible. In contrast, at temperatures higher than 110ºC, the phosphoseryl residues of caseins can be partially hydrolyzed, leading to irreversible changes in the casein micelle structure and salt distribution (Van Boekel 1999). In addition to altering protein configuration, heat treatment kills harmful microorganisms in cheese milk (Muliawan, 2004). At 29-30ºC, the growth of starter bacteria is at an optimum, but when the temperature increases during cheese production, acid development caused by production of acids by starter cultures is slowed due to reduction in bacterial growth. Use of lower cooking temperatures during cheese production can result in higher moisture content in cheese, increase lactic acid and other bacteria that allow development of off-flavors such as “bitter” and “unclean in cheese (Abson et al., 2014).

Salt

The primary role of salt in cheese manufacture is the reduction of water activity that prevents the growth of harmful bacteria and controls lactic acid production in cheese (El-Bakry, 2012).

In addition, salt contributes to the taste of cheese and acts as a flavor enhancer. Salt concentration in cheese varies from about 0.7 to 4g in 100g cheese (El-Bakry, 2012). Processed cheese has a higher level of salt compared to natural cheese since in processed cheese, the addition of emulsifying salts is essential. For example, sodium chloride is used to disperse proteins and fats to gain a homogenous texture (Dimitreli & Thomareis, 2004). In Cheddar cheese, the reduction of salt below 1.5% leads to an undesirable taste due to the growth of pathogen and spoilage bacteria that cause excessive proteolysis (El-Bakry, 2012). However, higher levels of salt (1.8-3%) produced a desirable high- intensity Cheddar flavor (Rutikowska,, Kilcawley,Doolan, Alonso-Gomez, 2008). Additionally, the interaction of salt with major components in cheese affects the functional properties of the final product. Salt impacts cheese texture properties by changing the water binding capacity of the caseins in the cheese matrix and the viscosity of the aqueous phase. Salt content also influences the texture of cheeses during aging (El-Bakry, 2012). For example, Mozzarella cheese with lower salt concentration softens faster during aging (Vincent Banville, 2016), and Mozzarella containing higher salt content is less meltable and stringy compared to those lower salt, which could be due to insufficient proteolysis caused by high salt content (Ah, 2017).

Aging

Aging of cheese contributes to the final texture through chemical and structural changes caused by casein proteolysis over time (Attaie, 2005; Rogers et al., 2009). There are two phases of texture change during storage. The first phase usually happens within 7 to 14 d after production. During this time, the rubbery and elastic texture of the fresh cheese softens via proteolysis of 20% of the caseins (Lawrence,Creamer, & Gilles, 1987). A more gradual change in cheese texture occurs during phase two of ripening, which occurs over a period of 14-90 d

(Attaie, 2005; Rogers et al., 2009). During this time, the remaining α_{s1}-casein and the other caseins are hydrolyzed. Unlike the first phase, which takes only days, the second phase occurs over a period of months (Lawrence et al.,, 1987). This degradation of the casein network over time results in a less firm and more deformable cheese (Brown, Foegeding, Daubert, Drake, & Gumpertz, 2003). However, the changes in cheese slow after 1 month when most of the caseins are hydrolyzed.

Cheese composition

Cheese quality is affected by its composition, which is dependent on the composition of milk used for cheese manufacture (Lawrence, Creamer, & Gilles , 1987). The required casein to fat ratio for making cheese is usually standardized by altering the fat content of milk prior to cheesemaking to give the cheese the required fat-in-dry matter and moisture in the fat-free substance. Lower fat cheeses are generally made from lower fat milk, resulting in higher protein to fat ratios than in full-fat cheeses (Rogers et al., 2009). Removing all or a part of the fat content from cheese can negatively impact the cheese flavor and texture and reduce its functionality. Cheeses with lower fat have a denser protein network, which results in firm, elastic, and grainy texture (Rogers et al., 2009). Protein content directly impacts cheese firmness: higher protein content results in a firmer cheese. Consumer sensory evaluation of lower-fat cheeses through focus groups showed that lower-fat cheeses had undesirable flavor and texture such as plain flavor and a rubbery, sticky, less meltable texture. It was also found that the users, in spite of regularly consuming reduced-fat cheeses, were still uncertain about choosing low-fat cheeses (Johnson & Chen, 1995).

In most types of cheese, the majority of moisture droplets are present within the protein matrix. Cheese with a higher level of moisture is generally softer because moisture acts as plasticizer in cheese structure. Also, increased moisture levels resulted in a decrease in the casein content. Because caseins are a backbone of cheese structure, less casein makes the cheese structure softer (Attaie, 2005). During cheesemaking, the concentration of casein in the curd increases as the curd is cut and approximately 97% of the whey is released from the curd (Amenu & Deeth, 2007). The rate and amount of whey expulsion also influence the functionality of cheese through the direct effect on moisture content, protein and fat losses in whey, and overall timescale of cheese production. Different cheesemaking process result in different amounts of residual whey after whey drainage, which impacts the final cheese texture. Thus, hard cheeses with low whey content and soft cheeses such as brie and cream cheese with high whey content can be manufactured using different procedures and processing variables.

Cheese machinability

Machinability is a comprehensive term that defines the ability of cheese to be shredded, sliced, or cut (Lucey et al., 2003). It is important for both manufacturers and consumers to reduce the size of cheese large cheese blocks, which can be 40 to over 640 lb, without damaging the cheese surface or producing fines, or the formation of small cheese particles.

Shreddability of cheese is defined as the ability with which the cheese block can be shredded on commercial equipment (V Banville, Morin, Pouliot, & Britten, 2014; Childs, Daubert, Stefanski, & Foegeding, 2007). The uniformity, size, and shape of cheese shreds are taken into account in defining shreddability of cheese. Ideally, cheese should have uniform shreds because the consistent size and shape allows shreds to melt easily and evenly (Childs et al., 2007).

Many factors are important in determining manufacturing cheese with a good shreddability. When cheese is high in moisture and has soft and pasty texture, it may clog in the shredder and result in excessive matting of cheese without anti-caking agents. In contrast, when cheese is low in moisture and has a crumbly texture, it may result in formation of particles and fines during processing (Vincent Banville, 2016). Kindstedt (1995) reported a higher degree of matting in Mozzarella shreds containing 45% fat compared with cheeses containing 10, 20, and 30 % fat, indicating that cheese with high fat and moisture produces low-quality cheese shreds (V Banville et al., 2014).

The age of the cheese is also a factor influencing the quality of cheese shreds. Kindstedt (1995) reported that young Mozzarella cheese did not produce good-quality shreds, but shreddability improved when cheese was stored for 3 wk at 4ºC. These alterations were due to excessive moisture on the surface and within the body of the cheese. It is hypothesized that desirable cheese shredding ability is associated with the optimal hydration of the protein phase. During aging, free water droplets are absorbed, and gradual swelling of the protein phase causes protein-water bonds at the expense of protein-protein interactions, resulting in a less rigid and more flexible protein network (Childs et al., 2007).

Sliceability is defined as the ability of cheese to be cut into thin pieces, resist cracks during slicing, and undergo a high level of bending before breaking (Perrie, 2012). During the size reduction process, the cheese matrix is fractured by an external force applied to the cheese using a blade or wire. The mechanical characteristics of cheese depend on its composition, structure, and rheological properties. A high moisture content gives a softer texture to cheese because protein content decreases as moisture increases. A higher moisture to protein ratio leads to greater adhesion in cheese and less brittleness, while low moisture content increases brittleness (Carunchia Whetstine, Drake, Nelson, & Barbano, 2006). Wotkinson et al. (2002) found that a large increase in adhesiveness potentially caused poor sliceability of the cheese as the moisture content of Cheddar cheese increased from 40% to 48%. O'Callaghan and Guinee (2004) showed a correlation between springiness and sliceability: as the cheese transfers through the slicer, unified and cohesive slices will be produced if it recovers rapidly. Thus, cheeses which are springy tend to have good sliceability, while sticky cheeses will adhere to the blade of slicers. Moreover, a study by Rasmussen (2007) on Cheddar cheese found that the frequency of fracturing increased as the cheese ripened from 7d to 12 months and the hardness and cohesiveness decreased. Also, a more brittle and crumbly texture resulted in poor physical properties for sliceability.

Cheese mechanical behavior

To efficiently make and process cheese, mechanical behavior must be investigated. Information on mechanical behaviors allows engineers to design optimized cheese processes and equipment. From a material perspective, cheese is a viscoelastic solid that displays nonlinear elastic behavior under industrial and oral processing (Melito et al., 2013; Rogers et al., 2009).

Rheological measurements

Rheology studies the deformation and flow of material in response to applied strain or stress (Steffe, 1996). Rheological testing has wide applications in the food industry, and cheese was one of the first foodstuffs to be tested by fundamental rheological techniques. In general, rheological measurements on cheese are performed for quality control and maintaining product consistency by cheese manufacturers and helps reduce future processing issues (Athar, 2011).

Oscillatory shear tests are broadly used for viscoelastic material characterization. The basic principle in oscillatory testing is to induce a sinusoidal shear deformation in the sample and measure the resulting stress. In general, oscillatory shear tests on soft materials can be divided into two regimes (Figure 2.3): linear viscoelastic response, which are measured by small amplitude oscillatory shear (SAOS) tests, and nonlinear viscoelastic response, which are measured by large amplitude oscillatory shear (LAOS) tests. In the linear viscoelastic regime, the stress response is proportional to the applied strain and no permanent microstructural deformation occurs. In the nonlinear viscoelastic regime, typically at high strains, the stress response is not proportional to the strain input, and the material undergoes permanent deformation (Steffe, 1996). Viscoelastic response is quantified by two material measures, namely the elastic (storage) modulus, G', and the viscous (loss) modulus, G''. G' is defined as the stored energy per deformation cycle and describes elastic properties, whereas G'' is defined as the energy lost per deformation cycle and represents the viscous portion of materials (Steffe, 1996). Cheese is a viscoelastic material; the value of the storage modulus is greater than that of the loss modulus, meaning that solid-like behavior is predominant (Brown et al., 2003; Bugaud et al., 2001; Guinee, Auty, & Mullins, 1999; Melito et al., 2013; Rogers et al., 2009).

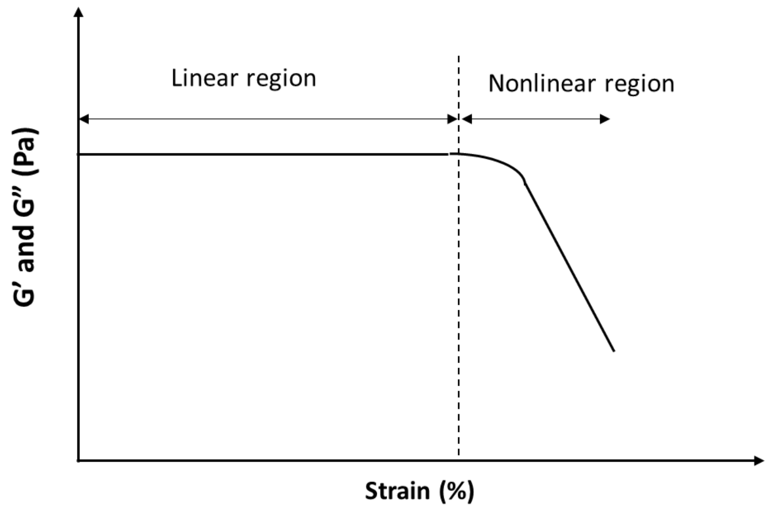

Figure 2.3. Schematic illustration of the linear and nonlinear viscoelastic region.

Small Amplitude Oscillatory Shear (SAOS) tests

SAOS tests provide useful data to determine rheological characterizations of complex fluids or soft materials (Hyun et al., 2011). Measuring the deformation response to applied stress or strain using strain amplitude oscillatory tests is useful for understanding viscoelastic behaviors, which have been shown to correlate strongly with sensory terms related to firmness and springiness (Brown et al., 2003). SAOS tests measure the mechanical properties of a material by applying small strain within the linear viscoelastic region (LVR) without damaging the material. In this test, both viscoelastic moduli are independent of strain amplitude, and the oscillatory stress response is sinusoidal. Amplitude sweeps can be performed in either stress or strain control mode, which gives stress sweep or strain sweep, respectively, to determine the LVR. In these tests, frequency is constant and stress or strain changes. The range of strain or stress in this test should cover both LVR and beyond LVR to understand full range of viscoelastic behavior of the material. Critical strain and critical stress are the stress and strain at which LVR ends, and the material deforms permanently due to the disruption of microstructure (Steff, 1996). Also, maintaining the strain at LVR prevents any permanent disruption in the structure of foods.

Large Amplitude Oscillatory Shear (LAOS)

Large amplitude oscillatory shear is a rheological fingerprint of materials that studies rheological properties under large stress or strain amplitude (Melito, Daubert, & Foegeding, 2012). In food science, LAOS more associated to with the final use of foods, food breakdown, and texture. LAOS is typically performed at relatively high strains (>1% for foods) because nonlinear viscoelastic behavior in most materials occurs under these conditions. This behavioral shift from the LVR to the nonlinear viscoelastic regime is commonly realized as a transformation from a constant value to a changing value of the magnitude of the complex modulus (G^*) during a stress or strain sweep (Hyun et al., 2011). The nonlinear behavior is determined by the magnitude of the ratio of the third harmonic viscoelastic moduli to the first harmonic (G'_3/G'_1), or by the magnitude of the ratio of the large-strain moduli to the minimum strain modulus (G'_L/G'_M) or strain stiffening ratio (S) (Hyun et al., 2011). Nonlinear behavior in viscoelastic solid materials is identified by $G'_3/G'_1 > 0.01$ (Melito et al., 2013). The nonlinear behavior is strain-hardening when the $G'_L/G'_M > 1.10$ and it is strain-softening when $G'_L/G'_M < 0.90$ (Anvari & Melito, 2019; Ewoldt, Hosoi, & Mckinley, 2008; Joyner (Melito) & Meldrum, 2016; H. S. Melito et al., 2013). More details about this nonlinear behavior analysis procedure are explained by Ewoldt et al., (2008). Elastic nonlinearity can be also quantified using the strain-stiffening ratio (S). When $S > 0$, the elastic nonlinearity is strain-stiffening; it is strain-softening when $S < 0$ (Ewoldt et al., 2008; Hyun et al., 2011).

Melito et al., (2013) conducted LAOS on three different commercial cheeses (Cheddar, Mozzarella and American cheese), where all cheeses showed $G_3'/G_1' > 0.01$ for all three cheeses at 25 and 50% strain at both 25 and 37ºC, demonstrating nonlinear behavior. They also reported that Cheddar cheese exhibited the greatest value of strain-hardening behavior compared to other cheeses, which was attributed to higher proteolysis and loss of elasticity of Cheddar cheese with increased aging compared to Mozzarella and American cheese. Another study conducted by Joyner (Melito) et al., (2017) showed an increase in the extent of nonlinear viscoelastic behavior in blue cheese as aged for 60 d. This result was also attributed to protein breakdown during aging.

Compressive fracture testing

Compression testing of food products measures the behavior of intact food samples under a compressive load. It can be used to understand large-strain and fracture behaviors of materials. In this type of test, the sample is compressed, and deformation at various force levels is recorded. The information obtained from compressive testing can be helpful when developing new products with desired textural properties (Ak & Gunasekaran, 1992), especially since fracture properties of food are more relevant to breakdown of food in the mouth and sensory perception (Brown et al., 2003; Foegeding & Drake, 2007).

Fracture happens when an applied strain results in adequate forces in the material to induce structural deformation severe enough to cause rupture (Foegeding & Drake, 2007; Rogers et al., 2009). Food fracture properties are commonly determined under uniaxial compression (Ak & Gunasekaran, 1992). In uniaxial testing, the crosshead velocity is typically held constant, and the material's response to loading is recorded. Rogers et al. (2009) showed that the values of fracture point in Cheddar cheeses with different fat contents correlated well with sensory lexicon terms related to hand firmness. Martín-alvarez and Cabezas (2006) also reported that the stress and strain at which Manchego cheese fractured under normal or torsional force were linked to sensory hand springiness and hand firmness.

In compressive testing, the dimensions of the sample need to be considered. Cheese samples should be significantly larger than the size of their fat globules and curd particles; testing accuracy decreases with decreasing sample size (Walstra & van Vliet, 1982). Cylindrical samples with a diameter of around 20 mm are commonly used for cheese samples. If the length of the cylinder is much greater than its diameter, the sample may bend during compression. On the other hand, if the diameter is much greater than the length, frictional effects become significant at the sample-plate surface Luyten (1988) found a length:diameter ratio of 1.3 to 2.0 to be acceptable for food samples like cheese.

Factors affecting cheese rheological behaviors

Fat content

Fat is one of the primary influential compositional parameters on the final texture of cheese. Reduced-fat cheeses often fail to reach an acceptable texture. One of the key difficulties with fat reduction in cheese is the development of a firm texture that does not break down easily during chewing, unlike the texture perceived in full-fat cheeses. Many studies have reported that as the fat content of cheese is reduced, the cheese develops an undesirable firm, rubbery texture (Mistry 2001; Gwartney, Foegeding, and Larick 2002; Rogers et al. 2009). For example, Brown et al. (2003) and Yates and Drake (2007) confirmed that reduced-fat cheeses were firmer and springier and showed lower amounts of adhesiveness and cohesiveness compared to full-fat cheeses. Fat droplets present within the protein matrix network act as a plasticizer to prevent the formation of crosslinks between the casein chains. A higher ratio of fat to protein allows cheeses to melt better, resulting in increased adhesiveness. Reduction of fat droplets also results in higher concentrations of protein, moisture, and pH (Bryant, Ustunol, & Steffe, 1995). Also, the calcium phosphate para-casein network becomes denser with less open spaces thus affecting texture (Mccarthy, Wilkinson, Kelly, & Guinee, 2016; Sánchez-Macías et al., 2012). Furthermore, cheese composition and interactions between casein and fat impact its rheological properties by changing resistance of cheese structure to deformation (Bryant et al., 1995; Rogers et al., 2009).

Moisture content

Moisture content is also an influential factor in cheese texture and consumer acceptance of cheese. Everard et al. (2006) showed that higher moisture content in Cheddar cheese decreased the texture profile analysis (TPA) terms of firmness, chewiness, and springiness. Zheng et al. (2016) also reported that low moisture content was related to higher firmness and resilience but lower springiness and cohesiveness in sliced Cheddar cheese (Zheng, Liu, & Mo, 2016).

Variation in moisture content occurs in the cheese due to different quality and amount of fat, protein, and minerals in the cheese milk, as well as differences processing conditions (Sahan et al., 2008). Fluctuation in moisture content affects the rheological behavior of cheese due to associated changes in pH and an increase in the volume-to-surface diameter of the fat droplets. Model processed cheese showed a decrease in storage modulus as moisture content increased, indicting a transformation from solid-like to fluid-like behavior, as well as decreased hardness and firmness, and increase meltability (Lee, Anema, & Klostermeyer, 2004).

Protein content

Higher protein to fat ratios in low-fat cheeses causes the lower fat cheeses to have a more compressed protein network and thus firmer texture compared to those of full-fat cheeses. To offset the increased protein concentration and decreased fat concentration, water is added into the cheese, but the texture is still firmer than that of full-fat cheeses (Johnson & Chen, 1995). The rubbery texture in reduced-fat cheese has been associated with the increase in a structural matrix per unit cross-sectional area (Everard et al., 2006). Higher protein content in sliced Cheddar cheese showed lower adhesiveness and higher firmness (Zheng et al., 2016). Additionally, the concentration, type, and rate of protein hydrolysis impacts the elastic modulus of cheese, as previously described; it also affects TPA parameters. Drake et al. (1997) found a correlation between intact casein concentration and fracture stress and firmness of Cheddar cheese with 7 to 33% fat content and 26 to 40% protein content. This correlation was associated with a more robust para-casein network and a greater number of intra- and inter-strand linkages.

Aging

The ripening of cheese, during which its fats and proteins break down by bacterial, fungal, and/or chemical activity, is an important factor in the final texture of cheese. This breakdown of casein network into shorter and simpler peptides makes the texture crumbly and less elastic, because shorter peptides have a lower chance of interacting with each other compared to long proteins.

Compositional changes also play a role in changes in cheese rheological properties during aging. O'Mahony, Lucey, & McSweeney (2005) showed that TPA values for hardness, cohesiveness, springiness, and chewiness decreased as aging time increased from 60 to 120 d of maturing due to high moisture in young cheese and decreased moisture in old cheese, as well as increased proteolysis in the older cheese compared to that in the younger cheeses (Lucey et al., 2003). Beal and Mittal (2002) reported that hardness (peak force to compress) of Cheddar cheese increases during aging, while fracture stress decreased. Fracture stress of blue cheese decreased during aging, indicating that rigidity of cheese decreased during storage due to protein breakdown caused by microbial activity (Joyner Melito et al., 2017).

Temperature

The shift from a solid material at refrigeration temperatures to a more fluid-like material with increased temperature is generally considered as the melting of cheese. Different amounts of fatty acids in milk fat influence its melting point: the ratio of solid to liquid fat at a certain temperature is dependent on the length of the fatty acid chains, the number of unsaturated bonds, and the position of fatty acid residues among the three positions on the triacylglyceride backbone. Changes in solid fat ratio impact the physical properties and casein–casein interactions within the cheese. As temperature reaches 20-40°C, the amount of liquid fat rises significantly (Lopez, Camier, & Gassi, 2006). Thus, cheese shows less solid-like behavior as the hydrophobic interactions within the protein matrix increases resulting in larger and denser protein aggregates (Rogers, McMahon, Daubert, Berry, & Foegeding, 2010).

Heating treatments during and after cheese production has a great influence on cheese rheological behavior of cheese because of induced microstructural changes (Kim et al. 2015;

Connan, Deslandes, and Gall 2007). Heat treatment during and after production can result in many interrelated modifications to cheese microstructures, such as melting, flow, softening, and stretching. At low temperatures, ~5ºC, the fat droplets are predominantly solid, which increases the firmness of the casein network by adding to the elasticity of casein matrix caused by weak hydrophobic interactions between casein proteins. At 15ºC, the fat globules are plastic, including both liquid and solid fat, which can change the textural and rheological properties in a complex way. At the primary stage of deformation, the fat droplets and the protein network deform as force (stress) is applied. As the fat starts melting with increased temperature, it moves more easily in the protein network and may both lubricate the surface of cheese and increase the extent of deformation under applied force. This can be reflected in a decrease in the storage and loss moduli (Stokes, Boehm, and Baier 2013; Michael H. Tunick 2010). Increasing the temperature to greater than 25ºC decreases the elastic shear modulus and increases the phase angle, indicating a transition from an unmelted cheese, largely elastic in rheological response, to a melted softer cheese, which shows more viscous behavior (Hsu, Chen, Lu, & Chiang, 2015).

pH

pH plays an important role in determining cheese texture because any alteration in pH is related to chemical and physical changes in the cheese protein network (Shahidi & Ambigaipalan, 2015). The changes in pH during cheesemaking and its effect on calcium losses to whey determine the final cheese microstructure and texture. Additionally, alternation of pH after cheese production, which occurs during aging and may involve both physical and chemical activities, can also cause significant changes in cheese texture and functionality. However, the texture changes caused by pH alterations differ among cheeses. For instance, cultured

Mozzarella cheese showed increased firmness due to redistribution of calcium and higher crosslinking in the casein network as pH increased as result of microbial activity after manufacture (Cortez, Furtado, Gigante, & Kindstedt, 2008). Increasing pH in cream cheese resulted in decreased firmness and increased meltability (Cortez, Furtado, Gigante, & Kindstedt, 2008). A study performed by Lee and Klostermeyer (2001) on process cheese spread showed that storage modulus and viscosity increased with increasing pH. Another study conducted by Everret and Olson (2004) reported increased fracture strain for Cheddar cheese as pH increased from 4.7 to 5.3. Zhong et al. (2007) reported a significant increase in storage modulus as pH increased from 5.8 to 12 in rennet casein gels. These alterations in cheese rheological behaviors from pH changes may be related to the number of net negative charges and the strength of the hydrophobic interactions in cheese.

Textural Properties of Cheese

Textural properties are an important factor in determining cheese quality, consumer acceptability, and application. Cheese texture may be defined as a composite of sensory attributes resulting from a combination of physical properties perceived by the sense of sight and touch. This texture can be investigated by sensory analysis.

Sensory evaluation

Sensory evaluation is a scientific method used to characterize material attributes using the five human senses (sight, smell, touch, taste, and hearing); data generated by human observation are analyzed by statistical tools. It is considered a necessary step in both new product development and quality control. In sensory studies, sample preparation and serving under controlled, consistent conditions plays an important role in minimizing biasing factors. (Meilgaard et al., 2006).

Descriptive sensory analysis, discriminative sensory analysis, and consumer tests are the most common techniques in sensory evaluation. Descriptive sensory analysis uses trained panelists to characterize the flavor, aroma, and texture of food products by measuring the intensity of specific attributes in the product on a 15-cm-line scale or other scales. Panelists are trained using product and attribute references; they should be able to detect, describe, and quantify each attribute (Meilgaard & Carr, 2006). Discriminative sensory testing is used to find differences between two or more samples using semi-trained panels. Consumer sensory testing involves a scaling method to determine the degree of liking or acceptability of products using untrained consumers (Lawless & Heymann, 2010).

Cheese sensory properties are the consequence of structural breakdown and mixing of cheese with saliva during mastication, and their evaluation is important in determining satisfaction by consumers (Rogers et al. 2010). Consumer perception of a cheese comprises several factors, including appearance, flavor, and texture. In addition, a trained sensory panel is another valuable tool in understanding what aspects of texture differentiate cheeses (Foegeding and Drake 2007). Descriptive sensory panels and texture terminology (lexicon) specifically designed for cheese have been used in the past to determine the texture attributes of many cheese varieties (Brown et al. 2003; Whetstine et al. 2006). The established texture lexicons comprise 4 parts: tactile response, first bite, breakdown during chewing, and residual mouthfeel terms (Brown et al., 2003; Foegeding and Drake 2007). The use of a consistent descriptive lexicon provides a "textural fingerprint" for a cheese that not only allows comparison with other cheeses analyzed with the same lexicon and standards, but also facilitates correlation with rheological properties.

Factors affecting cheese sensory attributes

There are several studies that demonstrate the influence of various factors on cheese sensory attributes. Fat reduction in different cheese varieties has been associated with increased graininess, hardness, springiness, and fracturability, and reduced smoothness, cohesiveness, and adhesiveness; these changes are related to the firmer structure of cheese caused by fat removal (Bryant et al., 1995; Drake & Swanson, 1996; Foegeding & Drake, 2007; Yates & Drake, 2007). Rogers et al. (2009) studied the effect of aging on sensory properties of full-fat and reduced-fat Cheddar cheese. Low-fat cheeses were springier and firmer than full-fat cheeses; this difference increased as the cheeses aged (Rogers et al .2009). Sánchez-Macías et al., (2012) reported that full-fat cheeses had lower roughness compared to low- and reduced-fat cheese after 28 d of storage. These findings were agreed with the quantitative analysis of proteolysis and degradation rate, which showed an overall decline in intact casein as cheeses aged, and decreased degradation rate of protein in cheeses with lower fat contents. Sensory evaluation on reduced-fat goat milk cheese showed lower flavor intensity and grainer, firmer, and less adhesive texture compared to full-fat cheeses (Sánchez-Macías et al., 2012). These studies showed that any changes in composition and aging time can alter cheese sensory characteristics and impact consumer acceptability.

Food tribology

Tribology is the study of friction, wear, and lubrication of interacting sliding surfaces. Friction and wear are caused by a complex set of microscopic interactions between two contacting surfaces that slide against each other (Axén et al., 2000). While earlier applications of tribology were limited to automotive industries, there are currently many tribological studies in other fields such as dental science, ocular science, and orthopedics. Food science is the newest addition to the application field: tribometry has been used to determine the friction behavior of food materials during oral processing for about two decades (Joyner, Pernell, & Daubert, 2014). Tribological interactions among oral surfaces have a major impact on how certain foods are perceived (Chen & Stokes, 2012; Stokes, Boehm, & Baier, 2013).

Friction

Friction is the force resisting motion when two objects slide over each other (Myant, Spikes, & Stokes, 2010; Oogaki et al., 2009). For hard surfaces, the ratio of the friction force (F, N) to the normal force (N, N) is the coefficient of friction, μ (unitless):

$$\mu = F/N \tag{2.1}$$

All mechanical, physical, chemical, and geometrical characteristics of the interacting surfaces and environmental conditions can impact the tribological behavior of the system. Commonly known factors affecting friction of hard and soft materials include normal force, sliding speed, loss of material by wear, lubrication, and temperature (Al-araji & Sarhan, 2011; Axén, Hogmark, and Jacobson, 2000; Joyner (Melito), Pernell, and Daubert, 2014; Myant, Spikes, and Stokes, 2010). To evaluate the tribological response of materials under varying velocity and load conditions, Stribeck curve, which was developed for friction analysis of hard bearings and Newtonian lubricants, can be used (Chen and Stokes 2012; Axén, Hogmark, and Jacobson 2000). In Stribeck analysis, the coefficient of friction is a function of lubricant viscosity, sliding speed and normal load (Chojnicka-Paszun, de Jongh, & de Kruif, 2012; Joyner et al., 2014; Moerlooze, 2011). There are three regimes on Stribeck curve (Figure 2.4): boundary, mixed, and hydrodynamic. In boundary regime, the surfaces are in close contact, and friction coefficient is high and constant to changes in normal force, sliding speed, and other system conditions. In hydrodynamic lubrication, the high sliding speed results in high fluid pressure in the contact area, leading to complete surface separation by a layer of fluid lubricant, and thus friction behavior depends on the lubricant properties. Between these two regimes, there is a mixed regime where the two contacting surfaces are still in contact but separated by a thin layer of lubricant and the friction coefficient decreases (Keck 2015; Stokes, Boehm, and Baier 2013). The friction coefficient is minimum in the junction of mixed and hydrodynamic regimes. These three regimes may correlate to various motions during food mastication (Chen & Stokes, 2012; Nguyen, Bhandari, & Prakash, 2016; Stokes et al., 2013).

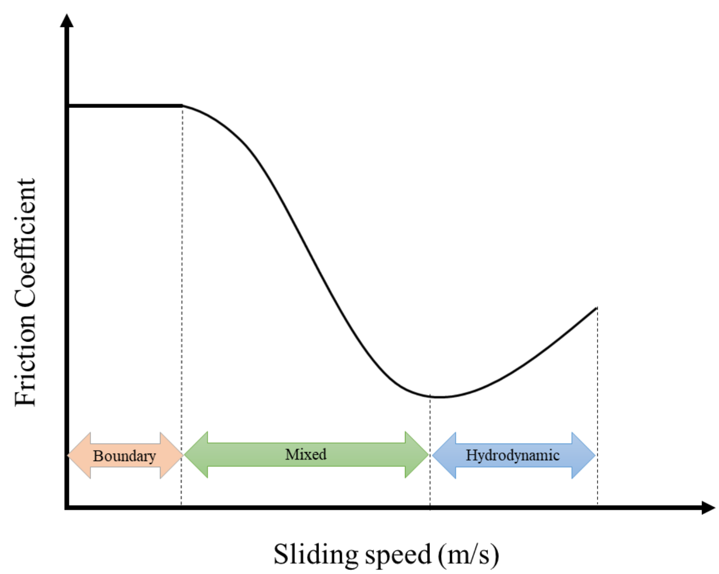

Figure 2.4. Example of a Stribeck curve.

Tribology is important in understanding the connections between food oral processing and texture perception since it involves study of both lubricant properties and surface properties of contacts in relative motion (Chen, Jianshe ; Stokes, 2012; Stokes, Boehm, & Baier, 2013b). In oral processing, foods experience both deformation (rheology) and breakdown through continuous chewing and saliva secretion. Therefore, rheology is dominant in the initial stage of oral processing where deformation of food between the teeth and tongue are involved. The later stage of oral processing is more relevant to tribology since the behaviors of food as a lubricant for contacting oral surfaces in relative motion are considered. Most foods experience boundary and mixed regime behavior during mastication; the hydrodynamic regime is more useful in lubrication studies in engineering industries. Some foods may experience behaviors similar to all three Stribeck regimes; for example, most low-viscosity beverages are governed by hydrodynamics at the initial stage and show boundary and mixed regimes when they are sipped and swallowed (Chen, Jianshe ; Stokes, 2012). The behavior of thick fluid and paste-like foods are closer to hydrodynamic regime due to their high viscosity at the initial stage of mastication. However, boundary and mixed behavior will be dominant as they are swallowed (Chen & Stokes, 2012).

The Stribeck curve may not always follow the original shape in foods because most foods are non-Newtonian and food tribological tests are performed on soft surfaces, while the Stribeck curve is designed for Newtonian lubricants on hard surfaces. The changes in surfaces and viscosity in samples may change the shape of Stribeck curve. Nevertheless, the Stribeck curve is still used to evaluate friction and lubrication behaviors of food to better understanding oral tribology.

Wear

Wear is defined as removal of material from a surface as a result of sliding or rolling contact (Axén et al., 2000). While two surfaces are in sliding or rolling contact for a given time period, a wear track with a certain pattern or shape, size, and depth is seen on the surface of material. These characteristics, such as deformation, cracks, grooves, or valleys, can indicate the surface wear status. Also, wear debris generated during testing can be a valuable source of information on the wear mechanism and surface wear status. Accordingly, the particle shape of debris, texture, and color of the wear track can be used for wear analysis (Ruff 1992; Axén, Hogmark, and Jacobson 2000).

The control of wear is important to ensure that tribological systems work efficiently and durably. Development of a low-wear surface is a complex task due to the numerous variables involved in wear. Influencing factors include the geometrical and topographical characteristics of the surfaces, and the overall conditions under which the surfaces are made to slide against each other, such as applied force, sliding distance, temperature, lubrication, and type of contact. Surface characteristics and hardness have significant influences on wear, as a rise in roughness and reduction in hardness may lead to in increased wear rates (Saikko, Calonius, and Kera 2001).

Wear can be classified as abrasive, adhesive, erosive, fretting, and surface fatigue (Axén et al., 2000). Wear is abrasive or adhesive when it is focused on sliding and polishing the surfaces. Abrasive wear, the most common wear type in lubricated machinery, occurs when two surfaces interact with one another, and the movement of harder material on the softer material results in the loss of material (Figure 2.5b). Adhesive wear occurs when materials stick to each other, resulting in material transfer between two surfaces or mass loss from either surface (Figure 2.5a). In general, adhesive wear can be identified by the presence of a transfer film on one or both of the sliding surfaces, while abrasive wear can be identified by grooves on one or both of the sliding surfaces in the direction of sliding (Ozcan & Filip, 2013).

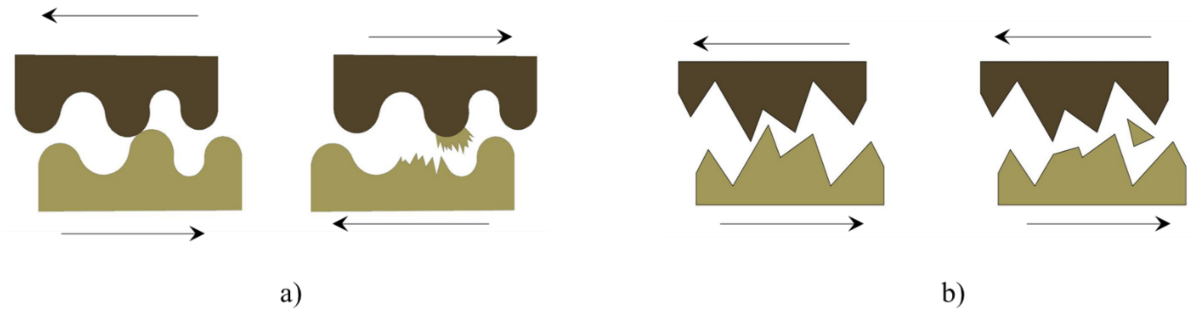

Figure 2.5. a) Adhesive wear and b) abrasive wear.

Erosive wear occurs when a sharp particle touches another surface at high velocity, such as during cutting by hard surfaces and produces pitting. Fatigue wear occurs after long-term repeated rolling and stress that weakens the surface of the material (Figure 2.6). Fretting wear occurs under small amplitude oscillatory motion between contacting surfaces, which are usually at rest, causing the surfaces to move because of the external vibration. Surface fatigue happens because of repeated rolling or sliding motions that leads to pits on the surface of the material. This type of wear is identified by crack formation and propagation by continuous growth of subcritical cracks, making the estimation of ultimate depth of the crack difficult.

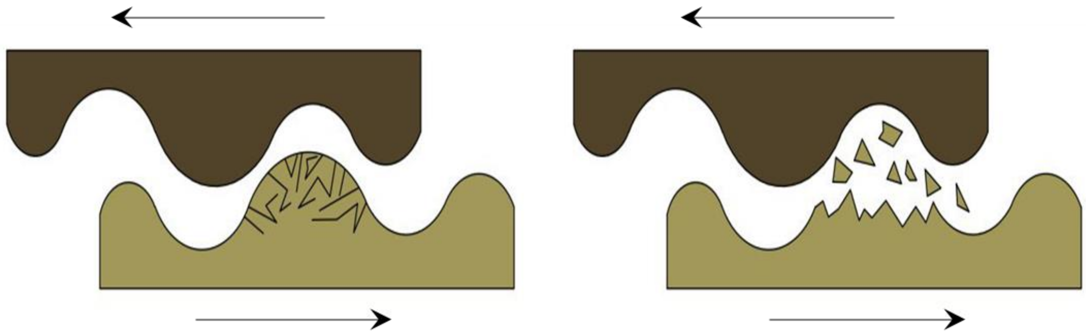

Figure 2.6. Fatigue wear.

As previously mentioned, most food tribology studies focus on lubrication and friction, and their relationship with sensory behavior of food. Wear and its relation to oral and industrial processing has been neglected. There are only some new studies that investigated wear of food products (Sparkman, Joyner, & Smith.; Tan & Joyner, 2018a; Zad Bagher Seighalani, & Joyner, 2019). The wear behavior of soft materials needs more investigation for a better understanding of how it contributes to food industrial and oral processing behaviors.

Wear of soft materials

Soft materials deform when they are subjected to external forces. Thus, the tribological behaviors for two contacting soft materials or between hard and soft contacting materials are different from those of hard materials. Wang et al. (2017) studied the wear mechanisms of textured and untextured steel contact (hard) surface against a polymer (soft) material and found that their wear behavior was correlated to the storage modulus of the soft materials and parameters of surface textures. Different amounts of wear mass and surface morphology were found for countersurfaces with varying surface textures: wear debris was lumpy at lower wear rates, whereas the wear mass was rod-shaped or twisted at increased wear rates. In addition, soft countersurfaces which have good ability of self-lubricating showed a lower wear rate (Wang, Zhang, & Wang, 2017).

Foods are soft solid material and understanding their wear and mass loss behaviors is important as these behaviors may provide useful information about food processing behaviors. Food wear is a new area in food science, and there are only few studies on wear of food products such as high protein bars (Sparkman & Joyner, 2019; Sparkman, Joyner, & Smith, 2019), solid fat (Tan, Silva, Martini, & Joyner, 2019), and cheese (Zad Bagher Seighalani, & Joyner, 2019). However, there is much to be discovered for a more complete understanding of food wear.

Wear measurement

Overall, there are multiple methods to measure wear of a material, including volume loss, mass loss, linear dimension loss, wear area, wear volume, topographical difference, and other indirect measures. Measuring mass and volume losses are the most common techniques when there is an excessive amount of mass removal from surfaces (Axén, Hogmark, and Jacobson 2000).

The volume of removed or displaced material during wear processes can be used to quantify wear and calculate the wear rate of the material. Generally, calculating wear volume is an accurate method when the worn region is regular in shape and is a reliable comparison among materials with various and unknown densities (Ruff 1992). According to Archard's law, the volume of the wear debris is relative to the applied normal force and sliding distance by a wear factor, which is presumed to be constant (Axén, Hogmark, and Jacobson 2000).

$$V = KFL/H \tag{2.1}$$

where V is the wear volume (m^3), F is normal load (N), L is sliding distance, H is hardness (Pa), and K is a unitless wear coefficient. Archard's law is applicable for homogenous hard materials but not necessarily soft materials because of violations of key assumptions such as negligable deformation under a normal load. Because the most common form of surface damage is mass loss, mass difference measurements are commonly used to estimate wear because of their relative simplicity and ease of performance (Axén et al., 2000; Ruff, 1992). This approach is suitable for many laboratory tests as well as in real applications if the worn component is removable and the mass losses are not small compared to the total mass (Ruff, 1992). Given this fact, when selecting a proper method for measuring wear rate, the type of wear and characteristics of material should be considered (Axén et al., 2000; Ruff, 1992).

Wear modeling

There have been significant developments in using modeling and optimization methods for modeling different systems in recent decades. Because models are imitations of real-world systems, modeling is a beneficial method for studying the influence of different parameters on the outcome of a process. Since modeling minimizes the number of experiments that need to be conducted to determine the effect of several factors on the quality and safety of the process outcome, it is a time and cost-saving tool for result prediction (Sagbas, Kahraman, & Esme, 2009)

There are two main types of modeling: empirical and mathematical (theoretical). Theoretical models are developed based on certain assumptions and general laws, and they cover a wide range of parameters and factor levels (Sagbas, Kahraman, & Esme, 2009). Theoretical models have been developed for artificial join wear (Abdelgaied et al., 2011b; Kadu, Awari, Sakhale, & Modak, 2014; Saha & Mondal, 2011). Empirical models are based on observations; while they do not explain the system from first principles, they can still be used to predict its behavior over a limited parameter range. When there is no theoretical model to use, empirical models can be created using statistical techniques such as Response Surface Methodology and linear and non-linear regression models (Karnesky & Puel, 2016).

There are several steps when building a successful model, including developing a problem statement, setting objectives, collecting data, conceptualizating the model, and translating the model (Karnesky & Puel, 2016). All modeling initiates with a problem statement, which involves the system that needs to be predicted. It is vital to explore and understand the problem in the system to generate an appropriate model. In the next step, the objective of the model should be identified. After this, data are collected to provide model input parameters. These data can be statistically analyzed to test the impact of each factor on the output. The selected input parameters should be those that significantly impact on output. During the next step, which is conceptualization, previous theories can be used as grounds for developing the model. To build an accurate model, it is essential to recognize how the actual system works and pinpoint the fundamental requirements. In the final step, the conceptual model is translated into a computer format in simulation software.

Because simulation models are an estimated imitation of real-world systems and do not exactly imitate the real-world system, they need to be verified and validated before application to make sure that model assumption is correct and free from logical errors. There are various techniques that can be applied to verify a model, including expert review of the model, generation of logic flow diagrams that include each logically possible action, and review of the model output for reasonableness under a variety of settings of the input parameters (Karnesky & Puel, 2016). This verification is also termed model validation. Model validation is defined as the degree of model accuracy compared to real-world data. Models will not be validated if their assumptions are not confirmed or the model fails to predict the real situation within a reasonable degree of accuracy.

Sensitivity analysis can be applied during model validation. It provides an overview of the most influential parameter(s) on the response by systematic evaluation of response changes to one or more parameters and determine how sensitive the model response is to a change in value (Kadu, Awari, Sakhale, & Modak, 2014). Many of the input parameters may not be relevant to the observed phenomena; sensitivity analysis identifies the parameters that most closely correlate to the response so that the remaining parameters can be neglected. The sensitivity index, which reflects the proportional relationship between the relative error in response and the relative error in parameters, is typically used for this analysis. For example, if a sensitivity index for a given parameter is 1.5 and the relative error in the parameter is 5%, then the relative error in response is 1.5 times 5%, or 7.5%.

Numerous studies have been published on developing a model for polymer wear (Alotta, Barrera, & Pegg, n.d.; Meng & Ludema, 1995; Viswanath & Bellow, 1995a, 1995b). These models have expressed wear as a function of operating parameters and material properties. For example, Singh et al., (2011) developed a mathematical model for adhesive wear prediction in carbon steel as impacted by heat treatment, intensity of shot peeling, and normal force. They found a regression model was highly significant and thus useful for accurate prediction of wear rate. Sagbas et al. (2009) developed an empirical model using Response Surface Methodology (RSM)for prediction of abrasive wear of derlin as a function of normal force and sliding distance. Joyner and Tan (2018) developed a numerical model for wear by considering deformation resulting from normal force to characterize wear behavior of different gels (k-carrageenan and whey protein) that can be used for other soft martials. Response Surface Methodology was used in another study to predict processing behavior of high-protein bars with varying different formulations using wear data ((Sparkman et al., 2019).

The Buckingham Pi theorem is another method for developing a model for complex systems like wear of soft materials. It uses dimensional analyses to express physical relationships among the variables in terms of a dimensionless group. This method offers the advantage of being more simple than the method of solving simultaneous equations to obtain the model constants. It also reduces the number of independent variables used in the model through grouping. Thus, Buckingham Pi theorem is a beneficial technique for complex systems for which there are a number of influential variables. Kar and Bahadur (1974) developed a mathematical model for adhesive wear of polymers using the Buckingham Pi theorem by considering pressure speed, and time and material properties including elastic modulus, surface energy, thermal conductivity, and specific heat. Fan et al. (2009) employed the Buckingham Pi theorem to develop a mathematical equation for the erosion rate in micro abrasion of glasses. Bobbili et al. (2015) developed a model for material removal rate by employing the Buckingham Pi theorem and including process parameters of pulse-on time, input power, flushing pressure, and other thermal properties.

Although there has already been a little research in modeling different wear situations during food processing, modeling soft solid material wear has received little attention in food science. The wear of soft materials such as hydrogels (Chen et al., 2017), soft graphite (Cao et al., 2016) k-carrageenan and whey protein gels (Tan and Joyner, 2018), and high protein bars (Sparkman et al., 2019) has been studied, but the field of soft material wear is still highly unexplored. Notably, the wear behavior of cheese has not yet been modeled. Therefore, this study aims to consider different factors affecting the wear behavior of cheese to present an innovative wear model.

Conclusions

Changes in composition and processing variables may result in an undesirable firm and rubbery texture which could lead to issues in processing steps such as slicing or shredding. We hypothesize that the difference in processing behaviors of cheese are related to differences in wear behavior of cheese. However, there is not enough information on cheese wear behavior in the literature to test this hypothesis. Furthermore, the mechanisms and factors influencing cheese wear behavior are generally unknown. Thus, this study aims to identify factors affecting wear behavior of cheese with different fat contents, quantify their wear behaviors and determine its relationship with rheology and sensory behaviors. The results of this study could be useful for the evaluation of cheese processing behavior. Thus, the effect of fat content, aging time, and production parameters on cheese wear need to be studied to help cheese industries to determine and predict processing behaviors of cheese in a cost-effective way. Additionally, developing a wear model for cheese will improve understanding of wear behavior of cheese and other soft solid materials by determining what parameters have the greatest impact on wear.

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Chapter 3: Wear: A New Dimension of Food Rheological Behaviors as Demonstrated on Two Cheese Types

Abstract

Determination of food rheological and tribological behaviors is imperative for understanding both processing behaviors and texture attributes. The objective of this study was to determine wear behavior of Cheddar and Monterey Jack cheeses. Wear measurements were performed at 50 mm/s sliding speed, 1N normal load, and 25°C. Cheese linear and nonlinear viscoelastic properties were also determined. Compared to Cheddar, Monterey Jack showed significantly greater small-strain storage and loss moduli values and lower extent of nonlinear viscoelastic behavior. Lissajous plots agreed with these results. Overall, Monterey Jack had lower penetration depth increase and lower mass loss during wear testing than Cheddar. The results of this study provided fundamental information on cheese rheology–wear relationships.

Keywords: Cheese, Rheology, Wear, Large amplitude oscillatory shear

Introduction

Wear is removal of material from a surface as a result of sliding or rolling contacts (Axén et al., 2000). As wear occurs, a wear track with certain pattern, shape, size, and depth is generated on the material's surface, indicating the wear status of the surface (Wang et al., 2017). Development of low-wear materials is a complex task due to multiple influential variables. Factors affecting surface wear include surface geometrical and topographical characteristics (Pal et al., 2008), applied force (Yin et al., 2017), sliding speed and distance (Khanafi-

Benghalem et al., 2010), temperature (Khanafi-Benghalem et al., 2010), lubrication (Ahn et al., 2003), and type of contact (Saikko et al., 2001).

Soft materials deform under applied forces, resulting in different tribological behaviors from those of hard materials. Soft materials have lower density than hard materials, leading to lower wear rate as the true area of contact decreases. They can also be self-lubricating, potentially reducing wear rate (Wang et al. 2017). Moreover, different amount of wear mass and surface morphology in the contact surfaces can indicate different wear mechanisms (Zmitrowicz, 2005).

In cheese, differences in composition and production steps can lead to different final functionalities. These differences become critical in processing steps that involve shear, such as slicing and shredding. Cheese sliceability and shreddability behaviors may relate to wear behaviors and may be caused by differences in cheese rheological properties. However, there is no published information on cheese wear behavior, wear mechanisms, and factors influencing food wear behavior. Thus, the objective of this study was to determine wear behaviors of Cheddar and Monterey Jack cheeses and their relationships with rheological behaviors.

Materials and Methods

Materials

Cheddar and Monterey Jack cheeses (Tillamook; North Tillamook, Oregon) in a block size of 907 g were bought from a local supermarket. Before testing, the outer layer of cheese (about 3mm) was removed.

Rheological measurements

Large amplitude oscillatory shear (LAOS) data were collected by performing strain sweeps using Anton Paar MCR 702 rheometer (Anton Paar GmbH; Graz, Austria) equipped with crosshatched parallel plates (20 mm diameter). Samples were equilibrated at room temperature (22 ± 2°C) for 1 h, sliced to 4 mm thickness using a commercial slicer (Globe 3600N Slicer, Globe Food Equipment Co., Dayton, OH), then cut into circular pieces using an aluminum punch. Shear strain was increased from 0.1 to 150% at a frequency of 5 rad/s and 25°C. Critical strain was calculated as the first strain at which the complex modulus changed by more than 2% from the previous value. Large amplitude oscillatory shear (LAOS) data were extracted from strain sweep tests at 0.1, 1, 10, and 56% strain.

Wear measurements

Wear tests were performed using Anton Paar MCR 702 rheometer equipped with a steel twin-ball on disc apparatus. Samples were sliced to 8 mm thickness with a commercial slicer and cut into approximately 80 x 80 mm squares. Samples were placed on the disc and the balls rotated at 1 N normal load, 50 mm/s sliding speed, and 25°C for 10 min. Penetration depth (mm) was recorded; mass removal was measured by calculating differences between sample weight before and after testing. End-tests wear patterns of each sample were recorded with a digital camera (Canon EOS Rebel T3i Digital SLR, Taiwan).

Data Analysis

All testing was performed in triplicate. Statistical differences ($\alpha < 0.05$) were determined by ANOVA followed by Tukey's test in Minitab (Version 16.0, Minitab Inc., PA, USA).

Results and Discussion

Strain sweep results

Monterey Jack showed significantly higher critical $G*$, stress, and strain values compared to Cheddar (Table 3.1), indicating that Monterey Jack had a less brittle and stronger network than Cheddar. Both cheeses showed solid-like viscoelastic behavior based on their phase angles. Monterey Jack had a significantly higher phase angle than Cheddar, indicating more fluid-like behavior in Monterey Jack. Differences in cheese viscoelastic properties could have been related to differences in aging period (Joyner Melito et al., 2017), but were more likely related to compositional (moisture/fat content) (Marshall, 1990; Rogers et al. 2010) and microstructural differences (Henno et al., 2017).

Table 3.1. Cheddar and Monterey Jack small-strain rheological properties.

Cheese	Critical strain (%)	Critical stress (kPa)	G* at critical strain (kPa)	Phase angle at critical strain (degrees)
Cheddar	5.63 ± 1.16^{b}	6.72 ± 0.003^{b}	66.3 ± 3.23^{b}	17.9 ± 0.31^{b}
Monterey Jack	8.54 ± 2.06^{a}	17.8 ± 0.21^{a}	87.6 ± 3.28^{a}	25.6 ± 2.040^{a}

Values are mean ± SD after three replications. Different superscripts in the same column indicate significant difference at $\alpha<0.05$.

LAOS results

Lissajous plots for both Monterey Jack and Cheddar showed distortion from an elliptical shape with increased strain (Figure 3.1), indicating nonlinear viscoelastic behavior at high strain. Monterey Jack and Cheddar generally showed different patterns at each strain, indicating that both strain and cheese type impacted cheese nonlinear viscoelastic behaviors. These results agreed with the quantitative LAOS data (Table 3.2).

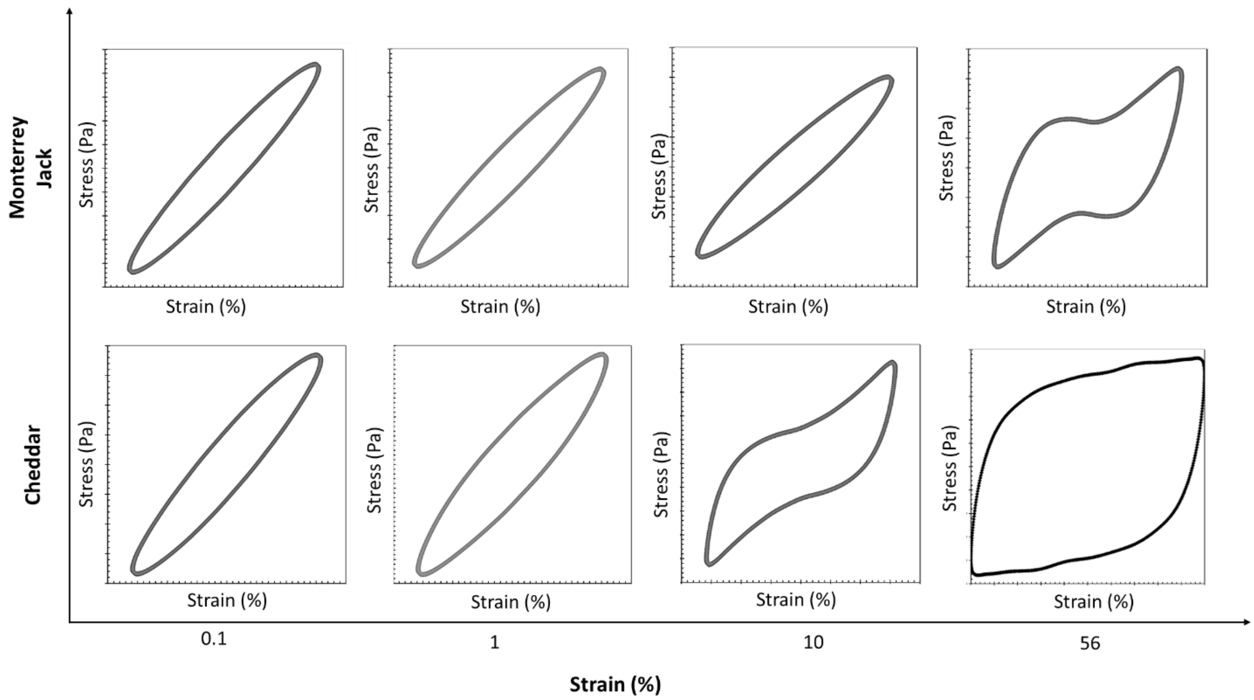

Figure 3.1. Lissajous plots for Monterrey Jack and Cheddar cheeses at different strains.

The ratio of the third (G'_3 or G''_3) to the first harmonic viscoelastic moduli (G'_1 or G''_1) can be used to determine extent of nonlinear behavior. G'_3/ G'_1>0.0l indicates nonlinear behavior, while G'_3/ G'_1<0.01 indicate linear behavior (Melito et al., 2013). In Cheddar, G'_3/ G'_1 values indicated nonlinear behavior at ≥1% strain, while in Monterey Jack, nonlinear behavior occurred at ≥10% strain. These results demonstrated permanent deformation in both cheeses at high strain (Table 3. 2).

Table 3.2. Viscoelastic parameters for Cheddar and Monterey Jack cheeses.

Cheese	Strain (%)	G'_L/G'_M (Pa)	G'_3/G'_1 (Pa)	Phase angle (degrees)
Cheddar	0.1	0.88±0.005[e]	0.01±0.003[de]	16.0±0.06[g]
	1	1.05±0.020[d]	0.013±0.004[d]	17.1±0.08[fg]
	10	1.41±0.031[c]	0.115± 0.003[c]	23.6±1.12[d]
	56	1.71±0.056[b]	0.435±0.041[a]	42.3±1.23[b]
Monterey Jack	0.1	0.092±0.052[d]	0.008±0.002[e]	18.1±0.040[ef]
	1	1.07±0.042[d]	0.009±0.001[e]	19.4±0.050[e]
	10	1.57±0.041[c]	0.014±0.003[c]	26.0±1.42[c]
	56	1.86±0.040[a]	0.34±0.035[b]	59.0±1.57[a]

Values are mean ± SD after three replications. Different superscripts in the same column indicate significant difference at $\alpha<0.05$.

The ratio of G'_L (large-strain modulus) to G'_M (minimum-strain modulus) is an indicator of elastic-related nonlinear behavior. G'_L/G'_M >1.10 denotes strain stiffing; G'_L/G'_M<0.90 denotes strain softening (H. S. Melito et al., 2013). When nonlinear behavior was observed in both cheeses (G'_3/G'_1 >0.01), G'_L/G'_M increased with increased strain, indicating increased strain hardening. These results showed that permanent deformation was more likely at higher strains because cheese microstructures could not stretch elastically to compensate for the higher applied strain. Cheese microstructure consists of a protein network with trapped fat droplets, water, and other molecules (Rogers et al., 2010). As applied strain increases, the protein network stretches and strain hardening behavior is observed due to strain-stiffing of network elements or shearing deformation of the protein network (Joyner (Melito) et al., 2017). Monterey Jack likely had a smaller extent of nonlinear behavior at a given strain than Cheddar because of structural differences between these types of cheese in terms of compositions, process and aging time (Brandsma and Rizvi 2001; Melito et al., 2013; Joyner (Melito) et al. 2017) that would allow Monterey Jack's structure to deform with less permanent damage than Cheddar's structure. The results agreed with the higher critical stress values in Monterey Jack than in Cheddar.

Wear testing

In soft materials, wear depth cannot be determined directly because the materials can undergo deformation without wear during sliding. Thus, penetration depth was used in place of wear depth because penetration depth includes both deformation and wear (Tan & Joyner, 2018a). In both cheeses, penetration depth increased as sliding distance increased (Figure 3.2). Cheddar showed greater increase in penetration depth than Monterey Jack during wear testing. Comparing wear tracks after completion of wear testing (Figure 3.3) also showed differences in terms of depth and pattern. In both cheeses, grooves and pits appeared in the wear tracks and cheese debris was generated, indicating adhesive wear. However, mass removal for Cheddar was significantly higher (0.602 g ± 0.04 g) than for Monterey Jack (0.246 g ± 0.06 g). Monterey Jack's wear track was smooth and shallow; Cheddar's wear track showed deep grooves, which were associated with higher mass removal. Lower penetration depth in Monterey Jack may have been related to higher firmness and elasticity that would decrease deformation under applied load. Higher firmness and elasticity may have been due to structural differences caused by different composition, process and ripening period, as mentioned in the previous section. Also, higher critical stress, critical strain, G'_L/G'_M, and G'_3/G'_1 values in Monterey Jack compared to Cheddar indicated its higher resistance to large deformation, which likely related to lower penetration depth and wear rate.

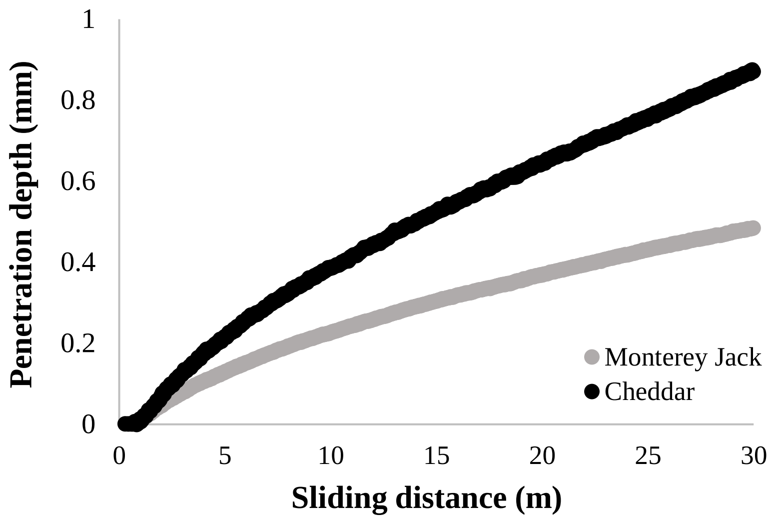

Figure 3.2. Penetration depth of Cheddar and Monterey Jack cheeses.

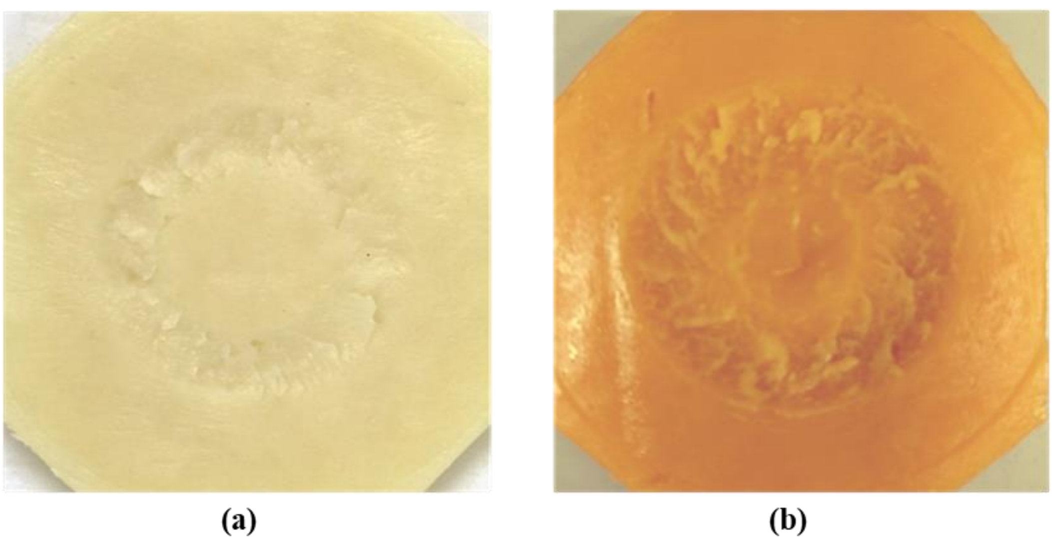

Figure 3.3. Image of wear tracks on a) Monterey Jack and b) Cheddar cheeses.

Conclusions

Overall, Monterey Jack had lower penetration depth and mass removal than Cheddar. These differences were attributed to different rheological behaviors: higher rigidity and smaller extent of nonlinear behavior were observed in Monterey Jack than Cheddar. This study was an initial step in understanding wear behavior of viscoelastic foods.

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Chapter 4: Identification of Factors Affecting Wear Behavior of Hard Cheeses

Abstract

Wear (mass loss) may be an important phenomenon in determining food processing behavior, as sticking and production of debris during slicing and shredding of cheese is one of the main concerns in cheese manufacturing. However, wear behavior of soft materials like food products has been little studies, partially because of its complexity. Thus, the objective of this work was to identify factors that significantly impact cheese wear behavior. Cheeses with different fat contents (40, 50, 52, and 54% fat dw) were stored at 5°C for up to 60 d and evaluated every 15 d. Wear measurements were performed at different normal forces (0.5 and 0.7 N), sliding speeds (30 and 50mm/s), and temperatures (5, 15, and 25°C) using a rheometer equipped with a tribo-system (steel twin-ball on disc). Penetration depth was recorded, and mass loss was measured by weighing samples before and after wear testing. Cheeses with different fat content showed notably different tribological behaviors under different conditions. All cheeses showed highest mass loss at 15°C, while mass loss was significantly ($p < 0.05$) lower at 5°C and 25°C. However, higher penetration depth was observed at 25°C compared to 5°C and 15°C. The effect of normal force on mass loss was different at various temperatures. Higher normal force resulted in significantly lower mass loss and higher penetration depth at 25°C in all cheeses except C40. However, higher normal force led to higher mass loss at lower temperatures. Penetration depth and mass loss were significantly ($p > 0.05$) greater at higher sliding speed in cheeses containing 40, 50, and 52% fat (dw). Both mass loss and penetration depth significantly ($p < 0.05$) increased with increasing aging time. A box plot prediction model showed that cheeses with mass loss between 0.07 and 0.12g were classified as “good sliceability”; mass loss above this range denoted the “poor sliceability” category. This study is a step forward to understanding food wear; the information generated can be used by the food industry to optimize processing behaviors through adjusting operating parameters.

Keywords: cheese, wear, mass loss, penetration depth

Introduction

Wear, or removal of material from a surface as a result of friction, is a phenomenon that occurs as two solid surfaces slide or roll on each other in relative motion (Axén et al., 2000). As wear occurs, a wear track with a certain pattern, shape, size, and depth is generated on the material’s surface, indicating the wear status of the surface (Wang et al., 2017). Development of low-wear materials for increasing their durability or improving processing behaviors in food industries is a complex task due to multiple influential variables. Contributing factors affecting wear include surface geometrical and topographical characteristics (roughness) (Pal et al., 2008), applied force (Yin et al., 2017), sliding speed and distance (Khanafi-Benghalem et al., 2010), temperature (Khanafi-Benghalem et al., 2010), lubrication (Ahn et al., 2003), type of contact (Saikko et al., 2001), and humidity (Ozcan & Filip, 2013). The impact of these parameters on wear varies in different materials with various physical and/or chemical characteristics and compositions.

The first investigations of wear were carried out on metals due to both their common use as bearing surfaces and because understanding their tribological behaviors is not as challenging as for soft materials. Hard materials have little time-dependent behavior and deformation is negligible when force is applied, while soft materials deform under applied forces, resulting in different tribological behaviors from those of hard materials. Furthermore, soft materials such as hydrogels can be self-lubricating, potentially reducing wear rate (Wang et al., 2017; Yarimitsu, Sasaki, Murakami, & Suzuki, 2016).

In cheese, differences in composition and production steps can lead to different final functionalities. These variances become critical in processing steps that involve shear, such as slicing and shredding. There are several studies that have investigated the effect of fat content on mechanical behaviors of cheese (Bugaud et al., 2001; Drake, Miracle, & McMahon, 2010; Marshall, 1990; Mohamed, 2015; Stokes et al., 2013b). Thus, it is likely that the level of fat content impacts the tribological behavior of cheese.

Cheese sliceability and shreddability behaviors are important for production of desirable cheese slices or shreds. Soft cheeses typically exhibit poor shreddability and sliceability because they stick to blades and create gummy balls, matted cheese shreds, or uneven cheese slices. Very firm cheeses may be crumbly in texture and generate debris (fines) during processing (Ah, 2017). Temperature, sliding speed, aging, and force applied to food products are important factors that are considered in processing operations, and their effect on products with different characteristics can vary. Wear behaviors may relate to these processing behaviors, and wear testing may be a suitable method to characterize or predict shredding or slicing properties of cheese. Since it is a new approach in food science, there are few studies on the wear behavior of foods (Sparkman, Joyner, & Smith, 2019; Zad Bagher Seighalani, & Joyner, 2019). Thus, the objective of this study was to identify factors affecting wear behavior of cheeses with varying fat contents. The results of this study can be used by the food industry to adjust processing equipment configurations and variables to optimize the processing abilities of cheese, and in particular could assist cheese manufacturers in providing high-quality sliced or shredded cheeses to consumers.

Material and methods

Materials

Hard cheeses (18 kg blocks) with different fat contents (40, 50, 52, and 54% fat dw) were provided by a regional cheese manufacturer (Glanbia Nutritionals, Twin Falls, ID, USA) over 6 mo. Proximate composition data for all cheeses is summarized in Table 4.1. Cheeses were manufactured in duplicate.

Table 4.1. Cheese proximate composition[1].

Cheese	Fat (%)	Moisture (%)	Salt (%)	pH
C40	40.05±0.21^{d}	42.61±0.3^{c}	1.60±0.34^{c}	5.10±0.05^{c}
C50	49.97±0.41^{c}	40.91±0.63^{b}	1.66±0.16^{c}	5.09+0.09^{c}
C52	51.90±0.01^{b}	37.62±0.21^{a}	1.92±0.03^{a}	5.20±0.02^{b}
C54	54.62±0.06^{a}	37.12±0.29^{a}	1.77±0.18^{b}	5.28±0.05^{a}

[1] Compositional data was provided by the manufacturer for each individual cheese block. Values are mean ± SD of two replications. Different letters within a column represent significant differences ($p < 0.05$).

Each 18 kg cheese block was cut into 2.5 kg blocks, vacuum-sealed into plastic bags using a vacuum sealer (VacMaster PRO350 Suction Vacuum Sealer) and stored at 5°C throughout the 60 d aging time for this study. Before testing, the outer layer of each cheese block (about 3mm) was removed and discarded; the reminder was used for wear measurement. Samples were tested 15, 30, 45, and 60 d after the date of production.

Wear measurements

Wear tests were carried out using Anton Paar rheometer (MCR 702, TwinDrive Rheometer, Austria) equipped with a steel twin-ball on disc sliding tribo-system. Samples were equilibrated at room temperature (22 ± 2°C) and sliced into 8mm thickness by a commercial slicer (Globe 3600N Slicer, Globe Food Equipment Co., Dayton, OH), and then cut into approximately 80*80 mm square. Tests were performed at two different normal forces (0.5 and 0.7 N) and sliding speeds (30 and 50 mm/s) and a duration of 10 min. The effect of temperature on wear behavior was determined by running test at three different temperatures: 5, 15, and 25°C. For all parameter combinations, the test time (10 min) was held constant. Penetration depth as a function of sliding distance (time) was recorded from each wear test. The weight of samples was measured before and after the test to calculate mass loss (g). The twin-ball geometry and disc were cleaned with 70% ethanol solution after each test. Five replicates of each sample were measured.

Boxplot prediction model for processing ability

Boxplot model prediction was created based on test response (mass loss) and expert classification to determine the processing (slicing) ability of cheese and find cut-off values for good and poor processing ability. The information about cheese processing ability with varying fat contents under different temperatures was provided by the experts from the regional cheese manufacturer that provided the samples and was based on more than 10 yr of experience in cheese production. Samples with good sliceability were denoted by 1; samples with poor sliceability were denoted by 0.

Data analysis

Mass removal and penetration depth were analyzed (IBM SPSS Version 21.0, IBM Corp., Armonk, N.Y., USA) using ANOVA followed by Tukey's multiple range test to determine significant differences at $\alpha = 0.05$. Box plots were generated from mass loss and expert classification data with the same software.

Results and discussion

Effect of temperature on wear behavior

There were significant differences ($p < 0.05$) in mass loss (Figure 4.1a) and penetration depth (Figure 4.1b) of the cheeses at different temperatures. Cheeses containing higher fat content (C50, C52, and C54) had the highest mass loss at 15ºC and had significantly lower mass loss at 5ºC and 25ºC. There were no significant differences between mass loss at 15ºC and 25ºC for C40, although it had significantly lower mass loss at 5ºC. The differences in the mass loss at different temperatures may be associated with the level of fat content and differences in the melting temperature of the fatty acids. Lower values of mass loss at 25ºC in the full-fat cheeses can be explained by melting of some fatty acids at this temperature and the role of fluid fat in the formation of lubrication layer on the wear track. By applying force and rotating the geometry on cheese surface during testing, liquid fat was expelled from the protein matrix and traveled to the surface of cheese (Figure 4.2) (Dagastine et al., 2011; Richoux, Aubert, Roset, Briard-bion, & Kerjean, 2008). The presence of fluid fat on the samples acted as a lubricant and decreased friction between cheese and geometry and resulted in a reduction in the amount of mass loss (Al-araji & Sarhan, 2011; Khanafi-Benghalem et al., 2010). However, the amount of fat in C40 was not sufficient to form a film on the cheese surface at 25ºC to reduce wear.

Also, there was likely a higher degree of protein adherence to the contact surfaces in low-fat cheese, which has higher protein to fat ratio, which may have increased the friction and lead to higher mass loss in low-fat cheese at 25ºC. In the full fat cheeses, the higher number of fat globules between the protein network would minimize protein adherence to the contact surface. This hypothesis is in agreement with previous studies that showed the impact of liquid lubricants in decreasing friction and wear (Guan, Zhou, Wang, Xia, & Liu, 2016; Kato & Adachi, 2001; Kerni, Raina, Irfan, & Haq, 2019; Kharde & Saisrinadh, 2011).

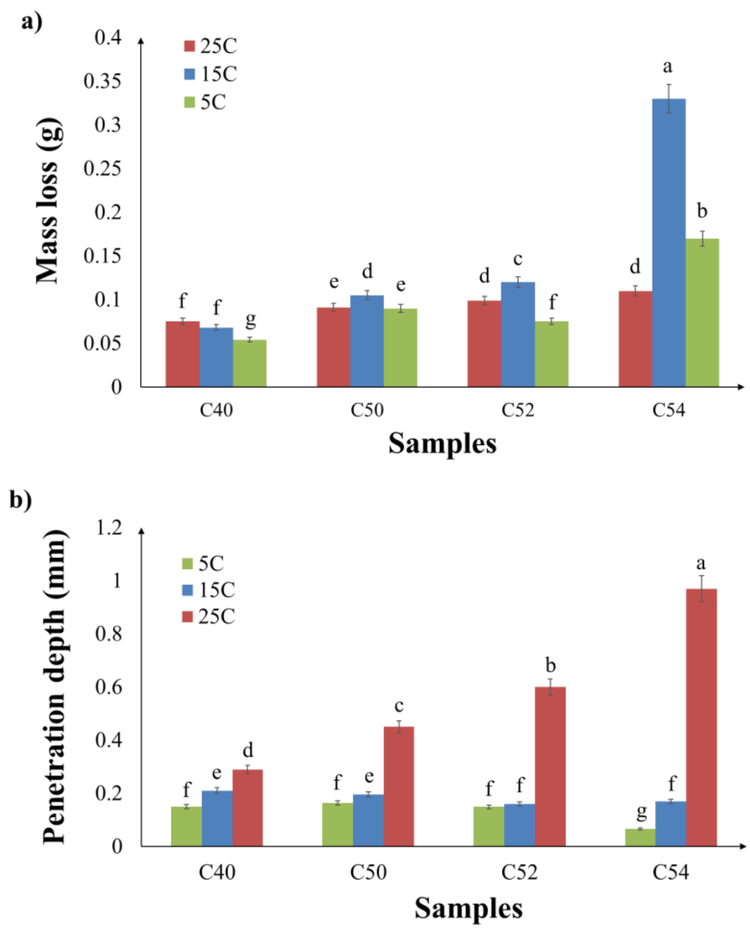

Figure 4.1. Effect of different temperatures (5, 15, and 15°C) on a) mass loss and b) penetration depth. Normal force and sliding speed were held constant at 0.7N and 50mm/s, respectively.

Figure 4.2. Images of wear tracks after the completion of wear tests at different temperatures 5, 15, and 25°C.

The low mass loss at 5°C in all cheeses may have been related to a thermal hardening phenomenon. Many fat globules are crystallized at low temperatures so solid fat content is high (Lopez et al., 2006). The high solid fat content may make the structure of the cheese harder, causing the samples to be more resistant to wear. It is well-known that the hardness of materials plays an important role in wear behavior (Khanafi-Benghalem et al., 2010). At 15ºC, the structures of the cheeses became softer as some of the solid fat reached its melting point, but the amount of melted fat was not sufficient to provide a lubricating layer on the cheese surface after it was expelled from the protein network and migrated to the cheese surface. Thus, the weak structure of samples at 15ºC resulted in low resistance to damage and wear. At 25°C, there is further melting of the solid fat, and the oiling-off phenomenon occurred in cheeses as observed by the shiny, reflective surface of the cheese samples and wear track compared to the cheese samples at lower temperature (Figure 4.2).

The different trends observed in C40 compared to the full-fat cheeses confirmed that fat content plays an important role in mass loss changes at different temperatures. In general, increasing temperature leads to microstructural changes in materials resulting in a hardness drop and makes materials more vulnerable to damage (Rojacz & Varga, 2015). However, the oiling-off phenomenon and its lubrication effect at 25ºC led to lower mass loss for the full-fat cheeses. This has important implications for processing.

All cheeses showed similar trends for penetration depth as affected by temperature (Figure 4.1b). However, the trend for penetration depth with temperature did not match the mass loss trends at different temperatures: penetration depth was significantly ($p < 0.05$) greater at 25ºC compared to those at 5 and 15ºC. Additionally, penetration depth increased more than twofold for C54 compared to C40, C50, and C52. Increased penetration depth at higher temperatures was attributed to weakening of the cheese microstructure due to fat melting, causing the microstructure to be less resistant to deformation and fracture. The greater increase of penetration depth at 25ºC for cheese with higher fat content was attributed to a higher amount of fat globules and thus higher a greater amount of fluid fat at higher temperatures. We hypothesize that the effects of temperature on penetration did not match those of mass loss because penetration depth is a combination of deformation and mass loss in soft materials. Thus, this finding showed that penetration depth in soft materials like cheese is significantly influenced by deformation, as also shown in a study done by Tan and Joyner (2018b) on k-carrageenan and whey protein gels.

Effect of normal force on wear behavior

Overall, temperature influenced the effect of normal force on mass loss (Figure 4.3). Higher normal force resulted in significantly lower mass loss at 25ºC in all cheese. While there were no significant differences between the mass loss at different normal force for C40, a reduced-fat cheese, at 5 and 15°C, mass loss showed significantly ($p < 0.05$) higher values at higher normal force at 5 and 15°C in the full-fat cheeses. The lower mass loss at higher normal force in full-fat cheeses could have been due to the lubrication effect of the expressed fat droplets from the protein network that migrated to the surface of cheese caused by applying higher force at 25°C. This lubrication effect hypothesis was supported by the mass loss data at 5 and 15ºC (Figure 4.4 b and c), which showed higher mass loss at higher normal force since a lubrication layer would not be created at lower temperature due to higher solid fat content. Sample C40 did not show significant differences in mass loss between the two normal forces as the lubrication effect may have been negligible due to the lower fat content. Also, at both levels of normal force, C40 displayed lower mass loss compared to cheeses with higher fat content, which could have been because of firmer microstructure from a stronger protein network and fewer fat droplets, which made the sample more resistance to damage and wear.

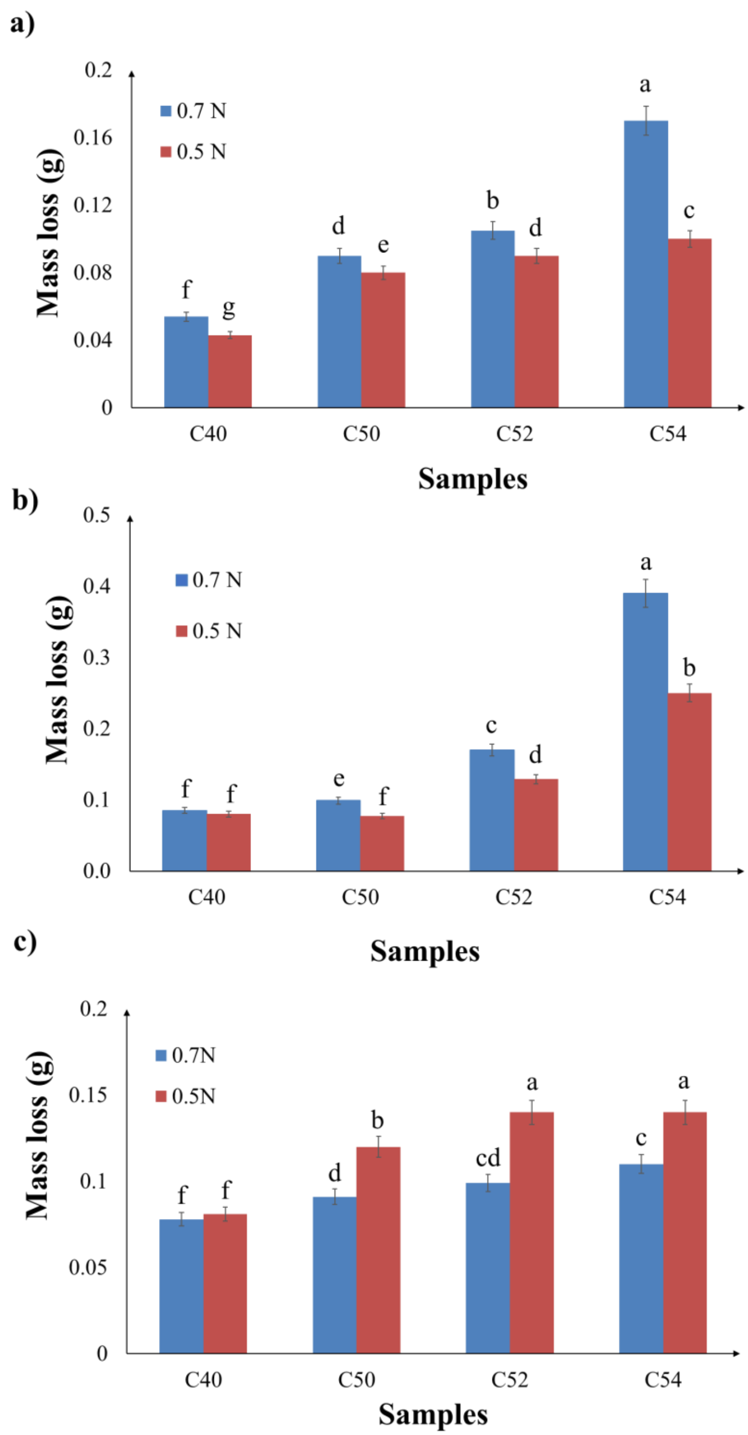

Figure 4.3. Effect of different normal forces (0.5 and 0.7N) a) on mass loss at a) 5ºC, b) 15ºC, and c) 25ºC. Sliding was constant at 30mm/s.

Higher penetration depth was observed at higher normal force at 25ºC for all cheeses (Figure 4.4). This result was in agreement with data obtained by Tan and Joyner (2018), which showed higher penetration depth at greater normal force for κ-carrageenan. However, this result was contrary to the mass loss data, which showed lower mass loss at 25ºC. This difference was attributed to the fact that penetration depth accounts for both deformation and mass loss. At 25ºC samples likely experienced a higher degree of deformation because of weaker structure caused by melting of solid fat, resulting in higher penetration depth, while mass loss was mitigated by a lubrication effect at this temperature. Higher normal forces generally cause more deflection, and thus the balls pushed further into the samples. In addition, the normal force impacts the pressure in the gap between the contact surfaces and consequently may change the wear behavior of the sample by drawing lubricant between the surfaces at lower contact pressures (Ningtyas, Bhandari, Bansal, & Prakash, 2017) Similarly, as the geometry pushes further into the sample at increased normal force, the contact area increases. As a result, more lubricant would be released from the cheese structure and the geometry would slide along the cheese surface with less friction, leading to less mass loss.

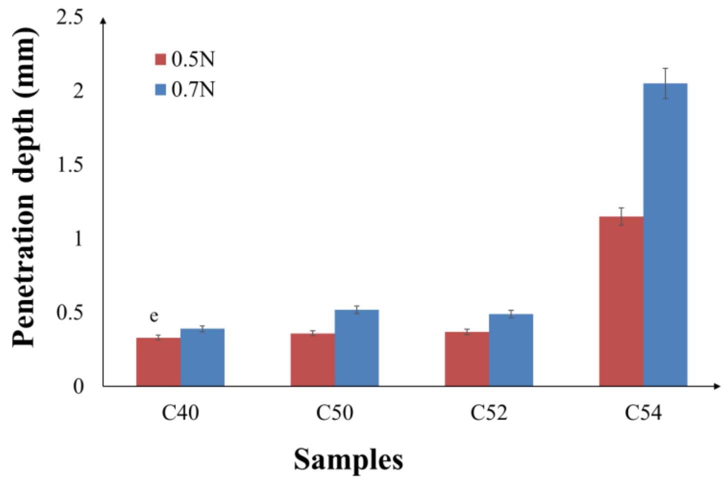

Figure 4.4 . Effect of different normal force (0.5 and 0.7 N) on penetration depth. Sliding speed and temperature were constant at 30 mm/s and 25°C, respectively.

As previously discussed, the layer of expressed fat on the surface was likely responsible for the lower mass loss at higher normal force. This result was in agreement with the findings of Al-araji and Sarhan (2011), who indicated that increased normal force can result in increased interface heating and promote formation of an oil layer, which could reduce friction and subsequently mass loss.

Effect of sliding speed on wear behavior

Sliding speed had a significant effect ($p < 0.05$) on both mass loss and penetration depth (Figure 4.5): all cheeses except C54 showed a significant increase in mass loss (Figure 4.5a) and penetration depth (Figure 4.5b) with increased sliding speed. The higher mass loss and higher penetration depth at higher sliding speed could have been due to increased friction, interface temperature, and shear strain caused by the higher number of contacts and sliding distance at this speed compared to the lower sliding speed (Antonov et al., 2018; Odabas, 2018). A high interface temperature could change cheese microstructure, resulting in a reduction in cheese rigidity and making it less resistant to deformation. Also, higher shear strain at higher sliding speed could disrupt the protein network and reduce the strength of the cheese (Antonov et al., 2018). Sample C54, which had the highest fat content, did not show significantly higher mass loss and penetration depth at the higher sliding speed, likely due to the lubrication effect created by melted fat from friction heating that protected the cheese from damage. Overall, it was concluded that deformability and rigidity of a material are important criteria for determining appropriate sliding speeds for cutting or other mechanical processes that involve shear. This result was in agreement with previous studies that showed that the third law of friction, which states that friction is independent of sliding velocity, is generally not valid for soft, rubbery materials (Antonov et al., 2018; Brostow, Lobland, & Narkis, 2006; Cross, 2006; Nuruzzaman & Chowdhury, 2012; Wmocrv, 2015).

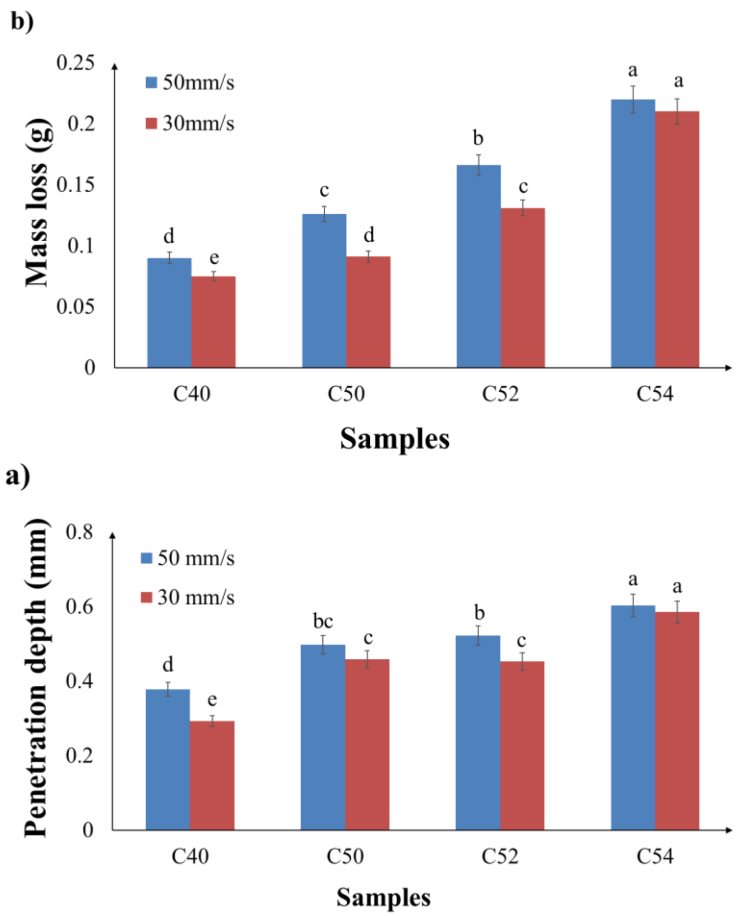

Figure 4.5 . Effect of different sliding speeds (30 mm/s and 50 mm/s) on mass loss. Normal force and temperature were constant at 0.7N and 25°C, respectively.

Effect of cheese aging time on wear behavior

In general, mass loss (Figure 4.6a) and penetration depth (Figure 4.6b) increased during storage. Mass loss significantly ($p < 0.05$) increased between the first month (d15 and d30) and second month (d45 and d60) for all cheeses. Penetration depth showed significant differences during the first 45 d of storage for all cheese, but there were no significant differences in penetration depth between 45d and 60d aging times. Higher mass loss and penetration depth of cheeses with increased aging time was probably due to the more deformable and stickier texture primarily resulting from proteolysis with a small contribution from lipolysis by various proteolytic and lipolytic enzymes, respectively, during storage (Rogers et al., 2009). These changes can be undesirable to cheese sliceability or shreddability as the cheese will significantly adhere to the blade or grater.

The changes in penetration depth and mass loss were more noticeable after d30 for the cheese containing highest fat content compared to other cheeses. This result was in agreement with Perrie (2012), who found that Cheddar cheese did not show good sliceability and stuck to the slicer during slicing when aged more than 30 d while cheeses aged for 15 to 30 d showed good sliceability due to a more flexible protein network that was more resistant to fracture. It has been shown that material properties play an important role in wear behavior (Kato & Adachi, 2001; Sagbas et al., 2009; Tan & Joyner, 2018a; Viswanath & Bellow, 1995b). Therefore, aging time, which influences both cheese microstructure and mechanical properties (Roberts & Vickers, 1994; Rogers et al., 2010; Yang, Rogers, Berry, & Foegeding, 2011), can considerably impact wear behavior.

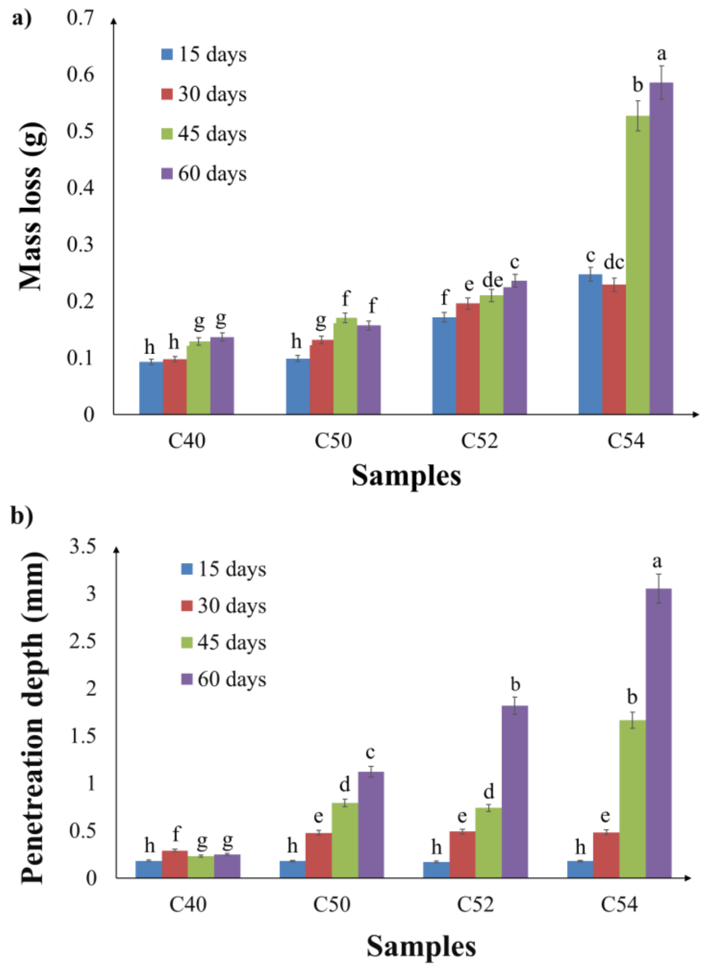

Figure 4.6 . Effect of different aging times (15, 30, 45, and 60d) on a) mass loss and b) penetration depth. Normal force, sliding speed, and temperature were constant at 0.7N and 50mm/s, and 25°C, respectively.

Processing ability in relation to mass loss

Samples with mass loss between 0.07 and 0.12 g showed good processing behavior, while samples with mass loss between 0.13 to 2.3 g showed poor processing behavior (Figure 4.7). These differences may have been related to their differences in viscoelastic behavior, and their resistance to fracture caused by testing temperature, fat content, aging time, and slicing speed. There were two outlying points with high mass loss (0.5 to 0.6 g), denoted by the asterisks on the plot that likely reduced the prediction accuracy.

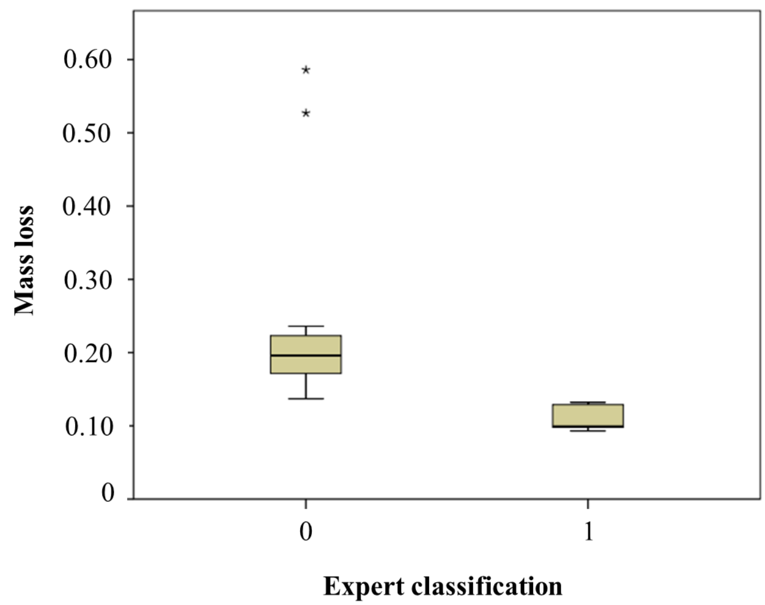

Figure 4.7. Mass loss and expert classification box plot for slicing ability. 0 denotes poor processing and 1 denotes good processing.

Note: * indicates outlying points corresponded to excessive mass loss.

The runs with good processing ability were those with low fat content, lower aging time, and low temperature, which was associated with low mass lass. The sample size which was used in this analysis was small (n=12), as the information related to sliceability of cheese at different normal forces was not available from experts as the slicer used in the cheese company was not adjustable for normal force. Also, the information from experts was based on a common speed slicing speed (300 rpm), which was equivalent to 50 mm/s sliding speed, so the data for the lower sliding speed of 30 mm/s were not included. However, this analysis provided useful information about selecting mass loss cut off values for determining processing ability. Further work on relationships between processing ability obtained from pilot plant study and wear testing may provide a more accurate prediction of processing ability.

Conclusions

Fat content, sliding speed, normal load, temperature, and aging time were significant variables affecting cheese wear behaviors. Overall, mass loss and penetration depth increased as fat content increased. For all cheeses except C40, the highest mass loss occurred at 15°C. Lower mass loss at 5 and 25°C compared to 15°C was likely due to solidification of fat globules at 5°C and oiling-off and a subsequent lubrication effect at 25°C. Penetration depth was higher at 25°C compared to 15 and 5°C due to thermal softening of fat at higher temperature, weakening the cheese microstructures. Mass loss and penetration depth increased as sliding speed increased. The effect of normal force differed by temperature. Higher normal force resulted in lower mass loss and higher penetration depth in all cheeses at 25°C due to more oiling off under higher normal force, while higher normal force led to higher mass loss and penetration depth at 5 and 15°C. Box plot classification showed that cheeses with lower mass loss (0.07–0.12 g) from a cheese with a weight of approximately 30 g had good processing ability. Thus, maintaining appropriate temperature, sliding speed, and normal load levels and finding appropriate aging time based on cheese composition can reduce cheese mass loss, improving its processing ability. Further information about the relationships between food processing behaviors and wear may be obtained from studies investigation a broader set of samples and processing parameters.

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Chapter 5 : Relationship Between Rheological, Sensorial Behaviors and Wear Behaviors of Cheeses Containing Various Fat Contents

Abstract

Studying rheological and sensory behaviors of cheese provides structural and texture-related information that could be useful for a better understanding of the complex wear behaviors of cheese and their relationships with cheese industrial and oral processing behaviors. Thus, the objective of this study was to determine the relationships of rheological and sensory properties with cheese wear. Rheological tests including large amplitude oscillatory shear (LAOS), strain sweeps at different temperatures (5, 15, and 25ºC) and frequencies (0.5, 5, and 50 rad/s), and large-strain compression at room temperature (22±2°C) were conducted for cheeses with varying fat contents (40, 50, 52, and 54% dw) aged for different periods (15, 30, 45, and 60 d). Descriptive sensory analysis was used to evaluate cheese sensory texture attributes. Overall, fat content, temperature, and aging time had significant impact on cheese viscoelastic parameters. Higher temperature, aging time, and fat content led to lower rigidity and greater extent of nonlinear viscoelastic behaviors in the cheeses. Mass loss showed negative correlations with critical strain, critical stress, complex modulus, and fracture stress, but had positive correlations with phase angle and fracture strain. Sensory data showed that texture attributes were affected by cheese fat content and aging time and had significant correlations with mass loss at high normal force and sliding speed. This study showed that rheology and sensory data can be used to provide fundamental information on the wear behaviors of cheese and other soft materials.

Keyword: rheology, large amplitude oscillatory shear, sensory texture, wear, cheese

Introduction

Sliced and shredded cheeses have been increasingly popular over the last several decades. To meet consumer expectations, the cheese industry has put significant effort into manufacturing functional slices or shreds of cheese with desirable palatability. However, cheeses with different fat contents may differ mechanical behaviors and texture that can impact their processing ability. Cheeses with brittle structure may crumble during processing, while cheese with soft and sticky texture may adhere to slicing or shredding equipment. In terms of sensory, cheeses with soft textures stick to the palate and teeth, and cheeses with firm texture tend to be crumbly and leave more residue in the mouth. These differences in textural and processing behaviors of cheese may be related to wear.

Understanding the rheological behaviors of cheese is an inseparable part of wear study of cheese because cheeses are viscoelastic soft solids that undergo deformation when subjected to force. In a previous study, Cheddar and Monterey Jack cheeses with different rheological behaviors showed different wear behaviors (Chapter 3: Zad Bagher Seighalani, & Joyner, 2019). Another study on wear behavior of high-protein bars showed how major bar ingredients can affect their rheological and wear behaviors (Sparkman, Joyner, & Smith, 2019). Thus, rheological behaviors that provide information about deformation and structural properties may be helpful for understanding the wear of soft solids.

Mass loss from the main block of cheese during the slicing and shredding of cheese may play a determining role in the quality of cheese slices or sherds and can be a method for determining cheese wear, and thus its sliceability or shreddability. In cheese manufacturing, different cheeses aged for different times may undergo processing steps under the same operational conditions (temperature, force, and speed), but the degree of stickiness and residual mass on the processing equipment may be different for cheeses with different textures and deformabilities. It is assumed that the mass loss can be minimized, and therefore, sliceability and shreddability of cheese can be maximized by using an understanding of cheese wear behaviors to select appropriate operation conditions. Unfortunately, there is no published information about how cheese rheology and sensory behaviors are related to their wear behavior. To better understand the relationships among soft solid rheological, sensorial and, wear behaviors, this study aimed to determine the correlations among viscoelastic parameters, sensory texture attributes, and mass loss under different conditions.

Materials and Methods

Materials

Cheddar cheeses (18 kg blocks) with different fat contents (40, 50, 52, and 54% fat dw) were manufactured in duplicates by a regional cheese manufacturer (Glanbia Nutritionals, Twin Falls, ID, USA). Proximate composition data for all cheeses are summarized in Table 5.1.

Table 5.1. Cheese proximate analysis[1] .

Cheese	**Fat (%)**	**Moisture (%)**	**Salt (%)**	**pH**
C40	40.05±0.21^{d}	42.61±0.3^{c}	1.60±0.34^{c}	5.10±0.05^{c}
C50	49.97±0.41^{c}	40.91±0.63^{b}	1.66±0.16^{c}	5.09+0.09^{c}
C52	51.90±0.01^{b}	37.62±0.21^{a}	1.92±0.03^{a}	5.20±0.02^{b}
C54	54.62±0.06^{a}	37.12±0.29^{a}	1.77±0.18^{b}	5.28±0.05^{a}

[1] Compositional data was provided by the manufacturer on each individual cheese block. Values are mean ± SD of two replications. Different letters within a column represent significant differences at $p < 0.05$.

Sample preparation

Cheeses were manufactured in duplicate by a regional cheese manufacture (Glanbia Nutritionals, Twin Falls, Idaho, USA). Each 18 kg cheese block was cut into 2.5 kg blocks, vacuum-sealed into plastic bags using a vacuum sealer (VacMaster PRO350 Suction, ARY Inc. Kansas City, USA) and stored at 5°C throughout the 60d aging time for this study. Before testing, the outer layer of each cheese block (about 3mm) was removed and discarded; the remainder was used for wear and rheological measurements, fracture testing, and sensory evaluation. Samples were tested 15, 30, 45, and 60d after the date of production.

Oscillatory rheometry

Rheological tests included strain sweeps, which provide useful information about mechanical behaviors in the linear viscoelastic region (LVR), and large amplitude oscillatory shear (LAOS), which gives valuable information about viscoelastic behavior and structure changes beyond the LVR. Strain sweeps were conducted using an Anton Paar MCR702 (Anton Paar, Gratz, Austria) equipped with 20 mm diameter crosshatched parallel plates. Sample blocks were equilibrated at room temperature (22±2°C) for 1 h, sliced to 4 mm thickness using a commercial slicer (Globe 3600N, Globe Food Equipment Co.; Dayton, OH, USA), then cut into circular pieces using an aluminum punch. After loading the samples into the rheometer, petroleum jelly was applied to the exposed sample edges to prevent drying during testing. Strain sweeps (0.01 to 100% strain) were conducted at 0.5, 5, and 50 rad/s. Samples were tested at 5, 15, and 25°C in triplicate.

Critical strain was calculated as the first strain at which the complex modulus changed by more than 2% from the previous value. The stress at this strain value was labeled as the critical stress.

Large amplitude oscillatory shear (LAOS) data, including strain-stiffening ratio (S), shear-thickening ratio (T), and G'_3/G'_1, were extracted from the strain sweep data at four different strains (0.1, 1, 10, and 56%). These strains were selected because their range included both the linear and nonlinear viscoelastic regions for all cheeses.

Large strain compression

Large strain compression testing was carried out using a TAXTPlus Texture Analyzer (Texture Technologies, Hamilton, MA, USA) equipped with a 50.8 mm diameter aluminum plate and 5kN load cell. Cheese samples were equilibrated at room temperature (22±2°C) for 1 hr before testing. Cheeses were cut into cylinders (approximately 20 mm diameter and 20 mm height) using a cylindrical stainless-steel borer. Samples were compressed to 50% of their original height at a crosshead speed of 50mm/min (Joyner (Melito), Francis, Luzzi, & Johnson, 2017). Peak force and distance at first fracture (first peak) were recorded, and fracture stress and fracture strain were calculated from these data. Six replicates were performed for each sample.

Sensory evaluation

Sensory evaluation of cheeses was conducted under the approval of the University of Idaho Institutional Review Board (IRB) for human subject participation (approval number 17-208). Nine panelists were recruited from the Washington State University/University of Idaho School of Food Science by e-mail. The panel was composed of 6 females and 3 males 18 to 60 yr in age (mean panel age= 31 yr). Panelists received approximately 16 h training in cheese descriptive texture analysis using a 15 cm line scale with anchors at 1.5 cm for low intensity and 13.5 cm for high intensity. Thirteen different texture attributes were divided into four different categories: hand terms, first-bite terms, chewdown terms, and residual terms (Table

5.2). Panelists were given nonmonetary incentives, including a $1.75 gift card for each session and a $50 gift card at the end of the project for training (10 sessions) and formal evaluation (32 sessions).

Sensory evaluation of the samples was performed using the descriptive sensory analysis method described by Rogers et al. (2009). Instruction and data collection during formal evaluations were carried out using Compusense® Cloud (Compusense Inc., Guelph, ON, Canada). Samples were coded using random 3-digit numbers and presented in individual lidded serving cups to minimize any texture changes during evaluation. Coded samples were given to panelists in random order at room temperature (22±2°C). At each formal evaluation session, 2 samples were evaluated. Panelists were provided with 13 cubes (1.2 cm^3) of each sample, reference cheeses for calibration, distilled water and unsalted crackers for a palate cleanser.

Table 5.2. Texture attributes designed for Cheddar cheese, adapted from Brown et al. (2003).

Attribute	Definition	Technique	Reference
Hand terms			
Firmness	The force required to compress the sample.	Press sample gently using thumb and 2 fingers for 1 to 2 s without breaking.	4= Muenster 7= Extra Sharp Cheddar 14= Parmesan
Springiness	The total amount of recovery of the sample (ability to recover its initial thickness rapidly after compression and deformation)	Press the sample using the thumb and first 2 fingers until it is depressed 30% for 1 to 2 s without breaking. Evaluate rate at which sample springs back after compression.	1= Parmesan 7= Extra Sharp cheese 13= Muenster
Rate of recovery	The speed at which the sample returns to its original shape	Press the sample between the thumb and first 2 fingers until it is depressed 30% and evaluate the speed or rate at which the sample returns to its original shape.	1 = Feta 4 = Velveeta 7 = Muenster
First-bite terms			
Firmness	The amount of force required to completely bite through the sample	Completely bite through the sample using the molars	3 = Velveeta 7 = Muenster 14 = Parmesan
Fracturability	The degree to which the sample fractures after biting	Completely bite through the sample using the molars	1 = Velveeta 7 = Extra Sharp Cheddar 14 = Parmesan
Chewdown terms			
Degree of breakdown	The amount of breakdown that occurs in the sample as a result of mastication (i.e., the amount of meltability or dissolvability)	Chew the sample 5 times and evaluate the chewed mass	1 = Parmesan 7 = Extra Sharp Cheddar 14 = Velveeta
Cohesiveness	The degree to which the chewed mass holds together (firmness of the internal joints in the cheese sample)	Chew the sample 5 times and evaluate the chewed mass	1 = Parmesan 9 = Muenster 14 = Velveeta
Smoothness of mass	The degree to which the chewed mass surface is smooth (i.e., evaluation for gritty or grainy particles)	Chew the sample 5 times and evaluate the chewed mass	3 = Parmesan 10 = Muenster 14 = Velveeta
Mouth coating	The extent to which the cheese coats the palate and teeth during mastication.	Chew the sample 5 times and evaluate the chewed mass	1 = Parmesan 8 = Muenster 14 = Velveeta
Adhesiveness	The degree to which the chewed sample sticks to the surfaces of the mouth and teeth (moving the tongue to detach the sample stuck in the palate)	Chew the sample 5 times and evaluate the chewed mass	1=Parmesan 7=Muenster 14=Velveeta
Moistness	The perceived moisture content of the cheese; ranging from dry to moist	Chew the sample 5 times and evaluate the chewed mass	1=Parmesan 7=Munster 12=Ricotta cheese
Residual terms			
Mouth coating	The degree of smoothness felt in the mouth after expectorating or swallowing the sample	Chew the sample 5 times, expectorate, and evaluate the residual in the mouth	1 = Parmesan 10 = Muenster 14 = Velveeta
Particles	The number of particles felt in the mouth after expectorating or swallowing the sample	Chew the sample 5 times, expectorate, and evaluate the residual in the mouth	1 = Velveeta 7= Extra sharp cheddar 14 = Parmesan

Note: Brands used for reference cheeses were: WinCo Foods (Muenster), Great Value (extra-sharp Cheddar), Athenos (feta), Kraft (Velveeta), BelGioioso (Parmesan), and Frigo (Ricotta).

Rheological, wear, and sensory results used for correlations

The results from wear measurements in Chapter 4 were used for correlation analysis to determine relationships of wear behavior with the rheology and sensory data collected in this study. Selected rheological parameters included critical strain, critical stress, complex modulus, phase angle, fracture strain, and fracture stress. All 13 sensory attributes were used for correlation. Selected wear parameters included mass loss at different normal forces (0.5 and 0.7 N) and sliding speeds (30 and 50 mm/s).

Data analysis

Mass loss and selected rheological data were analyzed using SPSS (Version 19.0, SPSS, Inc., PA, USA) with ANOVA followed by Tukey's multiple range test to determine significant differences ($p < 0.05$). Sensory results were analyzed by principal component analysis (PCA) and cluster analysis to compare similarities and show relationships among samples over aging time.

Results and Discussion

Strain sweep results

For all viscoelastic parameters, the effects of cheese fat content, temperature, aging time, and the interaction of cheese fat content with the other two parameters were significant ($p < 0.05$). F- ratio tables for strain sweep data at different frequencies are shown in the Appendix (Table A1, A2, and A3).

Fat content showed a significant effect on linear viscoelastic parameters ($p < 0.05$). This result can be mainly explained by the role of fat content in disruption of the protein network, which led to disrupting its continuity and reduced its ability to deform reversibly (Johnson & Chen, 1995). This result is in agreement with previous studies which showed that removal of fat leads to a lower fat to protein ratio, causing a dense protein structure and consequently a firmer cheese (Jiménez-Escrig, Jiménez-Jiménez, Pulido, & Saura-Calixto, 2001; Ma L, Drack M A, Barbosa Canovas G V, 1997; Rogers, McMahon, Daubert, Berry, & Foegeding, 2010).

The significant ($p < 0.05$) effect of temperature on the viscoelastic parameters was attributed to the phase change of some of the fat in the cheese from solid to liquid at the higher testing temperatures. Previous studies on cheese microstructure have shown that more of the fat is crystallized at lower temperatures, which strengthens the protein network structure through interactions with the casein proteins (Marshall, 1990; Tunick, 2010a).

Aging time also had significant ($p < 0.05$) effect on the rheological parameters. This finding can be explained by the chemical and structural changes in cheese over time, which are primarily associated with protein hydrolysis and re-equilibration of ions (Lawrence, Creamer, & Gilles, 1987; Rogers et al., 2010). These changes degrade the casein network and result in a less firm and more deformable as cheese ages (Joyner (Melito) et al., 2017; Rogers et al., 2009; Tunick, 2010b).

Critical strain and stress values decreased as cheese fat content, temperature, and aging time increased, as expected (Table 5.3). Smaller values of critical stress and strain for cheeses with a higher fat content (C52 and C54) indicated that the structure of these cheeses underwent permanent deformation at a lower force and deformation compared to those with lower fat (C40 and C50). Critical strain and critical stress were lower at higher testing temperatures, which was attributed to the decrease in rigidity of fat globules from partial fat melting, which decreased the stiffness of cheese (Dimitreli & Thomareis, 2004; Venugopal & Muthukumarappan, 2007; Yang, Rogers, Berry, & Foegeding, 2011). The decrease in cheese critical stresses and strains with aging were likely due to changes in the structure of the protein network (Table 5.3). Proteolysis during aging time leads to softening the structure and reducing rigidity of the cheeses (Venugopal & Muthukumarappan, 2007). These findings agree with studies done on Cheddar cheese aged for 9 months (Rogers et al., 2009), UK Cheddar cheese aged for 64 wk (Hort & Le Grys, 2001), and blue cheese stored up to 60d (Joyner (Melito) et al., 2017).

Complex modulus (G^*) values were significantly lower at 25°C compared to 15 and 5°C (Table 5.3) because the fat globules transformed from relatively rigid fillers when they were solid to soft fillers when the fat was partially melted. Moreover, the G^* values were lower for C54 compared to the other cheeses with lower fat contents. Reduction of G^* with increasing fat content may be related to the role of the fat globules in interrupting the casein network, decreasing its rigidity (Hassan, Awad, & Muthukumarappan, 2005; Rogers et al., 2010). G^* also decreased significantly over time, likely because of proteolysis effects (Joyner (Melito) et al., 2017; Rogers et al., 2009, 2010).

Table 5.3. Cheese rheological parameters at critical strain and a frequency of 0.5 rad/s.

Aging time	Temperature (°C)	Cheese	Critical strain (%)	Critical stress (kPa)	G* (kPa)	Phase angle
15	5	40	0.56 ± 0.00^{a}	0.45 ± 0.01^{b}	246.30 ± 11.22^{a}	16.57 ± 0.53^{ji}
		50	0.56 ± 00^{a}	0.50 ± 0.01^{a}	197.78 ± 3.45^{d}	16.06 ± 0.36^{j}
		52	0.32 ± 0.00^{c}	0.37 ± 0.02^{c}	187.58 ± 2.88^{e}	17.55 ± 1.26^{hi}
		54	0.18 ± 0.00^{d}	0.27 ± 0.02^{e}	152.31 ± 2.65^{f}	18.48 ± 0.20^{gh}
	15	40	0.56 ± 00^{a}	0.35 ± 0.02^{c}	127.91 ± 2.30^{g}	17.33 ± 0.26^{i}
		50	0.32 ± 0.00^{c}	0.30 ± 0.01^{d}	126.67 ± 6.30^{g}	18.09 ± 0.18^{h}
		52	0.18 ± 0.00^{d}	0.22 ± 0.04^{g}	126.70 ± 6.30^{g}	18.77 ± 1.27^{g}
		54	0.32 ± 0.00^{d}	0.18 ± 0.00^{h}	117.76 ± 1.13^{h}	19.89 ± 0.14^{e}
	25	40	0.44 ± 0.16^{b}	0.22 ± 0.01^{g}	129.30 ± 1.07^{g}	19.76 ± 0.27^{e}
		50	0.32 ± 0.00^{c}	0.15 ± 0.00^{k}	114.23 ± 2.40^{h}	19.60 ± 0.67^{e}
		52	0.18 ± 0.00^{d}	0.10 ± 0.01^{j}	101.87 ± 1.55^{i}	19.47 ± 0.70^{e}
		54	0.18 ± 0.08^{bc}	0.07 ± 0.01^{n}	102.80 ± 1.47^{i}	20.92 ± 0.11^{d}
30	5	40	0.31 ± 0.16^{c}	0.37 ± 0.02^{c}	243.50 ± 4.95^{a}	16.22 ± 0.26^{j}
		50	0.32 ± 0.00^{c}	0.22 ± 0.09^{eg}	230.59 ± 3.98^{b}	17.82 ± 0.18^{hi}
		52	0.32 ± 0.00^{c}	0.31 ± 0.01^{d}	255.00 ± 14.14^{a}	17.58 ± 0.28^{i}
		54	0.18 ± 0.00^{d}	0.22 ± 0.00^{g}	213.00 ± 6.86^{c}	20.34 ± 0.70^{d}
	15	40	0.32 ± 0.08^{c}	0.29 ± 0.00^{d}	151.00 ± 2.82^{f}	18.04 ± 1.13^{h}
		50	0.18 ± 0.00^{d}	0.22 ± 0.01^{g}	126.40 ± 1.59^{g}	18.52 ± 0.29^{g}
		52	0.18 ± 0.01^{d}	0.22 ± 0.00^{g}	126.50 ± 4.94^{g}	18.69 ± 0.54^{g}
		54	0.18 ± 0.01^{d}	0.19 ± 0.02^{h}	110.01 ± 14.11^{h}	19.80 ± 0.22^{e}
	25	40	0.32 ± 0.00^{c}	0.16 ± 0.02^{k}	98.00 ± 2.82^{i}	18.72 ± 0.32^{g}
		50	0.32 ± 0.00^{c}	0.18 ± 0.01^{h}	57.67 ± 4.54^{ml}	19.74 ± 0.14^{e}
		52	0.18 ± 0.01^{d}	0.16 ± 0.00^{k}	35.69 ± 4.95^{o}	19.68 ± 0.65^{e}
		54	0.18 ± 0.02^{d}	0.07 ± 0.01^{n}	42.23 ± 2.43^{mn}	20.87 ± 0.07^{d}
45	5	40	0.32 ± 0.00^{c}	0.24 ± 0.01^{f}	135.57 ± 4.24^{g}	16.83 ± 0.21^{j}
		50	0.18 ± 0.00^{d}	0.24 ± 0.00^{f}	133.11 ± 0.77^{g}	18.52 ± 0.23^{g}
		52	0.18 ± 0.00^{d}	0.20 ± 0.00^{g}	133.13 ± 4.42^{g}	19.12 ± 0.16^{f}
		54	0.11 ± 0.01^{e}	0.18 ± 0.00^{h}	130.18 ± 5.80^{g}	21.46 ± 0.09^{b}
	15	40	0.32 ± 0.02^{c}	0.28 ± 0.01^{de}	123.17 ± 4.24^{hi}	19.28 ± 0.14^{ef}
		50	0.18 ± 0.00^{d}	$0.22\pm\pm0.00^{g}$	125.50 ± 0.70^{hi}	18.52 ± 0.34^{g}
		52	0.18 ± 0.00^{d}	0.27 ± 0.02^{de}	65.83 ± 0.72^{k}	20.07 ± 0.08^{e}
		54	0.18 ± 0.01^{d}	0.12 ± 0.00^{j}	53.51 ± 4.70^{ml}	21.98 ± 0.07^{a}
	25	40	0.56 ± 0.00^{a}	0.48 ± 0.05^{a}	61.81 ± 4.94^{l}	20.26 ± 0.07^{d}
		50	0.10 ± 0.00^{e}	0.10 ± 0.00^{j}	66.08 ± 0.80^{k}	20.27 ± 0.12^{d}
		52	0.10 ± 0.01^{e}	0.08 ± 0.01^{n}	51.82 ± 1.66^{m}	21.27 ± 0.14^{b}
		54	0.18 ± 0.01^{d}	0.54 ± 0.06^{a}	56.26 ± 3.53^{l}	22.43 ± 0.21^{a}
60	5	40	0.32 ± 0.00^{c}	0.23 ± 0.01^{fg}	155.5 ± 6.36^{f}	20.38 ± 0.53^{d}
		50	0.18 ± 0.00^{d}	0.21 ± 0.00^{g}	132.61 ± 2.46^{g}	19.18 ± 0.04^{f}
		52	0.10 ± 0.00^{e}	0.25 ± 0.00^{f}	124.11 ± 4.78^{h}	20.68 ± 0.01^{d}
		54	0.10 ± 0.00^{e}	0.27 ± 0.03^{df}	157.60 ± 5.107^{f}	21.07 ± 0.06^{c}
	15	40	0.32 ± 0.01^{c}	0.20 ± 0.01^{g}	124.48 ± 21.09^{g}	20.38 ± 0.04^{d}
		50	0.18 ± 0.00^{d}	0.18 ± 0.00^{h}	120.36 ± 11.12^{g}	19.18 ± 0.24^{f}
		52	0.10 ± 0.00^{e}	0.14 ± 0.00^{i}	113.40 ± 31.95^{hi}	20.68 ± 0.05^{d}
		54	0.10 ± 0.00^{e}	0.10 ± 0.01^{m}	96.47 ± 27.65^{i}	21.07 ± 0.14^{bc}
	25	40	0.32 ± 0.00^{c}	0.15 ± 0.00^{k}	83.44 ± 2.25^{i}	21.32 ± 0.07^{b}
		50	0.32 ± 0.00^{c}	0.14 ± 0.00^{i}	75.16 ± 4.36^{j}	20.02 ± 0.14^{e}
		52	0.10 ± 0.00^{g}	0.06 ± 0.00^{n}	63.99 ± 6.68^{k}	20.85 ± 0.17^{d}
		54	0.10 ± 0.02^{f}	0.08 ± 0.00^{n}	61.03 ± 6.45^{k}	22.75 ± 0.07^{a}

Values are mean ± SD of three replications. Different letters within a column represent significant differences at $p < 0.05$.

Increased phase angle with temperature, fat content, and aging time indicated an increase in viscous-type behavior, although the overall viscoelastic behavior was solid-like at all conditions ($\delta < 45°$). Increased phase angle with increasing testing temperature may have been related to the partial fat melting that increased the viscous behavior of the cheese and weakened the gel network. This result agreed with the temperature effect on cheese phase angle found by Lucey et al. (2003) and Rogers et al. (2010). As previously mentioned, changes of phase angle were attributed to breakdown of the protein network over time, which makes the structure weaker.

The overall trends for critical strain, critical stress, complex modulus, and phase angle at 5 rad/s (Table 5.4) and 50 rad/s (Table 5.5) were similar to those at 0.5 rad/s, and they were significantly ($p < 0.05$) affected by fat content, temperature, and aging time.

Table 5.4. Cheese rheological parameters at critical strain and a frequency of 5 rad/s.

Aging time	Temperature (°C)	Cheese	Critical strain (%)	Critical stress (kPa)	G* (kPa)	Phase angle
15	5	40	0.56±0.00^{a}	0.41±0.01^{a}	246.25±3.68^{a}	15.74±0.15^{h}
		50	0.56±0.00^{a}	0.31±0.01^{b}	182.68±4.44^{e}	16.08±0.21^{gh}
		52	0.32±0.00^{b}	0.29±0.01^{c}	164.11±6.19^{f}	16.99±0.06^{g}
		54	0.14±0.00^{e}	0.23±0.01^{de}	161.26±11.86^{f}	18.38±0.13^{e}
	15	40	0.56±0.00^{a}	0.24±0.01^{d}	124.44±4.97^{i}	16.86±0.11^{g}
		50	0.44±0.17^{a}	0.33±0.08^{b}	129.84±12.88^{hi}	18.75±0.11^{e}
		52	0.25±0.09^{c}	0.20±0.01^{f}	82.63±2.54^{m}	18.59±0.35^{e}
		54	0.14±0.06^{de}	0.22±0.01^{e}	67.46±2.11^{n}	19.56±0.25^{d}
	25	40	0.25±0.09^{c}	0.18±0.01^{g}	60.83±2.35^{o}	18.62±0.20^{e}
		50	0.10±0.00^{f}	0.12±0.01^{j}	63.85±7.23^{no}	19.59±0.35^{d}
		52	0.10±0.00^{f}	0.15±0.01^{i}	50.43±1.98^{q}	17.86±1.55^{ef}
		54	0.14±0.06^{de}	0.08±0.00	52.11±1.94^{p}	19.70±0.20^{d}
30	5	40	0.25±0.10^{c}	0.34±0.02^{b}	212.99±13.51^{c}	16.86±0.18^{g}
		50	0.14±0.06^{de}	0.32±0.02^{b}	230.36±1.60^{b}	17.37±0.12^{ef}
		52	0.10±0.00^{f}	0.32±0.01^{b}	214.68±2.38^{c}	17.62±0.23^{ef}
		54	0.14±0.06^{de}	0.25±0.01^{d}	203.41±4.14^{d}	19.73±0.35^{d}
	15	40	0.32±0.00^{b}	0.20±0.00^{f}	201.68±1.20^{c}	17.59±0.20^{ef}
		50	0.10±0.00^{f}	0.17±0.01^{g}	121.64±1.13^{i}	18.70±0.23^{e}
		52	0.12±0.03^{f}	0.17±0.01^{g}	92.32±2.33^{l}	18.77±0.29^{e}
		54	0.10±0.00^{f}	0.14±0.00^{i}	135.41±3.76^{gh}	19.62±0.20^{d}
	25	40	0.25±0.10^{c}	0.12±0.01^{j}	103.74±4.60^{j}	18.54±0.43^{e}
		50	0.14±0.06^{de}	0.10±0.01^{kj}	61.01±1.66^{o}	19.21±0.18^{d}
		52	0.10±0.00^{f}	0.11±0.01^{j}	42.72±1.88^{r}	19.13±0.14^{d}
		54	0.14±0.06^{de}	0.11±0.00	57.13±1.82^{p}	20.27±0.26^{c}
45	5	40	0.32±0.00^{b}	0.29±0.01^{b}	118.04±3.10^{i}	16.62±0.33^{g}
		50	0.25±0.10^{c}	0.30±0.01^{b}	114.55±2.40^{i}	17.13±0.14^{ef}
		52	0.18±0.00^{d}	0.24±0.02^{d}	98.39±3.04^{k}	18.51±0.18^{e}
		54	0.16±0.03^{de}	0.15±0.01^{hi}	93.58±4.46^{l}	20.14±0.13^{c}
	15	40	0.25±0.10	0.19±0.01^{f}	107.55±3.69^{j}	19.24±0.28^{d}
		50	0.14±0.06^{de}	0.14±0.01^{hi}	124.08±3.14^{hi}	18.52±0.19^{e}
		52	0.14±0.06^{de}	0.15±0.01^{h}	82.30±2.22^{m}	19.36±0.03^{cd}
		54	0.09±0.01^{f}	0.10±0.01^{k}	51.82±2.12^{pq}	21.50±0.21^{b}
	25	40	0.25±0.10^{c}	0.11±0.00^{j}	68.07±2.96^{n}	19.14±0.13^{d}
		50	0.10±0.00^{f}	0.10±0.00^{k}	61.53±1.51^{op}	19.54±0.03^{cd}
		52	0.10±0.00^{f}	0.10±0.03^{kj}	45.83±0.64^{r}	20.19±0.21^{c}
		54	0.10±0.00^{f}	0.07±0.01^{l}	59.33±8.26^{op}	21.56±0.28^{b}
60	5	40	0.32±0.00^{b}	0.24±0.03^{d}	127.70±8.98^{hi}	19.19±0.22^{cd}
		50	0.32±0.00^{b}	0.24±0.02^{d}	103.54±4.50^{j}	18.13±0.15^{e}
		52	0.06±0.00^{g}	0.17±0.01^{g}	90.67±6.58^{l}	19.29±0.35^{d}
		54	0.06±0.00^{g}	0.10±0.01^{kj}	98.04±3.97^{k}	20.53±0.27^{c}
	15	40	0.25±0.10^{c}	0.16±0.03^{ghi}	104.19±4.02^{j}	19.39±1.06^{cd}
		50	0.25±0.10^{c}	0.17±0.02^{g}	94.42±2.73^{l}	20.14±0.13^{c}
		52	0.05±0.02^{gh}	0.10±0.00^{k}	99.30±1.80^{k}	19.33±0.45^{d}
		54	0.03±0.00^{gh}	0.09±0.01^{k}	96.30±6.24^{k}	21.11±0.17^{b}
	25	40	0.18±0.00^{d}	0.11±0.01^{kj}	66.04±5.02^{n}	21.29±0.35^{b}
		50	0.14±0.06^{de}	0.08±0.04^{lk}	80.83±0.78^{m}	20.44±0.45^{c}
		52	0.07±0.01^{g}	0.11±0.00^{kj}	67.29±2.19^{n}	19.64±0.42^{d}
		54	0.07±0.01^{g}	0.06±0.01^{lk}	57.14±9.48^{p}	22.06±0.24^{a}

Values are mean ± SD of three replications. Different letters within a column represent significant differences at $p < 0.05$

Table 5.5. Cheese rheological parameters at critical strain and a frequency of 50 rad/s.

Aging time	Temperature (°C)	Cheese	Critical strain (%)	Critical stress (kPa)	G* (kPa)	Phase angle
15	5	40	0.73±0.24^{a}	0.31±0.12^{a}	151.64±2.69^{a}	14.69±0.49^{i}
		50	0.56±0.00^{b}	0.23±0.03^{b}	146.08±6.71^{a}	15.29±0.34^{h}
		52	0.25±0.09^{e}	0.19±0.01^{d}	144.65±4.62^{ab}	16.28±0.21^{g}
		54	0.18±0.00^{g}	0.15±0.00^{f}	115.58±7.41^{d}	17.15±0.17^{e}
	15	40	0.32±0.00^{c}	0.19±0.01^{d}	99.70±3.19^{f}	15.66±0.39^{h}
		50	0.32±0.00^{c}	0.17±0.01^{e}	92.65±4.55^{fg}	17.16±0.16^{e}
		52	0.10±0.00^{i}	0.11±0.01^{h}	48.59±3.07^{klm}	17.08±0.09^{e}
		54	0.14±0.04^{h}	0.07±0.01^{ij}	52.49±3.07^{k}	18.13±0.14^{c}
	25	40	0.32±0.00^{c}	0.11±0.01^{h}	55.05±1.74^{k}	16.86±0.13^{f}
		50	0.21±0.15^{f}	0.07±0.01^{ij}	51.92±2.26^{k}	17.09±0.05^{e}
		52	0.08±0.02^{ij}	0.06±0.00^{j}	50.22±0.22^{k}	16.71±0.30^{f}
		54	0.10±0.00^{i}	0.07±0.00^{i}	32.86±3.43^{n}	17.08±0.11^{e}
30	5	40	0.32±0.00^{c}	0.32±0.03^{a}	146.59±4.90^{a}	15.47±0.32^{h}
		50	0.25±0.09^{e}	0.24±0.01^{b}	124.64±6.07^{c}	16.10±0.07^{g}
		52	0.16±0.02^{h}	0.21±0.02^{c}	108.63±11.61^{e}	16.11±0.10^{g}
		54	0.10±0.00^{i}	0.13±0.01^{g}	91.94±1.83^{g}	17.31±0.31^{d}
	15	40	0.25±0.09^{e}	0.19±0.01^{d}	125.49±4.61^{c}	16.35±0.14^{g}
		50	0.14±0.05^{h}	0.14±0.01^{f}	111.52±2.14^{de}	17.71±0.22^{d}
		52	0.08±0.02^{ij}	0.10± 0.01^{h}	114.91±2.92^{de}	17.72±0.37^{d}
		54	0.08±0.02^{ij}	0.11±0.00^{h}	88.94±4.98^{h}	18.50±0.37^{c}
	25	40	0.25±0.09^{e}	0.11±0.01^{h}	69.79±3.33^{j}	17.07±0.07^{ef}
		50	0.10±0.00^{i}	0.07±0.00^{i}	77.49±5.17^{i}	18.14±0.12^{c}
		52	0.06±0.00^{k}	0.05±0.00^{k}	67.79±4.19^{j}	18.33±0.29^{c}
		54	0.06±0.00^{k}	0.05±0.00^{k}	43.31±4.29^{m}	19.15±0.15^{b}
45	5	40	0.28±0.04^{d}	0.16±0.00^{e}	92.43±2.55^{g}	15.46±0.24^{h}
		50	0.18±0.00^{g}	0.18±0.01^{d}	95.58±3.73^{fg}	16.30±0.25^{f}
		52	0.08±0.02^{ij}	0.16±0.00^{e}	88.52±5.37^{h}	17.45±0.27^{d}
		54	0.12±0.02^{i}	0.11±0.00^{h}	67.14±5.92^{j}	19.18±0.28^{b}
	15	40	0.18±0.00^{g}	0.11±0.00^{h}	83.72±2.54^{ih}	18.17±0.23^{c}
		50	0.14±0.05^{gh}	0.13±0.00^{g}	81.98±3.32^{i}	18.00±0.07^{c}
		52	0.08±0.02^{ij}	0.11±0.00^{h}	59.69±3.89^{j}	17.09±0.07^{e}
		54	0.08±0.02^{ij}	0.05±0.02^{ijk}	27.79±4.18^{n}	19.27±0.28^{b}
	25	40	0.25±0.09^{e}	0.05±0.01^{jk}	56.02±1.71^{jk}	18.59±0.35^{c}
		50	0.10±0.00^{i}	0.06±0.00^{j}	28.96±3.43^{n}	18.10±0.04^{c}
		52	0.06±0.00^{k}	0.05±0.00^{k}	29.59±4.01^{n}	19.70±0.19^{b}
		54	0.06±0.00^{k}	0.05±0.00^{k}	35.63±6.80^{n}	20.41±0.24^{b}
60	5	40	0.32±0.00^{c}	0.08±0.01^{i}	78.17±4.03^{i}	18.00±0.08^{c}
		50	0.25±0.09^{e}	0.11±0.05^{gh}	62.16±2.53^{j}	17.28±0.34^{e}
		52	0.14±0.05^{gh}	0.05±0.01^{jk}	32.01±1.78^{n}	18.06±0.01^{c}
		54	0.08±0.02	0.06±0.01^{j}	38.55±3.85^{n}	19.14±0.09^{b}
	15	40	0.32±0.00^{c}	0.05±0.00^{k}	72.39±2.30^{j}	17.15±0.14^{e}
		50	0.14±0.05^{gh}	0.06±0.00^{j}	32.99±1.78^{n}	19.15±0.15^{b}
		52	0.09±0.01^{i}	0.03±0.00^{l}	22.44±2.27^{o}	18.04±0.01^{c}
		54	0.08±0.02^{ij}	0.06±0.00^{j}	29.39±2.19^{n}	20.36±0.18^{ab}
	25	40	0.26±0.07^{e}	0.23±0.02^{b}	51.57±1.77^{k}	19.95±0.15^{b}
		50	0.10±0.00^{i}	0.05±0.00^{k}	43.34±3.24^{lm}	19.09±0.10^{b}
		52	0.08±0.02^{ij}	0.06±0.00^{j}	56.90±2.14^{k}	18.12±0.02^{c}
		54	0.06±0.00^{k}	0.06±0.00^{j}	52.68±3.24^{k}	21.43±0.58^{a}

Values are mean ± SD of three replications. Different letters within a column represent significant differences at $p < 0.05$

LAOS Results

The nonlinear viscoelastic behavior of the four cheeses was further examined through the local viscoelastic material properties quantified within an oscillatory cycle. Elastic nonlinear behavior is quantified by the strain-stiffening ratio (S). When $S > 0$, the sample shows strain-stiffening behavior; strain-softening is shown when $S < 0$. Viscous nonlinear behavior is quantified using the shear-thickening ratio (T); the behavior is shear-thickening when $T > 0$ and is shear-thinning when $T < 0$.

Overall, all cheeses at different testing temperatures had S values close to zero at strains <1%, indicating a linear elastic response. For all cheeses at all testing temperatures, S values increased as strain increased (Figure 5.1), showing strain-stiffening behavior at high strains ($S > 0$). S values showed less strain-hardening at higher strain with increased cheese fat content, which could indicate a more easily deformable structure in full-fat cheeses. Lower S values were found at higher temperatures, indicating less stiffening. This was attributed to the melting of the fat globules and an increase in casein hydration that weakened the internal structure.

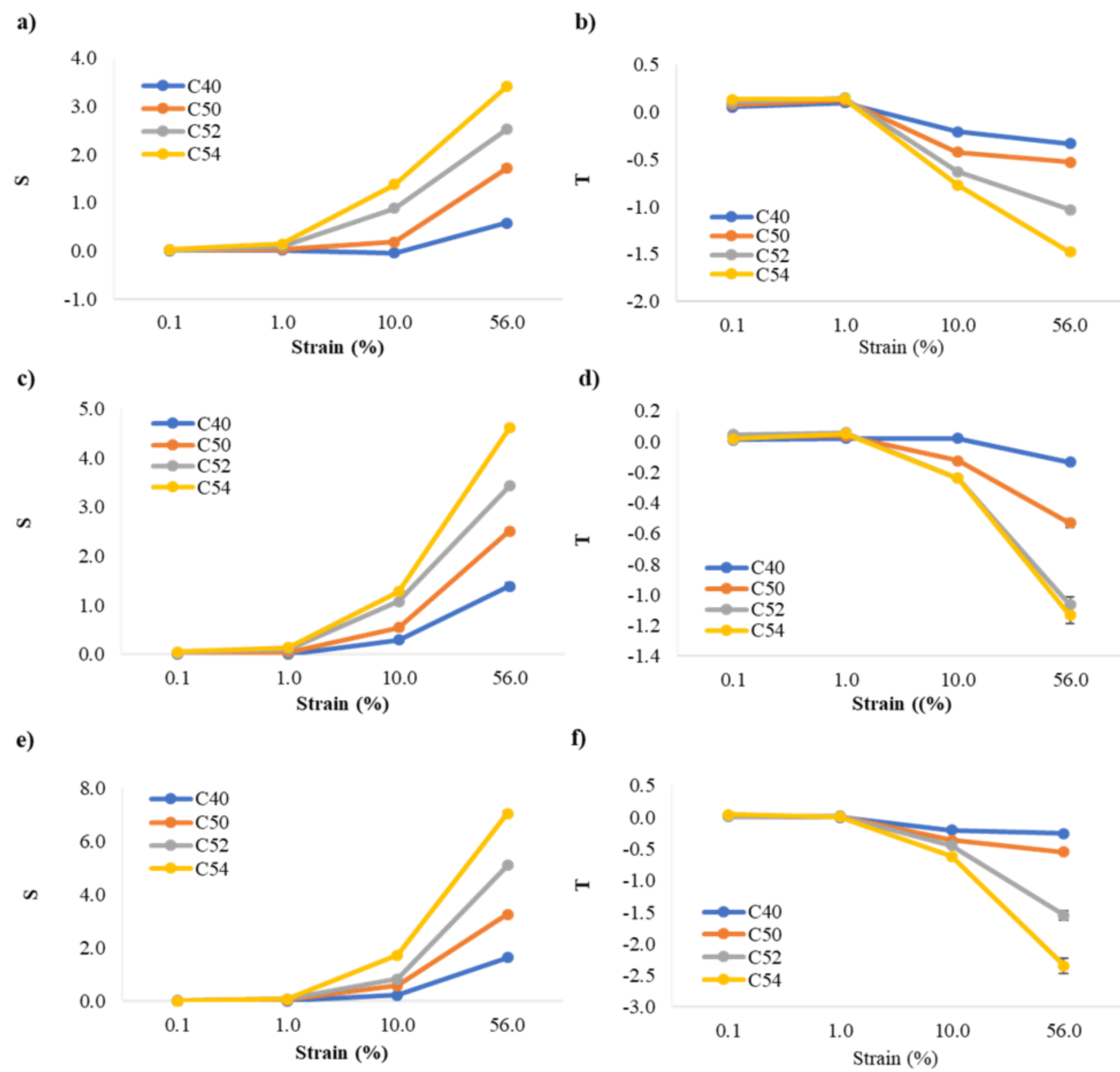

Figure 5.1.Strain stiffening ratio (S) and shear thickening ratio (T) in cheeses aged 15 d tested at 5°C (a and b), 15°C (c and d), and 25°C (e and f) and a frequency of 0.5 rad/s. S values are shown in parts a, c, and e; T values are shown in parts b, d, and f.

The ratio of the large-strain dynamic modulus to the minimum strain dynamic modulus (G'_L/G'_M) was also examined, as the misinterpretation of S values can happen because of its theoretical definition. S values indicate strain-stiffening behavior when the large strain modulus (G'_L) stiffens more quickly than the minimum strain modulus (G'_M). However,

G'_L/G'_M values also indicated strain-stiffening behavior: they increased with increasing strain (Table A4).

For all cheeses, T values decreased as strain increased (Figure 5.1b, 5.1d, and 5.1f) regardless of temperature. At low strains (<1%), T values were approximately zero, indicating linear viscous behavior for all cheeses at all temperature points. T values became negative as strain increased, indicating shear-thickening behavior. All cheeses exhibited shear-thickening behavior at strains outside of the LVR, which indicated permanent deformation and structural damage.

Similar trends for S and T values were observed at higher frequency (Figure 5.2) and longer aging time (Figure 5.3). All cheeses showed strain-stiffening behavior and shear-thinning behavior with increased strain at all testing temperatures. The greater extent of nonlinear behavior at greater aging times may be associated to the lower rigidity of the cheeses caused by microbial proteolysis during aging. In addition, changes in nonlinear behaviors at higher frequency may have been due to higher strain rate and less time for recovery in the samples.

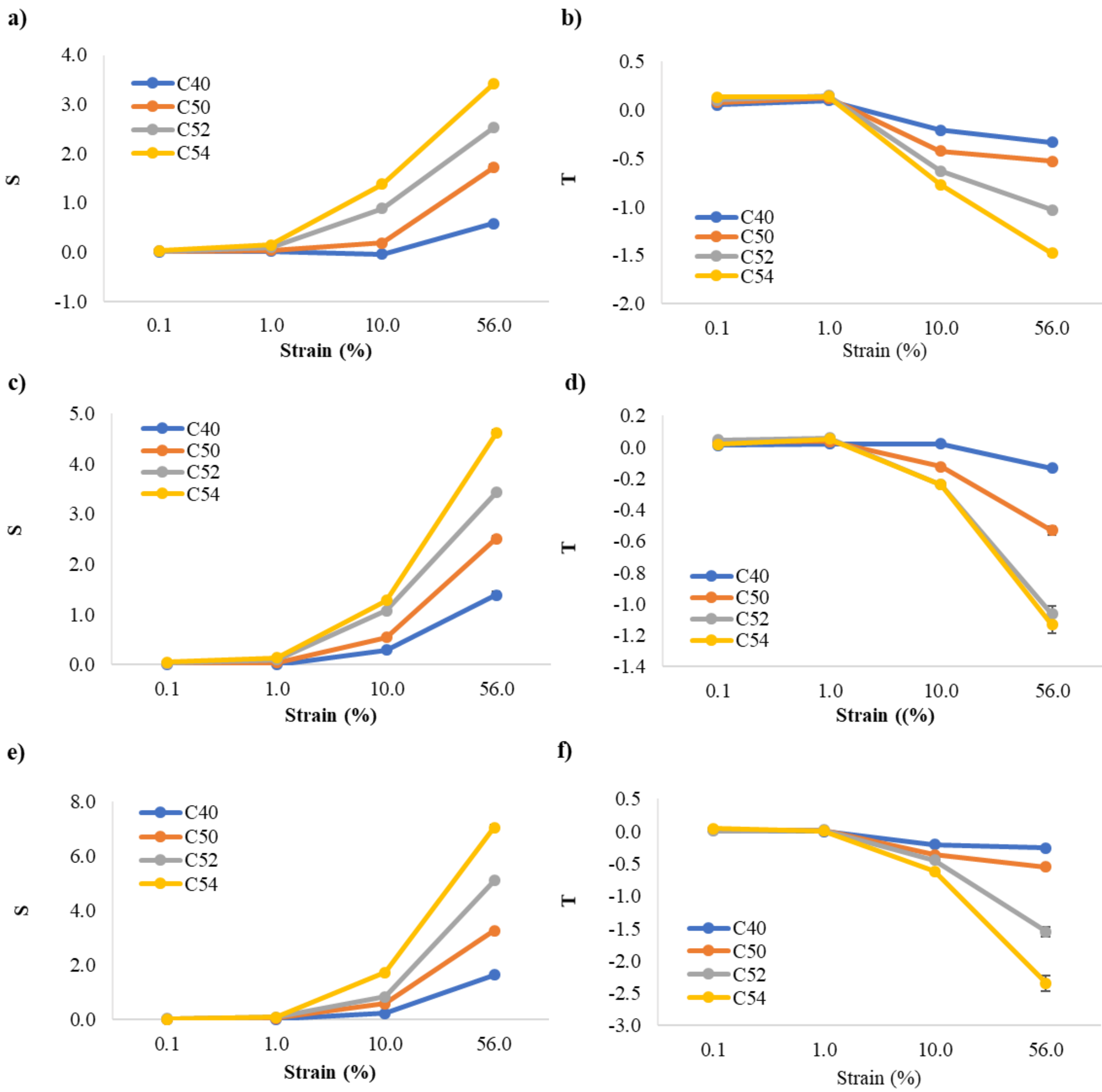

Figure 5.2.Strain stiffening ratio (S) and shear thickening ratio (T) in cheeses aged 30 d tested at 5°C (a and b), 15°C (c and d), and 25°C (e and f) and a frequency of 0.5 rad/s. S values are shown in parts a, c, and e; T values are shown in parts b, d, and f.

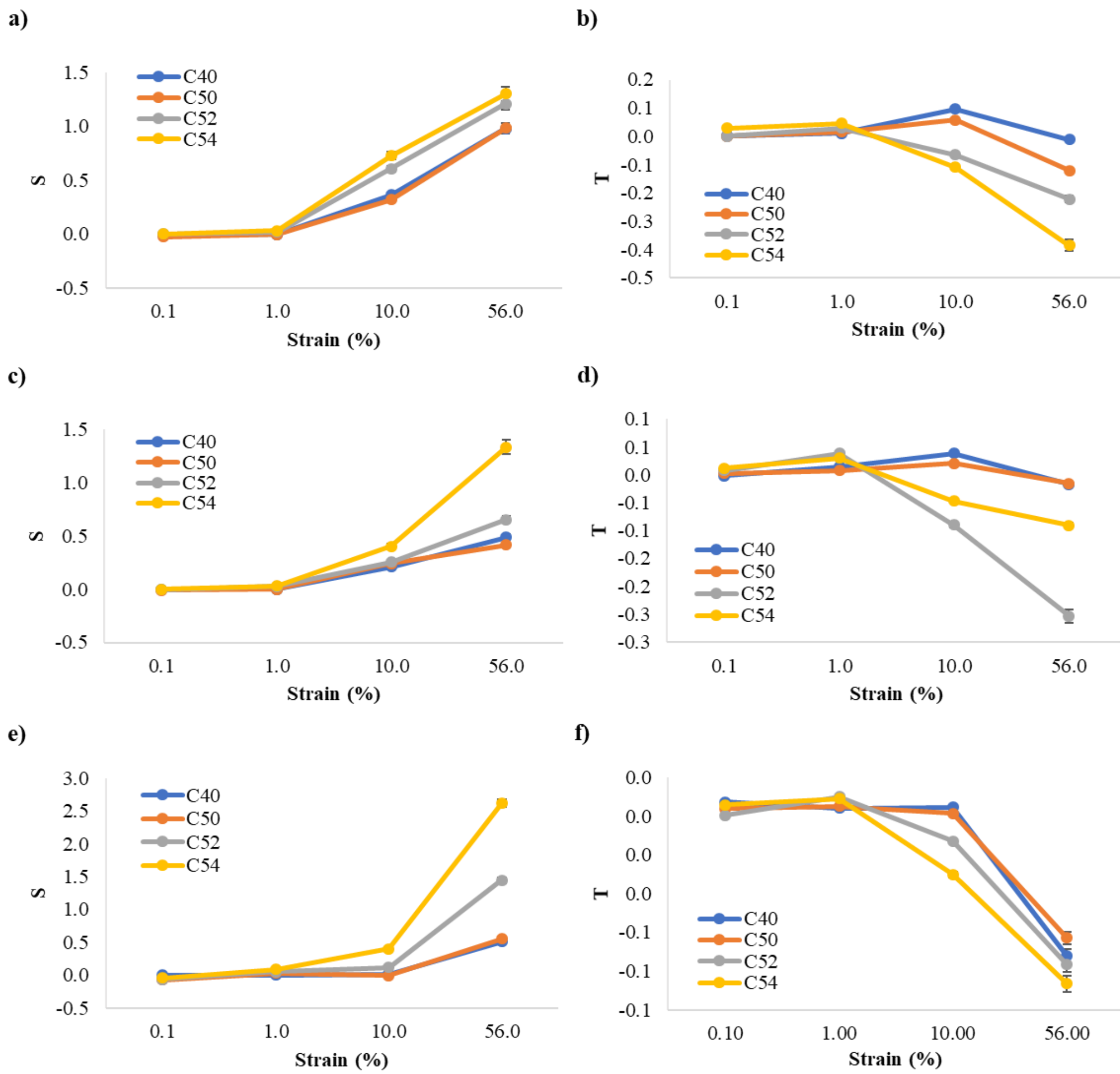

Figure 5.3.Strain stiffening ratio (S) and shear thickening ratio (T) in cheeses aged 15 d tested at 5°C (a and b), 15°C (c and d), and 25°C (e and f) and a frequency of 5 rad/s. S values are shown in parts a, c, and e; T values are shown in parts b, d, and f.

The ratio of G'_3/G'_1 indicates the extent of nonlinear for elastic-dominant samples. G'_3/G'_1 < 0.01 indicates linear viscoelastic behaviors and when the values are >0.01 indicates nonlinear viscoelastic behavior. G'_3/G'_1 values generally increased with increased strain for all cheeses at all testing conditions (Figure 5.4, 5.5, and 5.6), which was expected as the protein network of cheese is disrupted at high strains, resulting permanent deformation. Also, all cheeses at

0.1% strain generally showed linear viscoelastic behavior ($G'_3/G'_1 < 0.01$) regardless of testing conditions, which was expected. Cheeses with higher fat content showed higher G'_3/G'_1 values compared to cheese with lower fat content at all strains. This result indicated a greater extent of nonlinear viscoelastic behavior as fat content increased, likely due to the greater number of fat globules in casein network which would weaken the cheese structure. This result agreed with the findings of Anvari & Joyner (Melito) who found higher G'_3/G'_1 values for full-fat Cheddar cheese compared to those of low-fat, emulsion-containing Cheddar cheese (Anvari & Joyner (Melito), 2019).

Further examination of the data revealed that G'_3/G'_1 values for cheeses aged 15, 30, and 45 d showed nonlinear viscoelastic behavior at 10% and 56% at all temperatures; however C52 and C54 showed onset of nonlinear viscoelastic behavior at a lower strain (1%), indicating less resistant to strain and a more deformable structure when subjected to force. These data were in agreement with the critical strain data (Table 5.3). For the cheeses stored for 60 d, G'_3/G'_1 values showed nonlinear behavior at 1% strain even for C50 at all temperatures, which was expected because of protein breakdown and weaker structure as cheese ages. The increase in nonlinear behavior indicates a decrease in resistance to permanent deformation as cheese aged.

In all cheeses, the values of G'_3/G'_1 were significantly greater at 25ºC compared to the other testing temperatures (Figure 5.6), indicating that cheeses underwent permanent deformation more easily because of a less rigid structure caused by melting of some of the fat globules at 25ºC. Similar trends for G'_3/G'_1 values were observed for different fat contents, temperatures, and aging times (Tables A6 and A7). G'_3/G'_1 values increased at higher frequencies (5 and 50 rad/s) (Table 5.8 and 5.9). Higher values of G'_3/G'_1 at higher frequencies could have been due to higher structural damages or permanent deformation.

a)
b)
c)

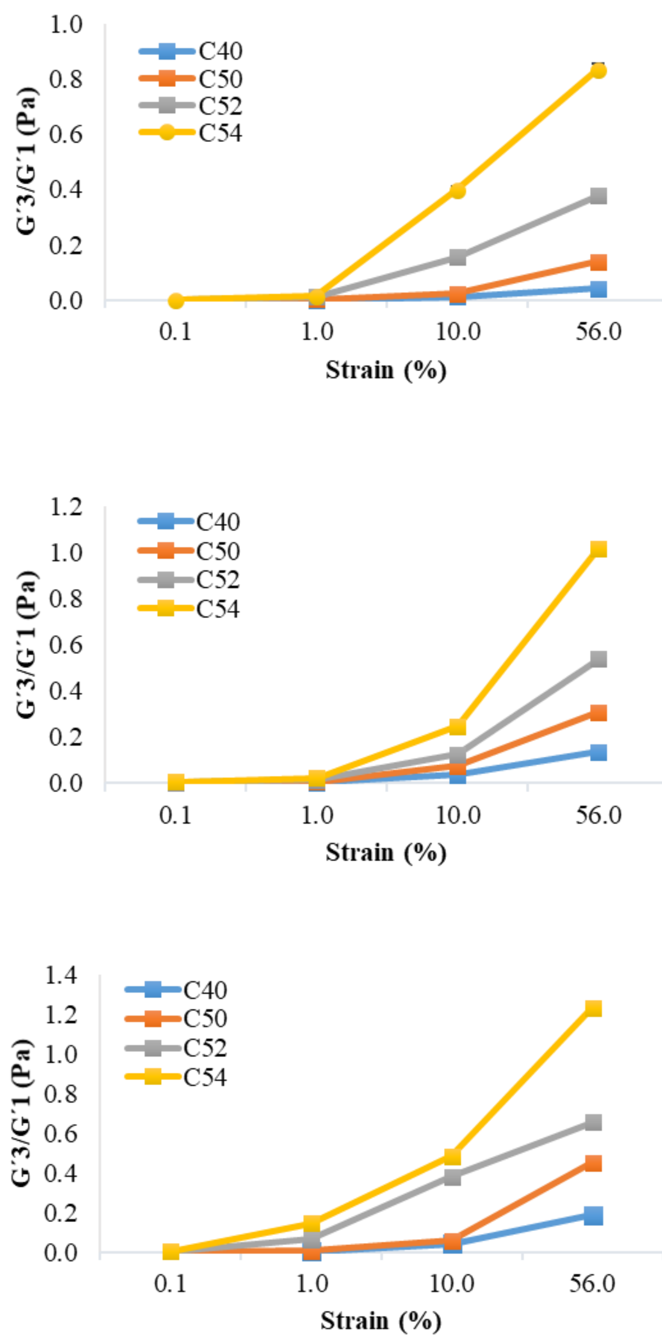

Figure 5.4. G'_3/G'_1 data for different cheeses at a) 5ºC, b) 15ºC, and c) 25ºC at 15d aging time.

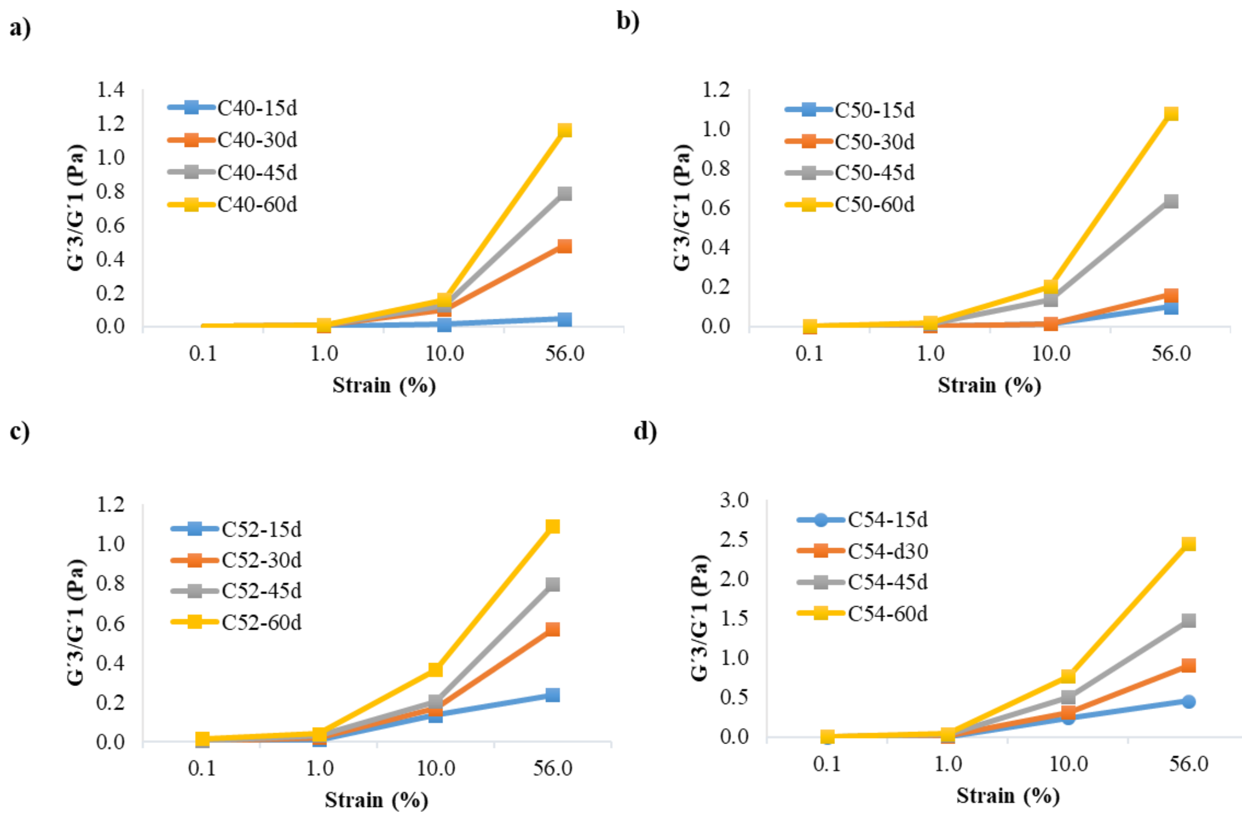

Figure 5.5. G'_3/G'_1 data for a) C40, b) C50, c) C52, and d) C54 at different aging times and a frequency of 0.5 rad/s.

The nonlinear response of the samples was also visualized graphically from the Lissajous-Bowditch plots. These plots, which are stress versus strain plots, are presented in Appendix (Figure A1, Figure A2, and Figure A3). As expected, plots had an elliptical shape in the linear viscoelastic region, which agrees with G'_3/G'_1 (<0.01). They were distorted from their elliptical shape in nonlinear viscoelastic limit where G'_3/G'_1 was >0.01. The distortion from elliptical shape could have been due to the influence of higher order harmonics at higher strain. Temperature, fat content, and aging time impacted on the shapes of Lissajous Bowditch plots for all cheeses and the shapes distorted from their elliptical shapes as temperature, fat content, and aging time increased, indicating increased nonlinear deformation of the cheeses under these conditions.

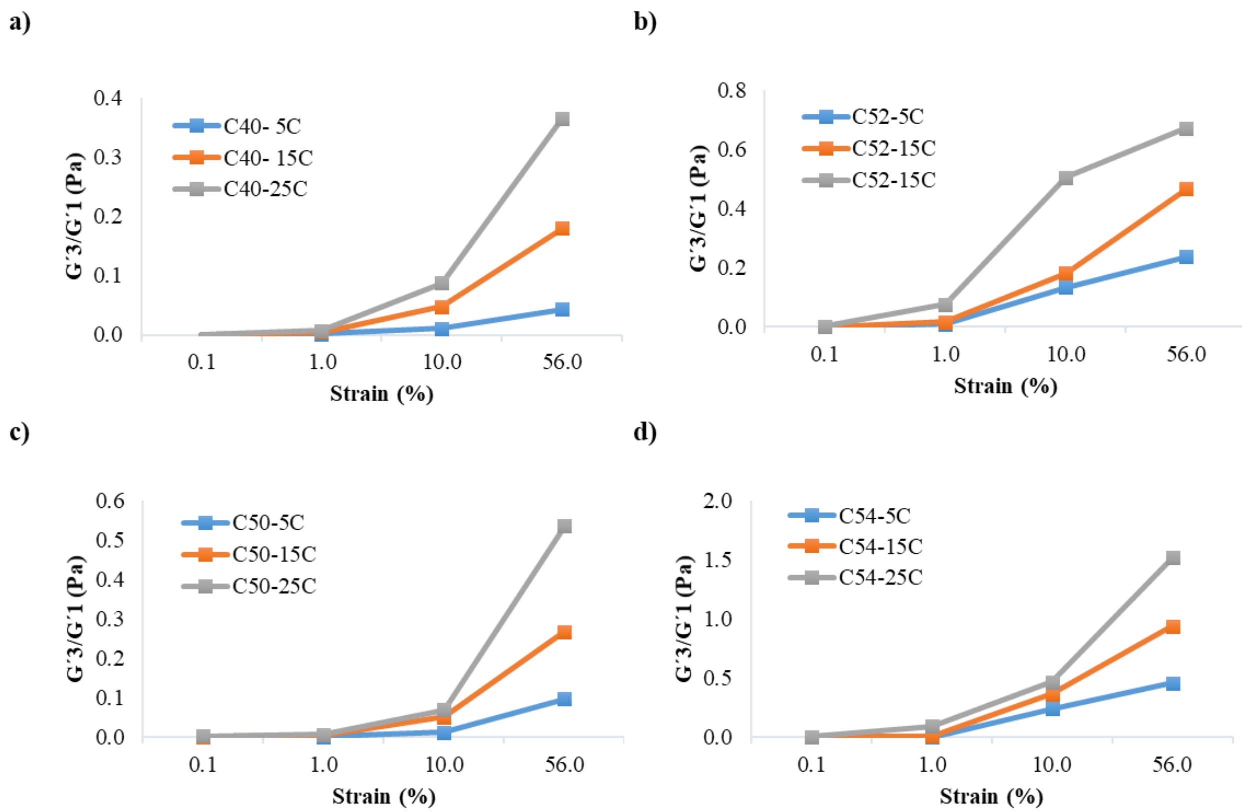

Figure 5.6. G'_3/G'_1 data for a) C40, b) C50, c) C52, and d) C54 at different test temperatures and a frequency of 0.5 rad/s.

Correlation between viscoelastic parameters and mass loss

Table 5.6 shows the result of the correlation analysis conducted between the cheese viscoelastic parameters and mass loss at different temperatures. It should be noted that all correlation coefficient values between 0.5-0.7 indicate moderate correlation between two parameters; correlations >0.7 were considered to be strong correlations. Critical strain, critical stress, and G^* were negatively correlated with mass loss at all testing conditions. This finding showed that lower mass loss will occur with a firmer structure. Phase angle showed a significant positive correlation with mass loss at the mentioned testing conditions, which indicated greater resistance to wear in cheeses with more elastic-dominant behavior (lower phase angle).

Table 5.6. Correlations among viscoelastic parameters and mass loss at different temperatures.

Viscoelastic parameters	M[1] at 30mm/s and 0.5N	M at 30mm/s and 0.7N	M at 50mm/s and 0.5N	M at 50mm/s and 0.7N
		5°C		
γ_c 0.5rad/s	-0.75*	-0.72*	-0.70*	-0.80*
σ_c 0.5 rad/s	-0.77*	-0.68*	-0.72*	-0.84*
G* 0.5 rad/s	-0.68	-0.69*	-0.90**	-0.74*
δ at 0.5 rad/s	0.69*	0.75*	0.64*	0.77*
		15°C		
γ_c 0.5rad/s	-0.59*	-0.66*	-0.52	-0.77*
σ_c 0.5 rad/s	-0.54	-0.60	-0.56	-0.75*
G* 0.5 rad/s	-0.82*	-0.85**	-0.81*	-0.46
δ at 0.5 rad/s	0.90**	0.94**	0.92**	0.66
		25°C		
γ_c 0.5rad/s	-0.77*	-0.36	-0.75*	-0.83*
σ_c 0.5 rad/s	-0.147	-0.80*	-0.77*	-0.76*
G* 0.5 rad/s	-0.15	-0.73*	-0.67	-0.70*
δ at 0.5 rad/s	0.36	0.52	0.49	0.62*

[1] M indicates mass loss

**Correlation is significant at α=0.01 (2-tailed).
*Correlation is significant at α=0.05 (2-tailed).

Large strain compression test

In general, fracture stress decreased, and fracture strain increased as fat content and storage time increased (Figure 5.7a and b). The significant decrease ($p < 0.05$) in fracture stress with increased fat content and aging time implied that the rigidity of the cheese structure decreased with increased cheese fat content and aging. This finding agreed with the strain sweep results. The impact from aging was expected as cheeses undergo structural changes such as protein breakdown caused by microbial proteases during aging which decreases cheese rigidity (Joyner (Melito) et al., 2017; Rogers et al., 2009, 2010). A similar trend was shown for blue cheeses stored up to 77 d (Joyner (Melito) et al., 2017) and goat milk cheese stored up to 30 wk (Attaie, 2005). The greater changes in fracture stress in C40 cheese compared to other cheeses could have been due to the higher protein to fat ratio that resulted in more proteolysis effect during aging. Lower fat content and thus higher development of the casein network in C40 resulted in a more rigid structure and more resistance to deformation under a normal load. Fat globules as soft fillers makes the structure of cheese weaker and less resistance to force (Bryant, Ustunol, & Steffe, 1995; Rogers et al., 2009). The significant decrease of fracture stress with increased fat content was in accordance with findings reported by Sahan et al., who observed higher hardness values during ripening in low-fat Kashar cheese compared to those for high-fat cheeses (Sahan, Yasar, Hayaloglu, Karaca, & Kaya, 2008).

Fracture strain was significantly different ($p < 0.05$) among the different cheeses at 15 d storage (Figure 5.7). Only C40 showed significant difference in fracture strain as aging time increased, which could have been due to its higher protein to fat ratio and thus a higher degree of proteolysis during aging, making the cheese more brittle and easier to deform under compression. After 15 d there was no significant differences between the fracture strains for full-fat cheeses (C50, C52, and C54), although they showed significant higher fracture strain compared to C40 at all time points. This difference in fracture strain was an indication of differences in network properties: the lower fracture strain in C40 indicated a firmer structure (Bowland & Foegeding, 1999).

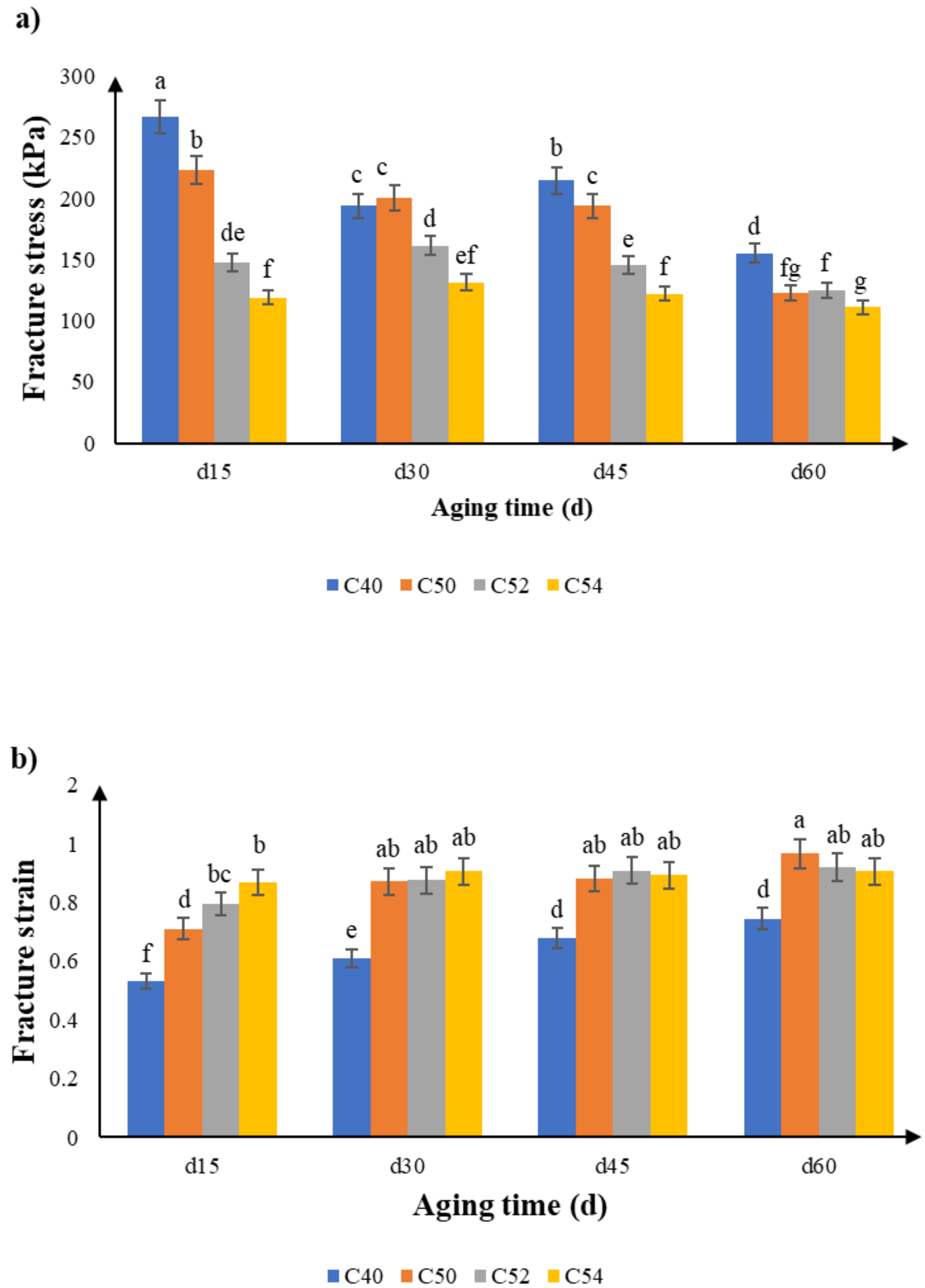

Figure 5.7. Fracture stress (a) and fracture strain (b) for all cheese samples at different aging times. Samples were compressed to 50% of their original height during testing.

Correlation between fracture properties and mass loss

Significant ($p < 0.05$ or $p < 0.01$) correlations indicated relationships between wear and fracture properties of cheese. Fracture stress showed negative correlations with mass loss, and fracture stress were significantly ($p < 0.01$) correlated with mass loss at 50 mm/s sliding speed at both normal forces (Table 5.7). Fracture strain and mass loss were positively correlated, and the correlation coefficients showed strong correlation strength at 0.7 normal force and 50 mm/s sliding speed. Thus, cheeses with higher fracture strain and lower fracture stress, or cheeses with a more deformable structure, generally showed more mass loss.

Table 5.7. Correlation between viscoelastic parameters and mass loss.

Viscoelastic parameters	**M1 at 30mm/s and 0.5N**	**M at 30mm/s and 0.7N**	**M at 50mm/s and 0.5N**	**M at 50mm/s and 0.7N**
Fracture stress	-0.430	-0.700	-0.847**	-0.883**
Fracture strain	0.452	0.836**	0.724*	0.767*

[1] M indicates mass loss

**Correlation is significant at α=0.01 (2-tailed).
*Correlation is significant at α=0.05 (2-tailed).

Descriptive Sensory Analyses

ANOVA results indicated that both fat content and aging time had significant ($p < 0.05$) effect on all texture attributes (Table 5.8). Values for hand firmness, springiness, rate of recovery, first-bite firmness, fracturability, and particles decreased as fat content and aging time increased (Table 5.9). Chewdown terms, including degree of breakdown, cohesiveness, smoothness of mass, mouthcoating, adhesiveness, moistness, and residual mouthcoating, increased with increased fat content and aging time in all cheeses (Table 5.9). Lower intensities in all hand and first-bite terms, particles, and higher chewdown mouthcoating and residual mouthcoating in C40 may have been due to a less interrupted protein matrix as a result of fat reduction. This result was in agreement with texture attributes observed for Gouda cheese with varying fat contents: lower-fat Goudas showed lower adhesiveness, cohesiveness, and degree of breakdown (Yates & Drake, 2007). Similarly, Cheddar cheeses have previously showed an increase in springiness and firmness, and decrease in smoothness of mass, adhesiveness, and cohesiveness (Drake & Swanson, 1996; Rogers et al., 2009).

The impact of aging time on the attributes was a result of repining process, which leads to breakdown of protein caused by microbial protease activity (Brown et al., 2003; Caspia, Coggins, Schilling, Yoon, & White, 2006; Roberts & Vickers, 1994; Rogers et al., 2010). A study similarly showed that the perception of firmness decreased as Monterey Jack and Mozzarella cheeses aged up to 38 d (Brown et al., 2003). It has also been documented that fat reduction resulted in a more connected microstructure in lower-fat cheeses and an increase in springiness and rate of recovery (Brown, Foegeding, Daubert, Drake, & Gumpertz, 2003; Sánchez-Macías et al., 2012).

Table 5.8. F-ratios from ANOVA of descriptive analysis sensory texture parameters for four cheese samples as evaluated by a trained panel (n=9).

Source of variation	**Cheese**	**Aging time**	**Panelists**	**Fat content*aging time**
	4	4	9	16
Hand terms				
Firmness	74.44*	66.00*	15.45	2.07
Springiness	101.58*	61.63*	32.44*	1.58
Rate of recovery	59.51*	38.22*	45.31*	2.33
First-bite terms				
Firmness	33.18*	23.65*	18.45*	1.30
Fracturability	52.50*	21.25*	23.76*	3.81*
Chew-down terms				
Degree of breakdown	39.93*	2.74	56.76*	1.55
Cohesiveness	44.72*	13.93*	45.81*	0.35
Smoothness of mass	34.12*	16.25*	32.15*	0.12
Mouth coating	69.84*	47.95*	19.56*	1.33
Adhesiveness	61.34*	82.29*	35.99*	0.97
Moistness	20.10*	27.39*	28.45*	0.67
Residual terms				
Mouth coating	100.74*	39.03*	48.93*	2.58*
Particles	181.35*	37.90*	28.59*	4.83*

* represents a significant difference at $p < 0.05$ in each attribute (row).

Table 5.9. Texture attributes of cheese samples as evaluated by a trained descriptive analysis panel and analyzed using Tukey's HSD

Cheese	Aging Time (day)	Hand terms			First bite terms	
		Firmness	Springiness	Rate of recovery	Firmness	Fracturability
C40	15	10.11±0.014^{a}	11.20±0.28^{a}	10.20±0.28^{a}	10.61±0.70^{ab}	9.17±0.91^{a}
	30	8.93±0.65^{c}	10.20±0.47^{b}	8.93±0.84^{b}	9.55±0.08^{b}	8.24±0.04^{b}
	45	7.97±0.14^{e}	9.43±0.60^{c}	8.65±0.15^{b}	9.35±0.30^{b}	7.35±0.25^{c}
	60	7.40±1.13^{fe}	8.533±0.04^{d}	7.39±0.07^{d}	7.96±0.76^{dc}	6.42±0.52^{d}
C50	15	9.44±0.14^{b}	9.91±0.15^{c}	8.91±0.15^{b}	8.41±0.32^{c}	7.19±0.91^{cd}
	30	7.87±0.88^{e}	9.17±0.94^{cd}	8.28±0.67^{cb}	8.31±0.12^{c}	6.54±0.25^{d}
	45	5.76±0.18^{j}	8.26±0.33^{d}	7.45±0.34^{cd}	8.18±0.09^{c}	5.79±0.53^{ef}
	60	6.08±0.11^{i}	7.10±0.24^{e}	6.15±1.41	7.70±0.47^{dc}	5.61±0.54^{ef}
C52	15	8.27±0.38^{dc}	9.40±0.55^{c}	8.40±0.55^{cb}	8.66±0.22^{c}	5.93±0.70^{e}
	30	6.29±0.34^{h}	9.01±0.69^{cd}	8.06±0.70^{c}	8.03±0.12^{d}	5.20±0.18^{f}
	45	6.06±0.08^{i}	6.42±0.11^{f}	5.34±0.52^{e}	7.68±0.21^{ed}	5.25±0.35^{f}
	60	6.33±0.42^{h}	6.29±0.34^{f}	6.35±0.70	6.86±0.65^{f}	4.53±0.43^{g}
C54	15	6.86±0.51^{gf}	7.63±0.82^{e}	6.63±0.82^{c}	7.98±0.63^{dc}	5.23±0.27^{f}
	30	5.41±0.1^{kj}	7.02±0.73^{ef}	5.99±0.77^{ed}	7.74±0.12^{edc}	4.65±0.21^{g}
	45	4.75±0.36^{ml}	4.51±0.40^{g}	4.43±0.31^{f}	7.38±0.29^{ef}	4.27±0.22^{h}
	60	4.94±0.93^{lk}	4.70±0.22^{g}	4.86±0.19^{fe}	6.02±0.73^{g}	3.87±0.78^{i}

Cheese	Aging Time (day)	Chewdown terms						Residual terms	
		Degree of breakdown	Cohesiveness	Smoothness of mass	Mouthcoating	Adhesiveness	Moistness	Mouthcoating	Particles
C40	15	4.55±0.70^{g}	4.70±0.70^{f}	5.12±0.70^{ji}	3.90±0.70^{nm}	3.16±0.4^{po}	4.47±0.70^{ml}	3.80±0.35^{m}	11.79±0.13^{a}
	30	4.62±0.42^{g}	5.35±0.55^{e}	5.41±0.60^{ih}	4.43±0.75^{ml}	3.63±0.71^{o}	5.65±0.30^{kji}	3.93±0.61^{m}	10.66±0.55^{b}
	45	5.10±0.15^{fg}	5.49±0.01^{e}	6.69±0.31^{hf}	5.12±0.3^{lk}	4.42±0.10^{nm}	6.35±0.29^{gf}	5.06±0.11^{lk}	9.21±0.10^{c}
	60	5.87±0.3^{ef}	6.31±0.70^{de}	6.77±1.02^{hf}	6.68±0.26^{g}	6.19±0.21^{gfe}	6.45±0.56^{fd}	6.46±0.49^{ih}	7.77±0.32^{e}
C50	15	7.01±0.74^{cd}	5.84±0.35^{e}	6.20±0.3^{g}	5.20±0.20^{kj}	4.71±0.42^{mlj}	5.77±0.46^{jih}	5.56±0.27^{k}	8.50±0.63^{dc}
	30	5.70±0.64^{e}	6.35±0.09^{d}	6.81±0.25^{f}	5.85±0.38^{jih}	5.00±0.29^{lijh}	6.46±0.21^{f}	6.29±0.10^{jih}	7.26±0.33^{fe}
	45	6.29±0.18^{d}	7.13±0.18^{c}	7.73±0.54^{dcb}	6.40±0.21^{hg}	5.43±0.46^{ih}	6.83±0.20^{e}	7.71±0.10^{d}	6.64±0.13^{hg}
	60	6.30±0.37^{d}	7.22±0.35^{c}	7.92±0.19^{c}	6.93±0.29^{fe}	7.25±0.40^{dc}	6.88±0.21^{ed}	7.73±0.62^{d}	6.45±0.21^{ih}
C52	15	7.06±0.74^{cb}	6.61±0.70^{d}	6.67±0.70^{f}	6.24±0.70^{ihg}	4.76±0.42^{mlj}	5.61±0.56^{lkji}	6.83±1.13^{hgf}	7.02±0.32^{gf}
	30	6.44±0.44^{d}	7.44±0.60^{c}	7.18±0.41^{ed}	6.35±0.57^{hg}	5.15±0.26^{jih}	6.20±0.41 ^{hgf}	7.27±0.34^{gfed}	6.47±0.31^{ih}
	45	6.57±0.53^{d}	7.97±0.20^{bc}	8.34±0.31^{b}	7.82±0.42^{d}	6.60±0.57^{ef}	6.83±0.25^{d}	8.27±0.37^{cb}	6.41±0.12^{jih}
	60	6.97±0.18^{cd}	7.84±0.6^{b}	8.02±0.73^{cb}	8.76±0.31^{cb}	8.56±0.31^{b}	7.26±0.70^{cb}	7.71±0.43^{d}	5.83±0.74^{kji}
C54	15	8.35±0.28^{a}	7.23±0.49^{c}	7.74±0.70^{dc}	6.68±0.31^{g}	5.81±0.96^{h}	6.16±0.70^{ihgf}	7.33±0.22^{fed}	5.59±0.54^{mlk}
	30	7.34±0.27^{b}	7.94±0.08^{b}	8.61±0.89^{ba}	7.14±0.40^{ed}	6.32±0.27^{f}	7.26±0.42^{cb}	7.63±0.33^{ed}	5.61±0.57^{lk}
	45	7.58±0.49^{b}	8.84±0.23^{a}	9.66±0.29^{a}	8.89±0.18^{b}	7.77±0.38^{c}	7.45±0.27^{b}	9.77±0.25^{a}	5.25±0.34^{nmlk}
	60	7.47±0.55^{b}	8.95±1.28^{a}	9.55±0.45^{a}	9.05±0.41^{a}	9.30±0.36^{a}	8.21±0.15^{a}	8.99±0.77^{b}	4.41±0.42^{o}

Principal component analysis

Principal component analysis (PCA) can be applied to descriptive analysis sensory data using a matrix of correlation coefficients to reduce the set of attributes to a smaller set based on patterns of correlation among the original variables and reveal general trends (Ghosh & Chattopadhyay, 2012). The PCA biplot of cheese data reduces the original 13 attributes into two principal components, accounting for 94.12% of the total variance (Figure 5.8). Principal component 1 (PC1) accounted for 87.59% of the variance observed, while PC2 accounted for 6.53% of the variance, indicating that most of the variation among the samples was described by these components. The first principal component was positively described by chewdown mouthcoating, cohesiveness, smoothness of mass, adhesiveness, and moistness, and was negatively defined by fracturability and particles. PC2 was mostly described by degree of breakdown and slightly described by springiness, rate of recovery, hand and first-bite firmness.

The first cluster, which consisted of C40 at 15d, C50 at 15d, and C52 at 15d, was characterized by hand and first-bite firmness, springiness, rate of recovery, fracturability, and particles. These attributes are commonly associated with both lower fat content and low aging time (Rasmussen & Rasmussen, 2007; Rogers et al., 2009, 2010). A second cluster consisted of C54 at 45d, C52 at 60d, and C45 at 60d, and was described more by cohesiveness, adhesiveness, moistness, smoothness of mass, chewdown mouthcoating and residual mouthcoating attributes. This result was expected as these attributes are associated high fat content and aged cheese (Rogers et al., 2009), and also found to be high compared to lower fat and lower aged cheese in descriptive analysis data (Table 5.9). The third cluster comprised C50 at 60d, C50 at 45, C54 at 30d, and C52 at 45d, and was characterized by a lower intensity of cohesiveness, adhesiveness, moistness, smoothness of mass, chewdown mouthcoating and residual mouthcoating attributes compared to the second cluster. Cluster 4 comprised C54 at15d, C52 at 30d, C40 at 60d, C50 at 45d and was characterized by degree of breakdown as well all the attributes characterizing the second cluster. This also showed that when the intensity of cohesiveness, adhesiveness, moistness, smoothness of mass, chewdown mouthcoating and residual mouthcoating attributes decreased, degree of breakdown increased. The fifth cluster included C40 at 30d, C40 at 45d, C50 at 30 d and characterized by fractureability and particles. From the clusters, it can be said that both aging time and fat content influenced grouping samples based on corresponded attributes.

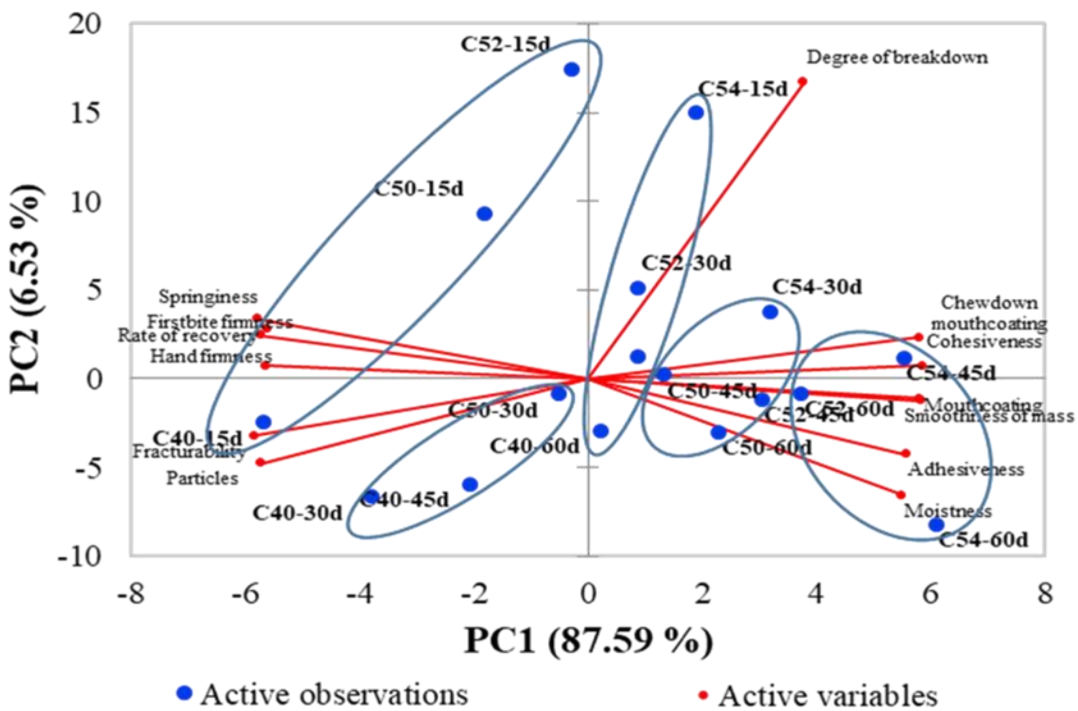

Figure 5.8. Principle Component Analysis (PCA) a) biplot and observations for cheese.

Note: Clusters are circled based on cluster analysis (Figure A4).

Overall, there were significant correlations among all attributes (Table 5.10). There were two major groups in terms of correlation. The first group, including hand firmness, springiness, rate of recovery, first-bite firmness, fracturability, and particles. This group was negatively correlated with the second group including degree of break down, cohesiveness, smoothness, chewdown mouthcoating, adhesiveness, moistness, and residual mouthcoating. The correlation between these two group emphasize that cheese textural attributes may be related to each other, likely due to structural properties that have a variety of effects on texture sensory perception. Therefore, it should be considered in the formation of new cheeses so that changing one textural attribute does not cause changes in other attribute that have correlation with it. Also, changes in the attributes could subsequently cause alternation in mechanical behavior of cheese.

Table 5.10. Correlation matrix for cheese textural attributes.

	Hand firmness	**Springiness**	**Rate of recovery**	**First-bite firmness**	**Fracturability**	**Degree of breakdown**	**Cohesiveness**	**Smoothness**	**Chewdown mouthcoating**	**Adhesiveness**	**Moistness**	**Residual mouthcoating**	**Particles**
Hand firmness	1	0.889**	0.885**	0.792**	0.870**	-0.644**	-0.878**	-0.910**	-0.881**	-0.843**	-0.873**	-0.907**	0.866**
Hand springiness		1	0.970**	0.836**	0.872**	-0.695**	-0.917**	-0.922**	-0.939**	-0.913**	-0.876**	-0.896**	0.838**
Hand rate of recovery			1	0.798**	0.841**	-0.691**	-0.904**	-0.907**	-0.928**	-0.886**	-0.864**	-0.898**	0.834**
First bite-firmness				1	0.856**	-0.690**	-0.837**	-0.761**	-0.850**	-0.885**	-0.796**	-0.817**	0.849**
Fracturability					1	-0.824**	-0.910**	-0.860**	-0.890**	-0.827**	-0.828**	-0.892**	0.943**
Degree of breakdown						1	0.749**	0.753**	0.755**	0.681**	0.622**	0.796**	-0.847**
Cohesiveness							1	0.888**	-0.911**	0.832**	0.820**	0.912**	-0.868**
Smoothness								1	0.897**	0.851**	0.871**	0.922**	-0.884**
Chewdown mouthcoating									1	0.945**	0.864**	0.923**	-0.878**
Adhesiveness										1	0.868**	0.842**	-0.811**
Moistness											1	0.787**	-0.794**
Residual mouthcoating												1	-0.927**
Particles													1

** Correlation is significant at the 0.01 level (2-tailed)

Correlations among sensory attributes and wear data

Overall, mass loss showed negative correlations with hand-firmness, springiness, rate of recovery, first bite-firmness, fracturability, and degree of breakdown. However, mass loss showed positive correlations with cohesiveness, smoothness of mass, both mouthcoating attributes, adhesiveness, moistness, and particles (Table 5.11). The relationship between increased mass loss and sensory attributes related to firmness and fracturability can be explained by considering cheese microstructure; less rigid and fracturable structures could reduce mass loss. Mass loss–sensory attribute correlations were significant at 0.7 N normal force and 50 mm/s sliding speed, indicating that these conditions may be more similar to oral processing conditions, or the force applied by palate and teeth and chewing speed or jaw movement. Also, hand firmness, springiness, and rate of recovery showed stronger correlation (≈0.9) to mass loss, while first-bite firmness and fracturablity, degree of breakdown, cohesiveness, smoothness of mass, chewdown mouthcoating, adhesiveness, moistness, residual mouthcoating, and particles showed moderate correlation (≈0.7). These results could have been due to presence of saliva for evaluating the attributes in the mouth, as well as the lubrication effect of salivary proteins, mainly proline-rich mucins, on food structure. These correlations may be improved if a lubricant similar to saliva is used during wear testing, making testing conditions more analogous to oral processing conditions. Overall, the correlations between sensory parameters and mass loss indicated a potential relationship between wear behavior and sensory texture.

Table 5.11. Correlation between sensory attributes and mass loss.

Viscoelastic parameters	M[1] at 30mm/s and 0.5N	M at 30mm/s and 0.7N	M at 50mm/s and 0.5N	M at 50mm/s and 0.7N
Hand-firmness	-0.34	-0.73*	-0.82*	-0.93**
Springiness	-0.69	-0.77*	-0.74*	-0.89**
Rate of recovery	-0.23	-0.76*	-0.76*	-0.91**
First bite-firmness	-0.22	-0.85**	-0.50	-0.71*
Fracturability	-0.16	-0.72*	-0.66	-0.72*
Degree of breakdown	-0.32	-0.70*	-0.47	-0.61*
Cohesiveness	0.10	0.56*	0.66	0.78*
Smoothness of mass	0.10	0.67*	0.68	0.82*
Chewdown mouth coating	0.10	0.65*	0.67	0.72*
Adhesiveness	0.16	0.78*	0.60	0.78*
Moistness	0.30	0.63*	0.63	0.61*
Residuals- mouthcoating	0.16	0.70*	0.69	0.70*
Particles	_0.17	0.63*	0.67*	0.73*

[1] M indicates mass loss
**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

Conclusions

Overall, cheese rheological properties were significantly influenced by fat content, aging time, and testing temperature. Cheeses with higher fat content showed significantly lower critical stress, critical strain, and G^* values, while phase angle was higher in cheeses with higher fat content and longer aging time, indicating that these cheeses were weaker and deformed under lower forces. Based on the LAOS data, the nonlinear viscoelastic behaviors of cheeses were also affected by fat content, aging time, and temperature. The extent of nonlinearity increased as strain, fat content, storage time, and temperature increased. Mass loss was positively correlated to critical stress, critical strain, andG^*, while it was negatively correlated to phase angle. Fracture results also indicated that fat content and aging time played a role in weakening cheese microstructure and increasing their tendency to breakdown. Fracture stress was negatively correlated with mass loss; fracture strain was positively correlated with mass loss. Sensory attributes significantly changed with fat content and aging time and were correlated with mass loss. These results showed that changes in wear behavior of cheese can indicate changes in cheese texture and rheological behaviors due to changes in fracturability and deformability.

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Chapter 6: Modeling of Cheese Wear Behavior

Abstract

Modeling of cheese wear is a beneficial strategy to better understand wear mechanisms and predict mass loss from a system. Accordingly, the objective of this study was to develop a mathematical model to predict cheese mass loss, which is an indicator of wear and could be a novel tool for determining processing ability. Wear tests were performed on cheeses containing different fat contents (40, 50, 52, and 54% dw) at different sliding speeds (0.03 m/s and 0.05 m/s), normal loads (0.5 and 0.7 N), temperatures (5, 15, and 25°C), and aging times (15, 30, 45, and 60 d). Mass loss and friction coefficient were recorded as the main responses. Maximum strength derived from large amplitude oscillatory shear (LAOS) data was selected as a key rheological property for the model. Friction coefficient was also considered as a separate dimensionless factor in developing model. Dimensional analysis based on the Buckingham Pi theorem was used to find the relationship between the factors influencing wear behaviors and to construct the wear prediction model. Sensitivity analysis was conducted to determine the impact of each independent variable on mass loss. The developed model showed a mean absolute error (MAE) of 0.001g, which is considered small compared to the average value of mass loss from the cheese samples (approximately 0.102 g for about 30 g sample), indicating a good fit of the model to corresponding experimental measurements. Sensitivity analysis results indicated that mass loss had the highest sensitivity to normal force, followed by sliding speed, friction coefficient, and maximum strength. The findings of this study are highly beneficial to cheese manufacturers for maximizing cheese processing ability and determining the functionality of novel cheeses and similar food products. The model and

sensitivity analysis also provide valuable fundamental information for wear behaviors of hard cheeses that may be applicable to other similar soft solid products, such as high protein bars or deli meats.

Keywords: wear model, mass loss, Buckingham Pi theorem, sensitivity analysis

Introduction

Cheeses are soft solid materials that come into contact with hard surfaces (blade) during slicing and shredding processes, and it is the primary point at which wear can occur. Soft cheese may stick to the slicer or shredder; crumbly cheese may produce significant amounts of debris. These issues need to be controlled as they could resulted in undesirable cheese slice and shred characteristics such as uneven slices and sticky shreds. Our findings in Chapter 4 and a study done by Sparkman et al. (2019) on high-protein bars showed that food mechanical and wear behaviors are related to processing ability and can be used to better understand processing behaviors of the foods. Wear testing may help to determine stickiness or unwanted removal of mass from cheese during size reduction processes, such as slicing or shredding, and thus could be a beneficial finding in determining the sliceability and shreddability of and selecting processing parameters for novel cheese products.

In the last several decades, many studies have focused on developing various forms of wear models and finding relationships of significant parameters for the wear of hard materials (DePaola & Toyofuku, 2014; Manhart, Kunzelmann, Chen, & Hickel, 2000; Saha & Mondal, 2011). Most models have expressed wear as a function of experimental variables e.g. sliding distance and pressure, key material properties e.g. roughness, hardness, shear strength, and elastic modulus, or a combination of these two groups (Meng & Ludema, 1995; Moerlooze, 2011; Pettersson, 2016; Sagbas et al., 2009; Viswanath & Bellow, 1995a). Archard's wear equation, $Q = KW/H$, is the most common wear equation (Archard, 1953), that provided a ground for developing wear models for different materials. In this equation, Q is the wear volume (m^3), W is normal load (N), H is hardness (Pa), and K is a wear constant. However, soft materials do not follow this wear model developed for hard materials because they deform considerably when force is applied; this model does not account for deformation during wear.

Buckingham Pi theorem is a dimensional analysis method that reduces the number of variables by grouping them based on fundamental dimensions. Therefore, it is a beneficial method for developing models for complex systems in which multiple variables are involved in the response. For example, Fan et al. (2009) employed the Buckingham Pi theorem to develop a model for the erosion rate in micro-abrasion of glasses based on thermo-mechanical approaches. Bobbili et al. (2015) developed a model for material removal rate by employing Buckingham Pi theorem that included process parameters of pulse-on time, input power, and flushing pressure, as well as material thermal properties. These models were efficient for predicting wear of that specific material but may face failure for other materials with significantly different properties and wear behaviors.

Following model development, sensitivity analysis can be conducted to evaluate how much each input variable is contributing to the model. The partial derivative method, which shows changes in output in respect to changes in each individual input, can be used for sensitivity analysis for a system described by a mathematical equation to compare the relative importance of the variables. Performing sensitivity analysis on the cheese wear model newly developed in this study can provide valuable information about which model parameters are most important in determining cheese wear. These parameters would also be important to consider when determining processing ability of novel cheeses or optimizing processing variables.

Existing fundamental wear models do not provide accurate predictions for soft (deformable) solids, and a fundamental wear model for these materials needs to be developed to accurately predict wear behaviors of soft solids, such as cheese. There are some wear models on soft material (Paul, Karambelkar, Rao, & Ekhe, 2015; Sagbas et al., 2009; Tan & Joyner, 2018b; Viswanath & Bellow, 1995a), but most models are empirical in nature and based on limited observations, which limits the applicability of the model to the specific sample and running conditions. Thus, this study aims to develop an accurate and reliable mathematical model by Buckingham Pi theorem to predict cheese wear as a function of operating variables and cheese properties and assess the sensitivity of the independent variables on mass loss.

Material and methods

Materials

Cheeses containing different fat contents (40, 50, 52, and 54) with 18 kg blocks of each cheese were manufactured by the Glanbia Nutritionals company (Glanbia, Twin Falls, Idaho, USA), and samples were made in duplicate. Cheese blocks were cut into 2.5 kg blocks, vacuum packed, and stored at 5°C throughout the 2 mo aging time for this study. Before testsing, the outer layer of cheese (about 3mm) was removed. The overall research design for the wear modeling is summarized in Figure 6.1.

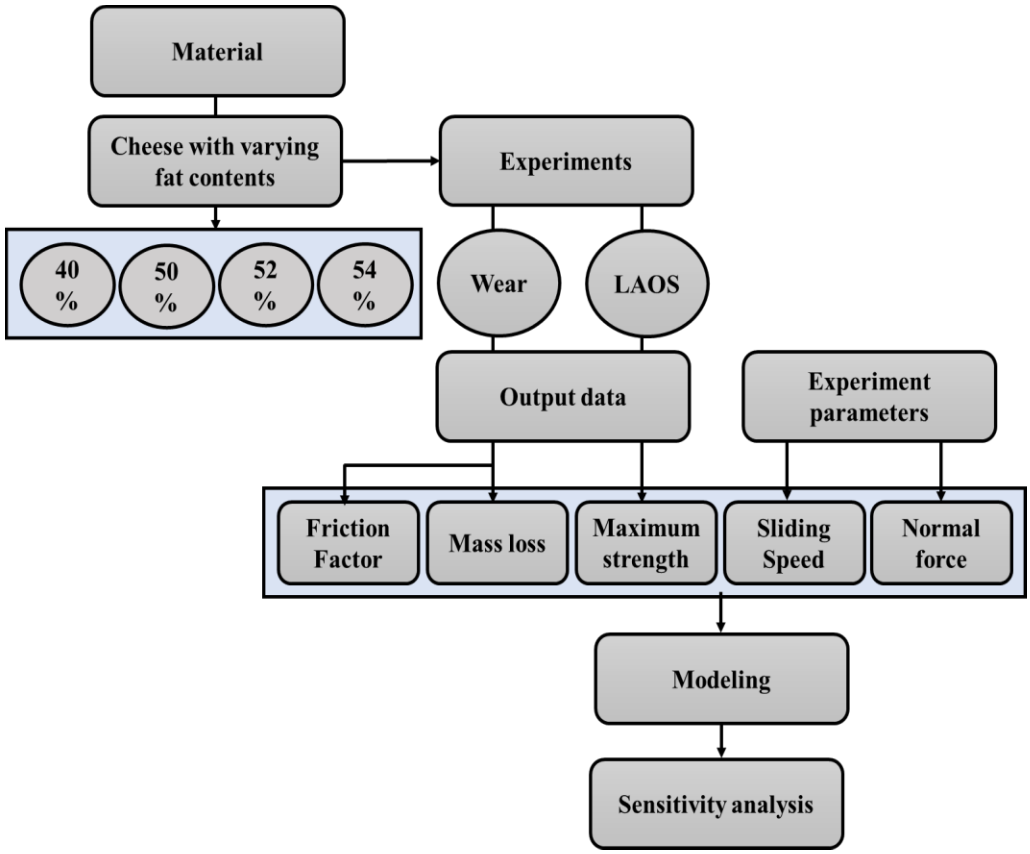

Figure 6.1. Overall view of experimental design.

(Note: fat content was based on dry weight.)

Rheological measurements

Full details of the test procedures are provided in Chapter 5. From the tests data, maximum stress in the strain-stress curve from strain sweeps was defined as maximum strength (Figure 6.2), where permanent deformation happens.

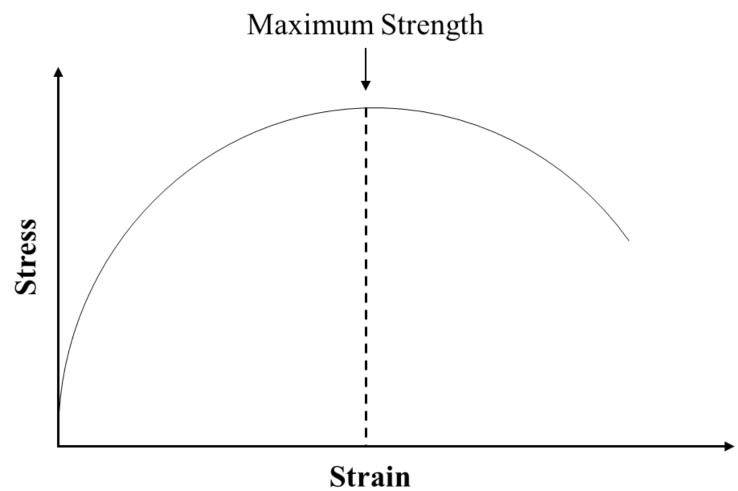

Figure 6.2. Schematic image of stress-strain plot and maximum strength

Wear measurements

Wear tests were performed using Anton Paar MCR 702 TwinDrive Rheometer (Anton Paar GmbH; Graz, Austria) equipped with a steel twin-ball on disc apparatus. Friction coefficient and mass loss were recorded and used for modeling. Full details of the wear measurement are provided in Chapter 4.

Development of wear model for cheese

Dimensional analysis, which is also called factor label method or unit analysis, was conducted via the Buckingham Pi theorem to develop an equation in which mass loss was expressed in terms of the testing variables and cheese properties (maximum strength and friction coefficient). The findings in Chapter 4 showed that operating conditions (temperature, sliding speed, and normal load), cheese fat content, and aging time played a significant role in determining cheese wear behaviors. Friction coefficient and maximum strength were selected as functions to explain material properties in our wear model. In other words, the expected mass loss at any given value of these two factors was assumed to be predicted by a mathematical equation derived from the experimental data.

Buckingham π theorem

Buckingham Pi Theorem was used to find the relationship between the parameters and construct possible dimensionless groups. Selection of variables is the first step toward developing a model using Buckingham Pi theorem. Accordingly, mass loss was used as the main dependent variable; independent variables included normal force and sliding speed (processing parameters), and maximum strength and friction coefficient (material properties). Variables, along with their dimensions and units, are summarized in Table 6.1.

Table 6.1. Physical quantities for dimensional analysis

Variables	**Symbols**	**Dependent/ Independent**	**Units**	**Dimensions**
Mass loss	W	Dependent	kg	M
Sliding velocity	V	Independent	$m.s^{-1}$	LT^{-1}
Normal force	F	Independent	$kg.m.s^{-2}$	MLT^{-2}
Maximum strength	S	Independent	$kg.m^{-1}.s^{-2}$	$ML^{-1}T^{-2}$
Friction coefficient	μ	Independent	-	$M^0L^0T^0$

M, L, and T are the dimensions of mass, length, and time, respectively

Pi group formation

Once the relevant variables were selected, Buckingham Pi theorem was used on the dimensions of the relevant variables and the primary dimensions. The number of dimensional variables (n) was 4, and primary dimensions are length (L), time (T), mass (M). Friction coefficient was a dimensionless parameter. Thus, there were two dimensionless parameters, called Pi (π) groups.

Fundamental quantities for π_1 were calculated as:

$$\pi_1 = WV^aS^bF^c \tag{6.1}$$

Each variable was expressed in the terms of M, L, and T. Substituting these dimensions into Equation 6.1 resulted in the following expression:

$$\pi_1 = (M)(LT^{-1})^a(ML^{-1}T^{-2})^b(MLT^{-2})^c \tag{6.2}$$

Exponents a, b, and c were calculated with the goal of generating a dimensionless π_1,

$T^0 = T^{-a-2b-2c}$

$L^0 = L^{a-b+c}$

$M^0 = M^{1+b+c}$

$a = 2$, $b = 1/2$, and $c = 3/2$

Based on these calculations, the equation for π_1 was written as:

$$\pi_1 = \left(\frac{WV^2S^{1/2}}{F^{3/2}}\right) \tag{6.3}$$

According to the Buckingham Pi theorem, if a quantity is already dimensionless, it is considered as a separate π term. Thus, friction coefficient (μ) was considered as a second π factor.

$$\pi_2 = \mu \tag{6.4}$$

In summary, the dimensional analysis reduced the number of variables from five (mass loss, normal force, friction coefficient, maximum strength, and sliding speed) to two dimensionless parameters. The first Pi group, $\left(\frac{WV^2S^{1/2}}{F^{3/2}}\right)$, includes the mass loss (W); the second Pi group was μ.

We can write π_1 as a function of π_2:

$$\pi_1 = f(\pi_2) \tag{6.5}$$

Therefore, the functional relationship between the two Pi groups can be expressed as:

$$\left(\frac{WV^2S^{1/2}}{F^{3/2}}\right) = Pf(\mu) \tag{6.6}$$

Differential Sensitivity Analysis

Sensitivity indices of mass loss to the individual parameters was calculated using the partial derivatives of mass loss (W) with respect to F, S, V, and μ. Sensitivity indices (Si) derived from the partial derivatives were developed for comparing the sensitivity of mass loss to each parameter. The final equation for calculating the total change of mass loss with respect to all parameters was determined to be:

$$dW = \frac{\partial W}{\partial F}\,dF + \frac{\partial W}{\partial V}\,dV + \frac{\partial W}{\partial S}\,dS + \frac{\partial W}{\partial \mu}\,d\mu \tag{6.7}$$

Model validation

Mass loss, maximum strength, and friction coefficient data from all replicates were averaged and used to fit the models. For model validation, experimental data were compared with predicted results obtained from the model by calculating Mean Absolute Error (MAE) (Equation 6.8) and predicted mass loss plotted against experimental data were used to check goodness of fit.

$$MAE = \sum \frac{W_o - W_p}{n} \tag{6.8}$$

where, n, W_o, and W_p are number of observations, experimental mass loss (g), and predicted mass loss (g), respectively. Plots corresponding to changes in mass loss with respect to each variable were created using Mathematica software (Wolfram Mathematica 12.0, Champaign, Illinois, USA).

Results and discussions

Model

The mass loss phenomenon was described by two Pi groups, and the relationship between them was written as $\pi_1 = f(\pi_2)$, where π_1 is $\left(\frac{WV^2S^{1/2}}{F^{3/2}}\right)$ and π_2 is friction coefficient. The relationship between two Pi groups was obtained by plotting π_1 versus π_2 (Equation 6.9, Figure 6.3). The linear regression analysis gave an R^2 value of 0.78, which confirmed that the two Pi groups were significantly related to each other.

$$\pi_1 = 0.0001\pi_2 - 0.00006 \tag{6.9}$$

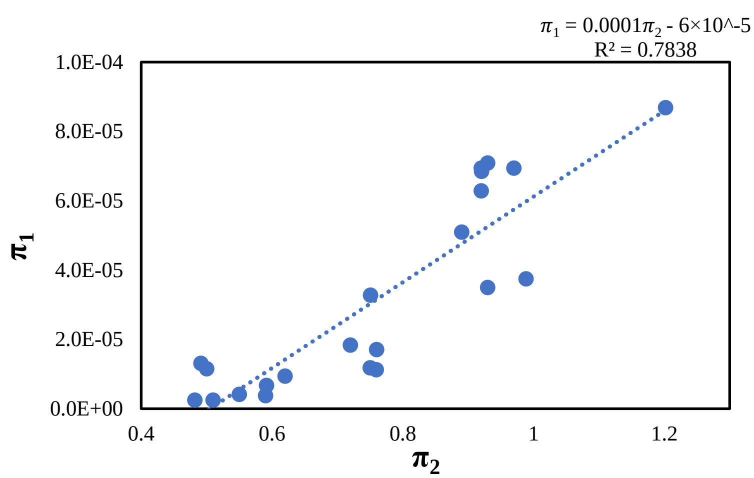

Figure 6.3. Linear regression for π_1 and π_2

π_1 and π_2 expressions were then substituted in the Equation 6.9:

$$\left(\frac{WV^2S^{1/2}}{F^{3/2}}\right) = (10^{-4}\mu - 6 \times 10^{-5}) \tag{6.10}$$

The final wear model (Equation 6.11) is:

$$W = (F^{\left(\frac{3}{2}\right)} \times \frac{10^{-4}\mu - 6\times10^{-5}}{V^2S^{\frac{1}{2}}}) \tag{6.11}$$

This final model can be used to predict the amount of mass loss created during wear testing of cheese under various conditions. Since mass loss may be an indicator of the amount of debris generated during processing, this model may be used to predict processing abilities of cheese and other soft solid foods.

Model fitting

Generally, the model showed moderate fit to the corresponding experimental measurements based on the plot of experimental versus predicted mass loss (Figure 6.4, R^2=0.58). The MAE value of 0.001g, which are considered small since the mass loss was approximately 0.102 g for about 30 g sample.

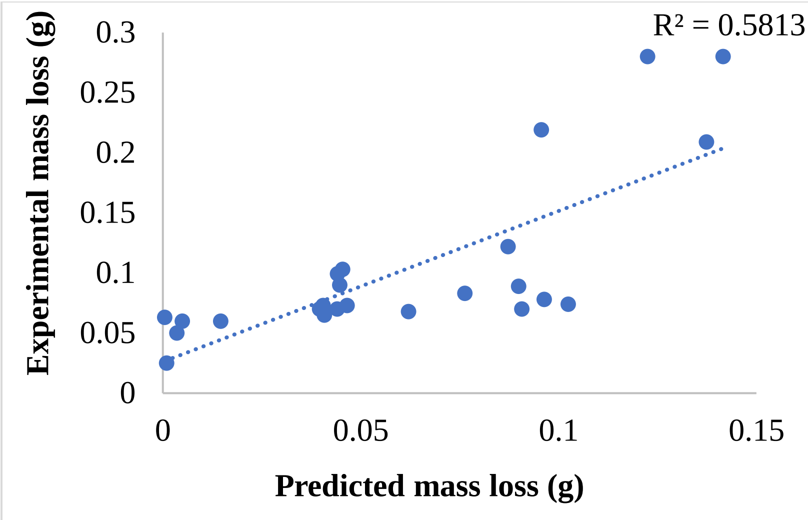

Figure 6.4. Plot of experimental mass loss data versus predicted mass loss

The model fit was affected by several data points that corresponded to excessive mass loss. It is assumed that there should be limits for each parameter under which this model works with high accuracy. The sensitivity analysis conducted in this study provides grounds for future work to test different ranges of values for each parameter to define the cutoffs of parameters and thus the conditions under which the model is appropriate for use. Therefore, the model fit still can be improved and optimized by considering the limits of parameters.

Sensitivity analysis results

Partial derivatives of mass loss to the normal force (Equation 6.12), friction coefficient (Equation 6.13), maximum strength (Equation 6.14), and sliding speed (Equation 6.15) were calculated as shown below.

$$\partial W/\partial F = \frac{3}{2} F^{\frac{1}{2}} \frac{(10^{-4}\mu - 6\times10^{-5})}{V^2 S^{\frac{1}{2}}} \tag{6.12}$$

$$\partial W/\partial \mu = 10^{-4} \times \frac{F^{\frac{3}{2}}}{V^2 S^{\frac{1}{2}}} = F^{\frac{3}{2}} \frac{10^{-4}}{V^2 S^{\frac{1}{2}}} \tag{6.13}$$

$$\partial W/\partial S = -\frac{1}{2}S^{-\frac{3}{2}}F^{\frac{3}{2}}V^{-2}(10^{-4}\mu - 6 \times 10^{-5})10^{-4} \quad (6.14)$$

$$\partial W/\partial V = -2V^{-3}F^{\frac{3}{2}}S^{-\frac{1}{2}}(10^{-4}\mu - 6 \times 10^{-5})10^{-4} \quad (6.15)$$

The rate of change in mass loss with respect to the change in normal force ($\frac{\partial W}{dF}$) while other parameters (friction coefficient, sliding speed, and maximum strength) were constant showed an increasing trend, meaning that the change in mass loss increased as normal force increased (Figure 6.5a). Change in mass loss with respect to friction coefficient showed a constant value as friction coefficient changed at constant normal force, sliding speed, and maximum strength (Figure 6.5b). However, based on Equation 6.13, partial change in mass loss with respect to friction coefficient depended on normal force, sliding speed, and maximum strength, indicating that any changes in these three factors affected the friction coefficient and subsequently affected mass loss. Change in maximum strength was inversely related to mass loss at constant normal force, sliding speed, and friction coefficient (Figure 6.5c). For example, if we conduct wear tests for two cheeses with different maximum strengths, the cheese with higher maximum strength (firmer structure) should have less mass loss provided that they are tested at the same normal force and sliding speed and have similar friction behavior. Change in mass loss was also inversely related to sliding speed at constant normal force, friction coefficient, and maximum strength (Figure 6.5d).

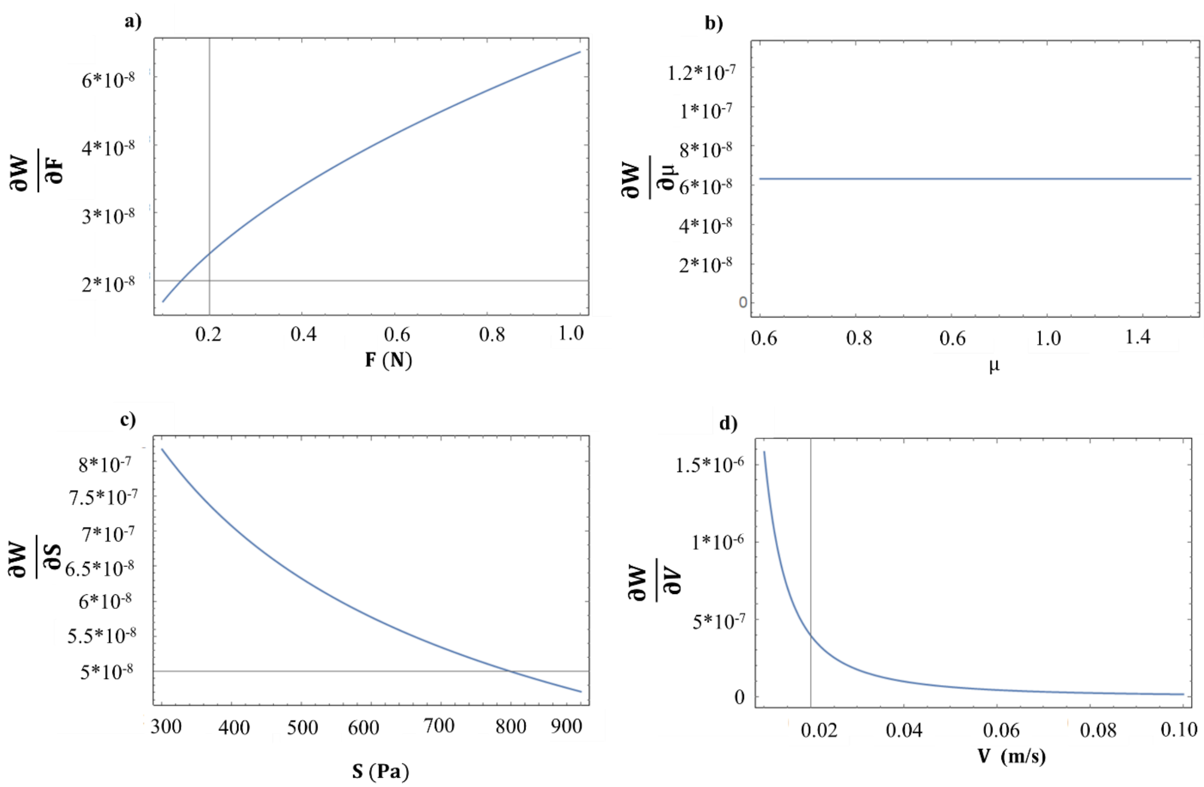

Figure 6.5. Plots of mass changes with respect to a) normal force, b) friction coefficient, c) maximum strength, and d) sliding speed.

The definition of the partial derivative indicates that the impact of the relative changes in each parameter on the relative changes in mass loss can be expressed by the product of the changes and its partial derivatives. Thus, sensitivity indices are presented as $Si(W|F)$ for mass loss changes with respect to normal force (Equation 6.15), $Si(W|V)$ for mass loss changes with respect to sliding speed (Equation 6.16), $Si(W|S)$ for mass loss changes with respect to maximum strength (Equation 6.17), and $Si(W|\mu)$ for mass loss changes with respect to friction coefficient (Equation 6.18).

$$Si\ (W|F) = (\frac{\partial W}{\partial F})dF = \frac{3}{2}F^{-1}dF \qquad (6.15)$$

$$Si\ (W|V) = \left(\frac{\partial W}{\partial V}\right) dV = -2V^{-1}dV \tag{6.16}$$

$$Si\ (W|S) = (\frac{\partial W}{\partial S})\ dS = -\frac{1}{2}S^{(-1)}dS \tag{6.17}$$

$$Si\ (W|\mu) = \left(\frac{\partial W}{\partial \mu}\right) d\mu = \frac{d\mu}{\mu - 0.6} \tag{6.18}$$

Sensitivity indices were calculated for three different parameter sets used in experiments (Table 6.2). For example, $Si\ (W|F)$ is 9.4×10^{-1}, indicating the relative change in mass loss is 9.4×10^{-5} times of the relative change in normal force. These three parameter sets showed that the highest relative change in mass loss was caused by normal force (10^{-6}) followed by sliding speed (10^{-9}), friction coefficient (10^{-10}), and maximum strength (10^{-13}). This result indicated that a small change in normal force had the greatest impact on change in mass loss compared to other parameters, while maximum strength had the lowest impact on mass loss.

Table 6.2. Parameter sensitivity analysis results for three different parameter sets.

Parameters							
Normal force (N)	**Sliding speed (m/s)**	**Maximum strength (Pa)**	**Friction coefficient (-)**	**S_i (W|F)**	**S_i (W|V)**	**S_i (W|S)**	**S_i (W|μ)**
0.5	0.05	9000	0.89	$9.4\times10^{-1}\ dF$	$-1.73\times10^{-3-}\ dV$	$-2.40\times10^{-9}\ dS$	$1.49\times10^{-4}\ d\mu$
0.7	0.03	9750	0.75	$9.3\times10^{-1}\ dF$	$-6.86\times10^{-3}\ dV$	$-5.71\times10^{-9}\ dS$	$6.86\times10^{-4}\ d\mu$
0.7	0.05	9392	0.62	$7.7\times10^{-1}\ dF$	$-1.93\times10^{-4}\ dV$	$-2.57\times10^{-10}\ dS$	$7.08\times10^{-5}\ d\mu$

Finally, the total change in mass loss with respect to all parameters can be calculated by:

$$dW = \frac{3}{2}F^{-1}dF - 2V^{-1}dV - \frac{1}{2}S^{(-1)}dS + \frac{d\mu}{\mu - 0.6} \tag{6.19}$$

Practically, the sensitivity analysis showed which parameters were key for reducing mass loss during processing of cheese to obtain desirable slices or shreds. The results revealed that normal force and sliding speed had the most significant effect on mass loss. Accordingly, normal force and sliding speed are two parameters that should be first considered for optimizing cheese processing ability. Sensitivity analysis can be performed at an early stage of cheese product development and process design, where it is still possible to influence the selection of important parameters for obtaining high-quality shreds or slices. It can also be concluded that the model and sensitivity analysis equations may solve processing issues in a more cost-effective way, providing consumers with high-quality products with reduced time and cost for product development and scaleup.

Conclusions

The dimensionless groups derived from the Buckingham Pi theorem provided fundamental knowledge about the relationships among the most influential parameters including normal force, sliding speed, maximum strength, and friction coefficient. Friction coefficient, which was a dimensionless parameter, was considered as a separated Pi group. The developed model can predict mass loss based on the input variables with acceptable accuracy (R^2=0.58). Sensitivity analysis revealed that change in mass loss was more sensitive to changes in normal force, while it had the least sensitivity to cheese maximum strength. The developed model may help predict wear behaviors of cheese under different operating conditions, and the sensitivity analysis provided valuable information on how much each input contributes to mass loss, both of which are beneficial for optimizing cheese processing behaviors. In addition, these findings provide fundamental knowledge for future studies on wear modeling of other soft materials.

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Chapter 7: Conclusions and Future Works

The preliminary work for this project (Chapter 3) showed the differences in wear behaviors of between two types of cheese, Monterey Jack and Cheddar, with different rheological behaviors. Further studies showed that sliding speed, normal force, temperature, and cheese fat content, and aging time were influential factors on cheese wear. Penetration depth, which comprises deformation depth and wear depth, increased with increased normal force, temperature, sliding speed, and cheese fat content and aging time. However, mass loss and penetration depth did not always show similar trends under a given parameter set. The impact of normal force on mass loss was significantly influenced by temperature. All cheeses except C40 showed higher mass loss at 15ºC and significantly lower mass loss at 5 and 25ºC. There were no significant differences between mass loss at 15ºC and 25ºC for C40. The differences in the mass loss and penetration depth at various temperatures may have been due to the level of fat content and different melting temperature of fatty acids that resulted in differences in cheese rigidity and fractureability and subsequently different resistant to damage. Higher normal force resulted in significantly lower mass loss at 25ºC compared to other temperatures in all full-fat cheeses, but there was no significant difference in mass loss at two distinct normal forces for C40. Penetration depth increased with increased temperature for all cheeses. The lower mass loss at higher normal force in full-fat cheeses can be explained by the lubrication effect from the release of melted fat from the protein network by applying higher force, which was likely reduced due to the low fat content in C40. All cheeses except C40 showed a significant increase in penetration depth with increased normal force. All cheeses except C54 showed a significant increase in mass loss and penetration depth with increased sliding speed. The increase in mass loss and penetration depth in C52, C50, and C40 was attributed to increased friction heating and increased shear caused by the higher number of contacts and sliding distance, while in C54 a lubrication effect from the expressed fat likely reduced the increase in mass loss. Mass loss noticeably increased between the first month and second month for all cheeses. Penetration depth was significantly different among the first 45 d storage for all cheese, but there were no significant differences between 45 and 60 d aging times. The increase in mass loss and penetration depth with aging time was likely due to a more deformable and stickier texture resulted from microbial activity. Box plot results showed that samples with mass loss between 0.07 and 0.12 g showed good processing behavior, while samples with mass loss between 0.13 and 2.3 g showed poor processing behavior.

Fat content showed a significant effect on cheese linear and nonlinear viscoelastic parameters, which was attributed to the role of fat content in the disruption of the protein network that led to a reduced ability of the microstructure to deform reversibly. The significant effect of temperature on the viscoelastic parameters was attributed to the melting of some of the fatty acids in the cheese at the higher testing temperatures. Aging time also had a significant effect on the rheological parameters, which was likely due to the chemical and structural changes caused by protein hydrolysis over time. Fracture stress decreased and fracture strain increased as fat content and aging time increased, probably due to the role of fat globules as soft fillers, which made the cheese microstructure weaker, and protein breakdown caused by microbial proteases during aging that made the cheeses less resistance to deformation by applied force. Mass loss showed negative correlations with critical strain, critical stress, complex modulus, and fracture stress, but had positive correlations with phase angle and fracture strain. These findings showed that lower mass loss would occur with a firmer structure. Phase angle showed a significant positive correlation with mass loss, which indicated greater resistance to wear in cheeses with more elastic-dominant behavior. Thus, cheeses with higher fracture strain and lower fracture stress or cheeses with a more deformable structure generally showed more mass loss. Overall, differences in wear behavior of cheeses may have been related to their differences in viscoelastic behavior and their resistance to fracture.

Sensory data showed that texture attributes were affected by cheese fat content and aging time. There were significant correlations between sensory data and mass loss at normal force of 0.7 N and sliding speed of 50 mm/s. Hand firmness, springiness, rate of recovery, first-bite firmness, fracturability, and particles decreased as fat content and aging time increased. The values of the chewdown parameters, including degree of breakdown, cohesiveness, smoothness of mass, mouthcoating, adhesiveness, moistness, and residual mouthcoating, increased as fat content and aging time increased. The changes in sensory parameter values with increased fat content were attributed to the number of fat globules: a higher number of fat globules could lead to disconnected microstructure and result in a weaker texture. The impact of aging time on sensory attributes was a result of the ripening process, which leads to protein breakdown caused by microbial protease activity. Mass loss showed negative correlations with hand firmness, springiness, rate of recovery, first bite firmness, fracturability, and degree of breakdown. However, mass loss was positively correlated with cohesiveness, smoothness of mass, both mouthcoating attributes, adhesiveness, moistness, and particles. These results showed that cheeses with different sensory characteristics could lead to different wear behaviors.

The developed model can predict mass loss based on normal force, sliding speed, maximum strength, and friction with acceptable accuracy (R^2=0.58). Sensitivity analysis revealed that the change in mass loss was more sensitive to changes in normal force, while it was least sensitive to cheese maximum strength. This model and findings from the sensitivity analysis provide valuable fundamental information about the relationship between parameters and the degree of their influence on wear behaviors of hard cheeses that may be applicable to other similar soft solid products.

The findings of this study are beneficial in improving processing behaviors of cheese in cheese industries. However, there are several areas of future work for this project. To better determination of relationship between cheese wear and processing behaviors, a larger study could be conducted on the classification of cheese processing abilities. Also, using a qualitative grading scale for sliceability of cheese based on visual observation of defects in cheese slices would be an improved measure for determining sliceabity in the laboratory, and the data may be used for correlation with experimental wear data.

To generalize the relationships between rheological and fractural properties with wear behavior, a comparison of soft cheese, semi-hard, and hard cheese would be beneficial. Also, applying a wider range of sliding speed, normal force, and temperature could better determine the parameter values for optimized processing abilities of different cheeses.

Since material microstructures undergo changes during wear processes, microscopy techniques would assist in the elucidation of a wear mechanism and understanding cheese structure changes caused by wear. In particular, surface roughness is a crucial factor determining wear behavior, and investigation of surface properties would help to better understand wear behaviors of soft solids.

Overall, the developed model is a good starting point for prediction of wear behavior of cheese, but future work is required to develop more accurate wear model for soft solid food products. Dimensional analysis can be extended to include more parameters that might impact food wear behaviors.

Furthermore, the developed model may be applied to other soft solid materials as well as food products such as deli meats and protein bars. To confirm this, wear and rheological measurements should be performed on these products, and the data used to determine the accuracy of the model and improve model accuracy as necessary.

Appendix

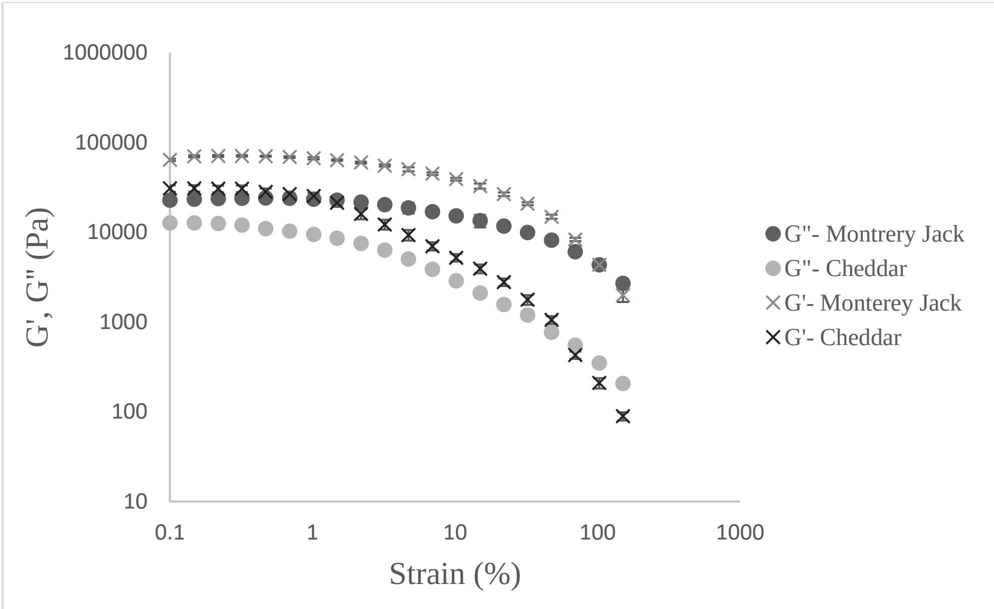

Figure A. 1. Cheese strain sweep results

Table A. 1. F-ratios from Analysis of Variance of strain sweep test parameters for four cheese samples with different fat contents, ageing times, temperatures, and at 0.5 rad/s frequency analyzed using three-way ANOVA[1]

Source of variation	Critical strain (%)	Critical stress (Pa)	G* (kPa)	Phase angle (degrees)
Fat content	252.81*	2.93*	3.92*	150.46*
Aging time	121.6*	2.80*	24.67*	183.84*
Temperature	8.309*	7.04*	99.71*	164.90*
Fat content*Aging	14.06*	0.87*	6.88*	6.23*
Fat content*Temperature	14.24*	0.81*	1.09*	4.54*
Temperature*Aging	8.57*	1.03*	9.30*	6.37*

[1] * indicates significant differences at α=0.05.

Table A. 2. F-ratios from Analysis of Variance of strain sweep test parameters for four cheese samples with different fat contents, ageing times, temperatures, and at 5 rad/s frequency analyzed using three-way ANOVA[1]

Source of variation	Critical strain (%)	Critical stress (Pa)	G* (kPa)	Phase angle (degrees)
Fat content	70.44*	1.44	290.01*	156.86*
Aging time	35.44*	8.30*	653.84*	130.61*
Temperature	33.71*	19.28*	2906.42*	197.54*
Fat content*Aging	5.35*	1.49	27.57*	7.46*
Fat content*Temperature	4.73*	2.21	15.51*	9.59*
Temperature*Aging	7.56*	1.26	313.25*	4.50*

[1] * indicates significant differences at α=0.05.

Table A. 3. F-ratios from Analysis of Variance of strain sweep test parameters for four cheese samples with different fat contents, ageing times, temperatures, and at 50 rad/s frequency analyzed using three-way ANOVA[1]

Source of variation	**Critical strain (%)**	**Critical stress (Pa)**	**G* (kPa)**	**Phase angle (degrees)**
Fat content	69.39*	16.93*	289.27*	323.76*
Aging time	26.66*	6.77*	712.88*	420.63*
Temperature	32.47*	25.31*	1103.64*	422.630*
Fat content*Aging	3.00*	2.01	10.70*	15.56*
Fat content*Temperature	2.55*	0.90	25.61*	18.75*
Temperature*Aging	5.46*	5.08*	203.34*	16.04*

[1] * indicates significant differences at α=0.05.

Table A. 4. G'_L/G'_M data for cheeses containing different fat contents at tested at different temperatures.

Cheese	Temperature °C	Strain (%)	Samples C40	C50	C52	C54
G'_L/G'_M (Pa)	5	0.1	0.90±0.005	0.90±0.004	1.00±0.001	1.00±0.001
		1.0	0.90±0.008	0.99±0.005	1.03±0.004	1.04±0.002
		10.0	1.01±0.004	1.039±0.027	1.81±0.005	1.975±0.006
		56.2	1.86±0.035	1.928±0.039	4.16±0.142	6.591±0.26
G'_L/G'_M (Pa)	15	0.1	0.94±0.003	0.99±0.004	1.00±0.004	1.01±0.005
		1.0	0.99±0.002	1.01±0.003	1.06±0.002	1.148±0.032
		10.0	1.23±0.032	1.78±0.023	1.97±0.006	2.47±0.051
		56.0	1.97±0.232	2.38±0.125	4.21±0.150	6.94±0.290
G'_L/G'_M (Pa)	25	0.1	1.00±0.020	0.91±0.05	1.01±0.021	1.02±0.013
		1.0	1.01±0.013	1.11±0.373	1.22±0.08	1.83±0.009
		10.0	1.163±026	1.56±0.262	2.13±0.217	2.94±0.482
		56.0	4.554±0.347	5.31±0.485	6.64±0.523	7.39±0623

Values are mean ± SD of three replications.

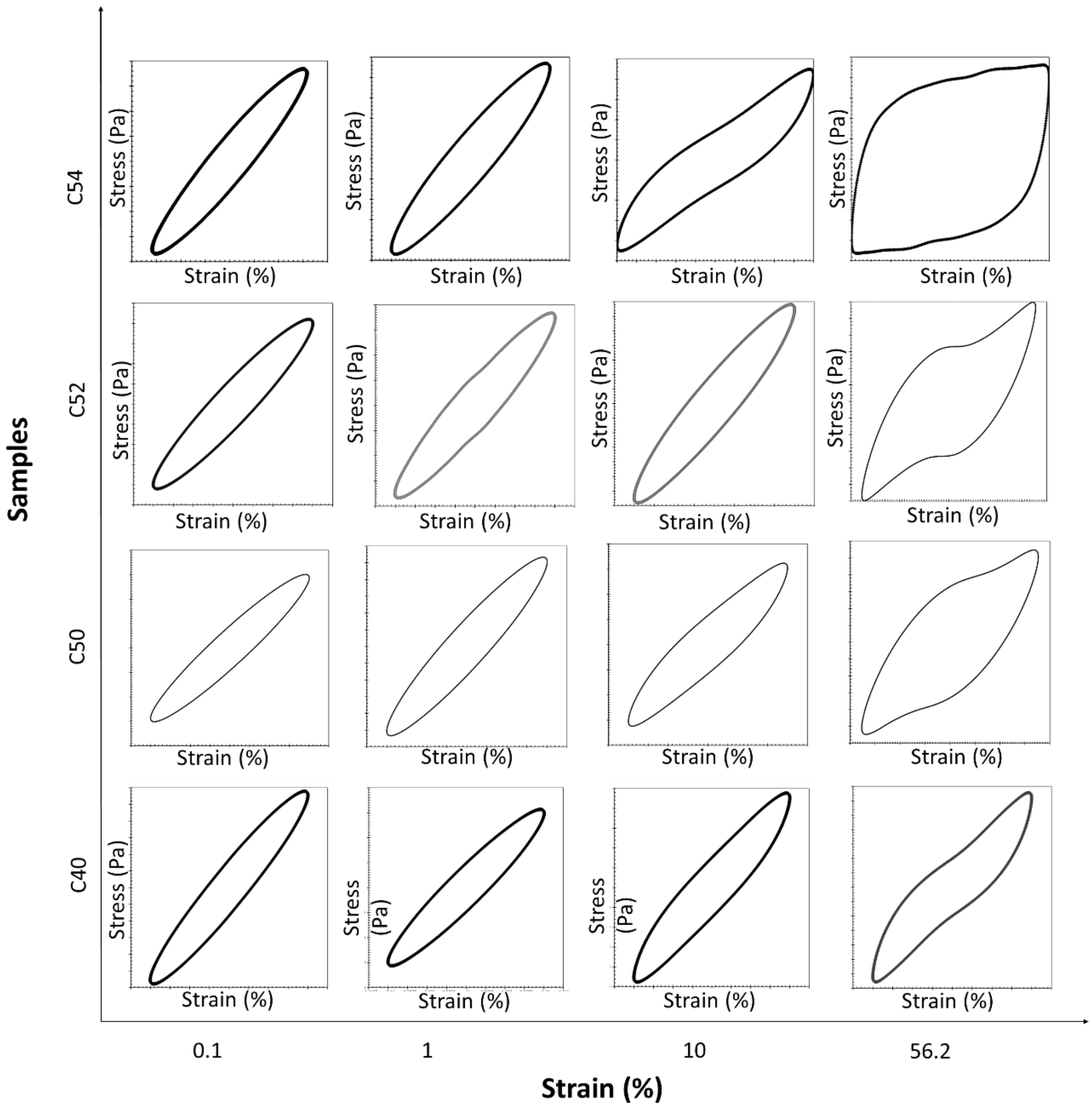

Figure A. 2**.** Lissajous plot for cheeses containing different fat contents stored for 15d. Testing temperature was 5°C.

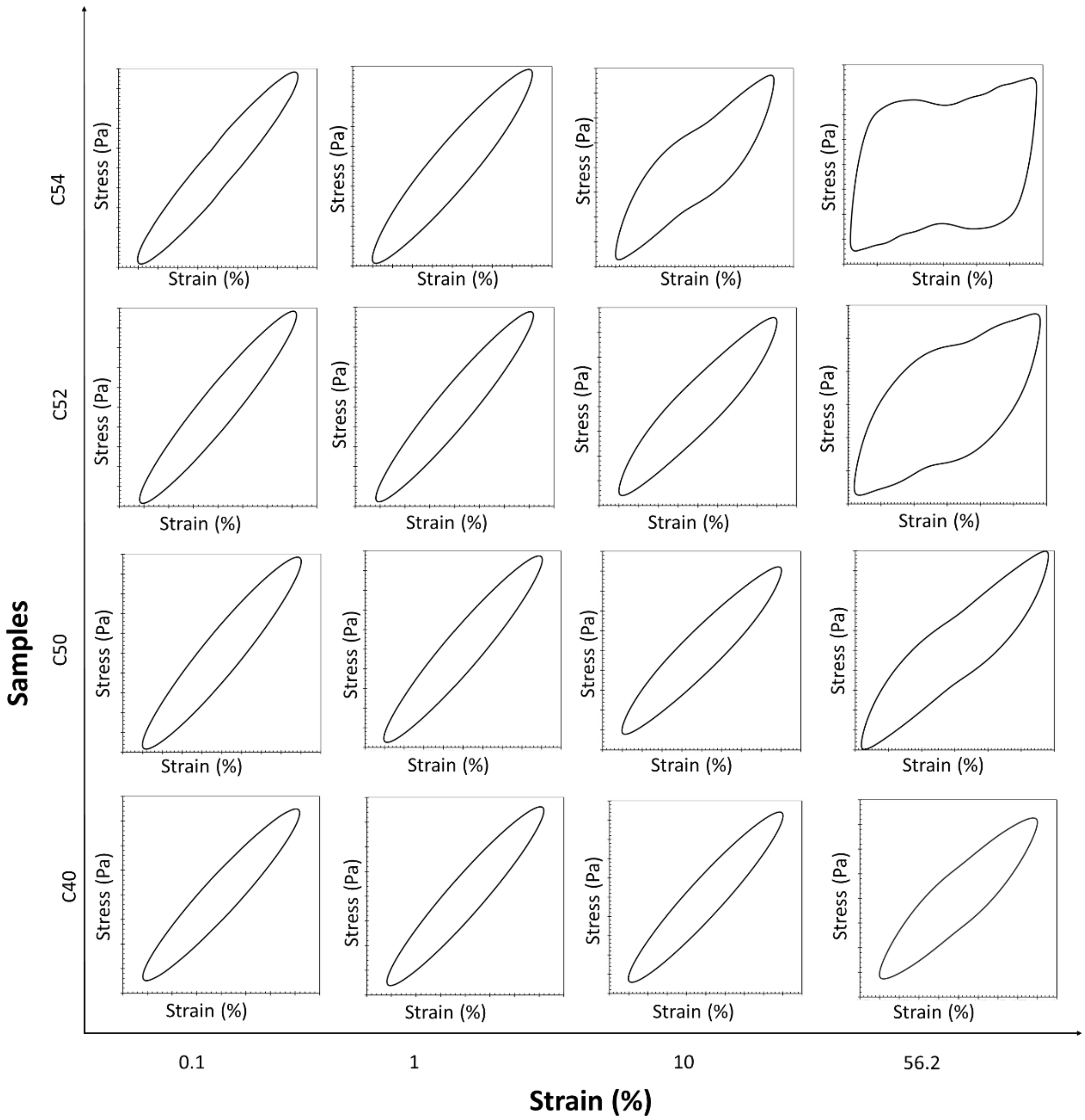

Figure A. 3. Lissajous plot for cheeses containing different fat contents stored for 15d. Testing temperature was 15°C.

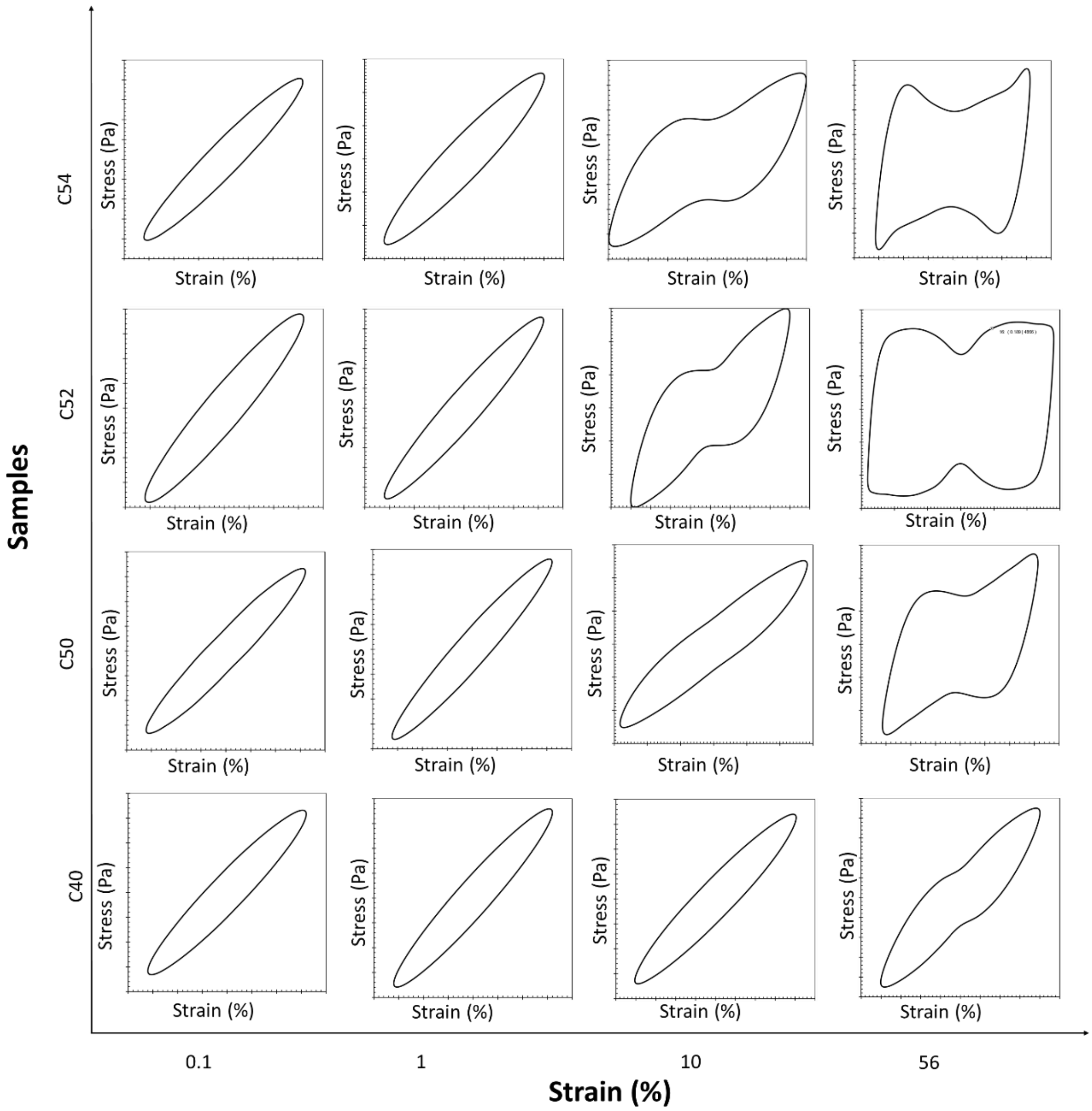

Figure A. 4**.** Lissajous plot for cheeses containing different fat contents stored for 15d. Testing temperature was 5°C.

Table A. 5. G´₃/G´₁ data at different temperatures and a frequency of 0.5 rad/s for cheeses aged up to 60 d.

Aging Time	Temperature °C	Strain (%)	Cheese C40	C50	C52	C54
15	5	0.1	0.000±0.000[a]	0.001±0.000[a]	0.002±0.000[a]	0.001±0.000[a]
		1	0.001±0.000[c]	0.002±0.000[b]	0.009±0.000[a]	0.008±0.001[a]
		10	0.011±0.001[c]	0.012±0.000[c]	0.133±0.005[b]	0.241±0.045[a]
		56	0.043±0.003[d]	0.097±0.031[c]	0.236±0.034[b]	0.457±0.056[a]
	15	0.1	0.002±0.000[b]	0.001±0.000[c]	0.001±0.000[c]	0.005±0.002[a]
		1	0.003±0.001[b]	0.004±0.001[b]	0.008±0.001[a]	0.008±0.003[a]
		10	0.037±0.004[b]	0.0204±0.037[b]	0.039±0.006[b]	0.122±0.029[a]
		56	0.138±0.034[d]	0.171±0.028[c]	0.231±0.042[b]	0.479±0.031[a]
	25	0.1	0.001±0.000[b]	0.001±0.000[b]	0.001±0.000[b]	0.002±0.000[a]
		1	0.003±0.001[c]	0.008±0.001[c]	0.060±0.003[b]	0.080±0.003[a]
		10	0.040±0.004[b]	0.018±0.002[c]	0.323±0.051[a]	0.103±0.034[b]
		56	0.185±0.038[a]	0.267±0.025[b]	0.204±0023[c]	0.578±0.038[a]
30	5	0.1	0.000±0.000[c]	0.002±0.000[a]	0.000±0.000[c]	0.001±0.00[b]
		1	0.003±0.001[b]	0.002±0.004[b]	0.011±0.001[c]	0.011±0.001[a]
		10	0.039±0.015[b]	0.034±0.005[b]	0.089±0.011[a]	0.072±0.021[a]
		56	0.120±0.043[c]	0.332±0.036[b]	0.306±0.002[b]	0.452±0.005[a]
	15	0.1	0.001±0.000[a]	0.001±0.000[a]	0.001±0.000[a]	0.002±0.001[a]
		1	0.003±0.001[b]	0.009±0.003[a]	0.012±0.03[a]	0.012±0.002[a]
		10	0.049±0.003[c]	0.045±0.010[c]	0.062±0.012[a]	0.056±0.011[a]
		56	0.213±0.061[d]	0.375±0.042[b]	0.313±0.023[c]	0.415±0.04[a]
	25	0.1	0.001±0.000[a]	0.001±0.000[a]	0.001±0.000[a]	0.001±0.000[a]
		1	0.007±0.003[b]	0.010±0.00[b]	0.020±0.008[a]	0.028±0.002[a]
		10	0.050±0.0011[a]	0.066±0.023[a]	0.084±0.005[a]	0.076±0.016[a]
		56	0.235±0.042[b]	0.281±0.045[b]	0.307±0.028[a]	0.435±0.037[a]
45	5	0.1	0.000±0.000[b]	0.001±0.000[a]	0.001±0.000[a]	0.001±0.000[a]
		1	0.002±0.001[c]	0.010±0.003[a]	0.015±0.003[b]	0.013±0.003[a]
		10	0.024±0.005[d]	0.121±0.024[c]	0.135±0.010[b]	0.188±0.037[a]
		56	0.311±0.061[c]	0.275±0.052[b]	0.428±0.048[b]	0.568±0.015[a]
	15	0.1	0.002±0.000[a]	0.001±0.000[b]	0.001±0.000[b]	0.002±0.000[a]
		1	0.006±0.000[c]	0.009±0.000[b]	0.019±0.000[b]	0.014±0.00[a]
		10	0.039±0.002[c]	0.048±0.001[b]	0.041±0.001[c]	0.107±0.004[a]
		56	0.356±0.0045[d]	0.412±0.017[c]	0.494±0.026[b]	0.575±0.018[a]
	25	0.1	0.002±0.000[c]	0.001±0.000[d]	0.003±0.000[b]	0.005±0.000[a]
		1	0.008±0.001[b]	0.008±0.002[b]	0.011±0.002[a]	0.013±0.007[a]
		10	0.038±0.000[c]	0.054±0.003[b]	0.050±0.003[b]	0.134±0.005[a]
		56	0.160±0.024[c]	0.234±0.036[b]	0.224±0.021[b]	0.531±0.051[a]
60	5	0.1	0.002±0.000[c]	0.002±0.000[c]	0.014±0.000[b]	0.022±0.000[a]
		1	0.002±0.000[d]	0.026±0.002[c]	0.193±0.006[a]	0.144±0.004[b]
		10	0.033±0.000[d]	0.066±0.005[c]	0.460±0.014[a]	0.265±0.003[b]
		56	0.371±0.015[b]	0.443±0.042[a]	0.494±0.031[c]	0427±0.053[a]
	15	0.1	0.003±0.000[d]	0.005±0.000[c]	0.006±0.000[b]	0.016±0.000[a]
		1	0.007±0.000[d]	0.010±0.000[c]	0.016±0.003[b]	0.025±0.000[a]
		10	0.028±0.003[d]	0.075±0.003[c]	0.129±0.002[b]	0.180±0.002[a]
		56	0.292±0.027[d]	0.341±0.017[c]	0.631±0.039[b]	0.766±0.051[a]
	25	0.1	0.005±0.000[c]	0.006±0.000[b]	0.005±0.000[c]	0.021±0.000a
		1	0.009±0.000[b]	0.016±0.001[c]	0.020±0.002[a]	0.019±0.004[a]
		10	0.035±0.002[d]	0.146±0.004[b]	0.097±0.004[c]	0.191±0.016[a]
		56	0.313±0.047[c]	0.413±0.040[b]	0.610±0.024[a]	0.709±0.031[a]

Values are mean ± SD of three replications. Different letters within a row represent significant differences at $p < 0.05$

Table A. 6. G´$_3$/G´$_1$ data at different temperatures and a frequency of 5 rad/s for cheeses aged up to 60 d.

Aging Time	**Temperature °C**	**Strain (%)**	**Cheese** C40	C50	C52	C54
15	5	0.1	0.000±0.000[a]	0.001±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.000±0.000[d]	0.000±0.001[c]	0.005±0.000[b]	0.008±0.000[a]
		10	0.062±0.003	0.060±0.002	0.287±0.003	0.302±0.002
		56	0.137±0.004	0.234±0.005	0.489±0.002	0.422±0.004
	15	0.1	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.002±0.000[c]	0.001±0.000[d]	0.008±0.000[b]	0.010±0.000[a]
		10	0.051±0.000[c]	0.062±0.002[b]	0.056±0.003[b]	0.101±0.003[a]
		56	0.389±0.002[c]	0.383±0.002[c]	0.445±0.002[b]	0.502±0.002[a]
	25	0.1	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.001±0.000[c]	0.000±0.000[d]	0.006±0.001[b]	0.009±0.001[a]
		10	0.005±0.000[d]	0.009±0.001[c]	0.077±0.003[b]	0.092±0.002[a]
		56	0.285±0.004[d]	0.348±0.007[b]	0.332±0.002[b]	0.432±0.005[a]
30	5	0.1	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.002±0.000[c]	0.006±0.001[b]	0.006±0.000[b]	0.009±0.000[a]
		10	0.098±0.006[b]	0.103±0.003[b]	0.149±0.004[a]	0.155±0.007[a]
		56	0.433±0.008	0.405±0.006	0.359±0.005	0.615±0.009
	15	0.1	0.000±0.000[b]	0.000±0.000[b]	0.001±0.000[a]	0.001±0.000[a]
		1	0.002±0.000[b]	0.005±0.000[b]	0.010±0.000[a]	0.020±0.005[a]
		10	0.090±0.001[c]	0.010±0.001[c]	0.176±0.003[b]	0.0186±0.003[a]
		56	0.569±0.009[c]	0.501±0.002[c]	0.571±0.006[b]	0.641±0.006[a]
	25	0.1	0.000±0.000[b]	0.000±0.000[b]	0.001±0.000[a]	0.001±0.000[a]
		1	0.003±0.000[b]	0.007±0.000[b]	0.014±0.002[a]	0.018±0.002[a]
		10	0.047±0.001[d]	0.096±0.003[c]	0.174±0.005[b]	0.192±0.004[a]
		56	0.522±0.004[c]	0.404±0.006[d]	0.550±0.006[b]	0.694±0.006[a]
45	5	0.1	0.000±0.000[b]	0.000±0.000[b]	0.000±0.000[b]	0.001±0.000[a]
		1	0.000±0.000[c]	0.003±0.000[b]	0.015±0.020[a]	0.019±0.002[a]
		10	0.154±0.004[c]	0.157±0.005[c]	0.177±0.002[b]	0.251±0.006[a]
		56	0.486±0.006[a]	0.473±0.007[b]	0.426±0.005[c]	0.499±0.008[a]
	15	0.1	0.000±0.000[b]	0.001±0.000[a]	0.001±0.000[a]	0.001±0.000[a]
		1	0.002±0.000[b]	0.009±0.001[a]	0.009±0.002[a]	0.009±0.000[a]
		10	0.161±0.003[c]	0.167±0.005[c]	0.195±0.027[b]	0.257±0.04[a]
		56	0.420±0.008[c]	0.467±0.008[c]	0.516±0.042[b]	0.593±0.034[a]
	25	0.1	0.000±0.000[b]	0.001±0.000[a]	0.001±0.000[a]	0.001±0.000[a]
		1	0.004±0.000[d]	0.008±0.00[c]	0.015±0.002[b]	0.020±0.001[a]
		10	0.123±0.004[c]	0.193±0.006[b]	0.194±0.003[b]	0.297±0.005[a]
		56	0.208±0.025[c]	0.417±0.043[b]	0.469±0.028[b]	0.655±0.072[a]
60	5	0.1	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.001±0.000[d]	0.002±0.000[c]	0.013±0.001[b]	0.017±0.001[a]
		10	0.055±0.002[d]	0.124±0.004[c]	0.255±0.003[a]	0.121±0.005[b]
		56	0.450±0.008[d]	0.476±0.004[c]	0.514±0.007[b]	0.639±0.005[a]
	15	0.1	0.000±0.000[b]	0.000±0.000[b]	0.001±0.000[a]	0.001±0.000[a]
		1	0.002±0.000[d]	0.005±0.000[c]	0.013±0.003[b]	0.029±0.002[a]
		10	0.039±0.006[d]	0.132±0.009[c]	0.156±0.008[b]	0.215±0.034[a]
		56	0.354±0.029[d]	0.494±0.073[c]	0.525±0.072[b]	0.650±0.039[a]
	25	0.1	0.000±0.000[b]	0.000±0.000[b]	0.000±0.000[b]	0.001±0.000[a]
		1	0.004±0.000[b]	0.010±0.000[b]	0.018±0.003[a]	0.018±0.002[a]
		10	0.019±0.002[c]	0.039±0.003[c]	0.094±0.005[b]	0.126±0.008[a]
		56	0.154±0.003[d]	0.443±0.006[b]	0.439±0.004[c]	0.613±0.006[a]

Table A. 7. G'_3/G'_1 data at different temperatures and a frequency of 50 rad/s for cheeses aged up to 60 d.

Aging Time	Temperature °C	Strain (%)	Cheese C40	C50	C52	C54
15	5	0.1	0.000±0.000[a]	0.001±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.000±0.000[c]	0.000±0.000[c]	0.005±0.000[b]	0.007±0.000[a]
		10	0.082±0.002[c]	0.091±0.002[ab]	0.087±0.002[b]	0.95±0.0005[a]
		56	0.237±0.005[c]	0.259±0.044[b]	0.309±0.003[a]	0.313±0.007[a]
	15	0.1	0.000±0.000[b]	0.000±0.000[b]	0.001±0.000[a]	0.001±0.000[a]
		1	0.002±0.000[b]	0.005±0.000[b]	0.015±0.002[a]	0.010±0.003[a]
		10	0.051±0.007[c]	0.113±0.009[b]	0.146±0.006[a]	0.132±0.008[a]
		56	0.309±0.084[d]	0.340±0.006[c]	0.401±0.028[b]	0.607±0.055[a]
	25	0.1	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.001±0.000[b]	0.001±0.000[b]	0.014±0.006[a]	0.011±0.005[a]
		10	0.055±0.007[c]	0.203±0.005[c]	0.231±0.003[b]	0.290±0.005[a]
		56	0.385±0.020[d]	0.430±0.012[c]	0.496±0.021[b]	0.606±0.034[a]
30	5	0.1	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.001±0.000[c]	0.003±0.000[b]	0.09±0.002[a]	0.010±0.003[a]
		10	0.080±0.008[c]	0.074±0.004[c]	0.138±0.006[b]	0.196±0.005[a]
		56	0.278±0.007[c]	0.258±0.014[c]	0.309±0.006[b]	0.430±0.007[a]
	15	0.1	0.000±0.000[b]	0.000±0.000[b]	0.001±0.000[a]	0.001±0.000[a]
		1	0.001±0.000[b]	0.004±0.000[b]	0.014±0.000[a]	0.015±0.003[a]
		10	0.069±0.005[d]	0.094±0.006[c]	0.169±0.006[b]	0.232±0.008[a]
		56	0.299±0.014[c]	0.289±0.019[c]	0.319±0.0021[b]	0.686±0.019[a]
	25	0.1	0.000±0.000[a]	0.000±0.000[a]	0.001±0.000[a]	0.000±0.000[a]
		1	0.001±0.000[c]	0.005±0.000[b]	0.016±0.003[a]	0.022±0.005[a]
		10	0.084±0.003[c]	0.187±0.013[b]	0.195±0.025[b]	0.224±0.028[a]
		56	0.308±0.031[c]	0.401±0.052[b]	0.411±0.043[b]	0.679±0.072[a]
45	5	0.1	0.000±0.00[a]	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.001±0.000[c]	0.002±0.000[b]	0.009±0.000[a]	0.012±0.005[a]
		10	0.097±0.025[b]	0.130±0.039[ba]	0.131±0.043[ba]	0.190±0.052[a]
		56	0.319±0.075	0.332±0.081	0.384±0.097	0.492±0.082
	15	0.1	0.001±0.000[a]	0.001±0.000[a]	0.001±0.000[a]	0.001±0.000[a]
		1	0.004±0.000[b]	0.003±0.000[b]	0.016±0.004[a]	0.015±0.003[a]
		10	0.140±0.015[a]	0.154±0.038[a]	0.137±0.009[a]	0.122±0.018[a]
		56	0.313±0.036[b]	0.503±0.62[a]	0.411±0.28[a]	0.528±0.039[a]
	25	0.1	0.001±0.000[a]	0.000±0.000[a]	0.001±0.000[a]	0.001±0.000[a]
		1	0.005±0.000[b]	0.005±0.000[b]	0.022±0.008[a]	0.028±0.005[a]
		10	0.155±0.014[b]	0.177±0.053[a]	0.166±0.021[a]	0.178±0.032[a]
		56	0.435±0.031[b]	0.481±0.024[b]	0.506±0.043[a]	0.515±0.032[a]
60	5	0.1	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]	0.000±0.000[a]
		1	0.001±0.000[b]	0.003±0.000[b]	0.019±0.004[a]	0.023±0.002[a]
		10	0.036±0.006[b]	0.059±0.008[b]	0.139±0.012[a]	0.167±0.023[a]
		56	0.393±0.028[b]	0.390±0.034[b]	0.543±0.072[a]	0.610±0.052[a]
	15	0.1	0.000±0.000	0.001±0.000	0.001±0.000	0.001±0.000
		1	0.001±0.000[c]	0.006±0.000[b]	0.023±0.004[a]	0.025±0.008[a]
		10	0.025±0.012[c]	0.154±0.017[b]	0.139±0.025[b]	0.189±0.027[a]
		56	0.340±0.023[c]	0.573±0.046[b]	0.795±0.078[a]	0.631±0.052[a]
	25	0.1	0.000±0.000[a]	0.000±0.000[a]	0.001±0.000[a]	0.001±0.000[a]
		1	0.003±0.000[c]	0.008±0.001[b]	0.030±0.003[a]	0.028±0.006[a]
		10	0.031±0.006[d]	0.051±0.017[c]	0.093±0.023[b]	0.186±0.034[a]
		56	0.396±0.041[b]	0.387±0.059[b]	0.752±0.082[a]	0.716±0.073[a]

Values are mean ± SD of three replications. Different letters within a row represent significant differences at $p < 0.05$

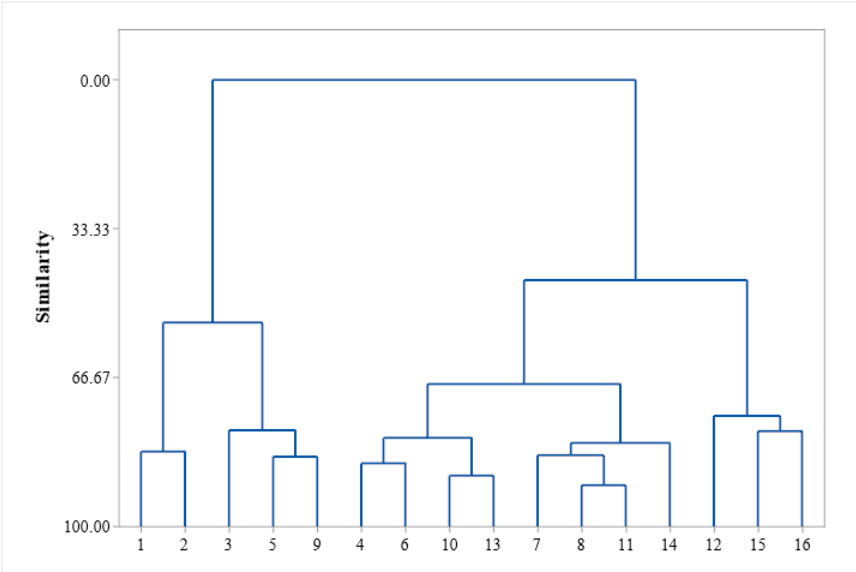

Figure A. 5**.** Cluster Analysis *for sensory evaluation*

Table A. 8. Samples codes for cluster analysis.

Codes	Samples
1	C40-15
2	C40-30
3	C40-45
4	C40-60
5	C50-15
6	C50-30
7	C50-45
8	C50-60
9	C52-15
10	C52-30
11	C52-45
12	C52-60
13	C54-15
14	C54-30
15	C54-45
16	C54-60