ABSTRACT

ROGERS, NEAL ROBERT. The Effect of Fat Content and Aging on the Texture of Cheddar Cheese. (Under the direction of E. Allen Foegeding).

Low fat cheese has recently gained popularity for the health conscious consumer, but these cheeses often have undesirable characteristics such as lack of opacity and rubbery textures which contribute to negative consumer perceptions. The overall structural reasons for these differences are not understood. Determining why these textural differences occur, and what role fat plays in this structural change, was the goal of this research.

In this study, two sets of cheeses were tested. The first set consisted of five cheeses, two of these cheeses were at normal fat contents for Cheddar cheese (33% fat), two were at "low" fat contents (6% fat), and one cheese at a "reduced" fat content (16% fat), these were tested at 0.5, 3, 6, and 9 months of age. The second set of cheeses consisted of Cheddar cheeses with fat contents of 3%, 8%, 13%, 18%, 23%, 28%, and 33% tested at 2, 4, 8, and 12 weeks of age.

Sensory analysis was conducted using an established sensory lexicon broken into sets of terms related to hand, first bite, and chewdown (breakdown of the cheese during chewing) aspects of texture. Structural properties of the first set of cheeses were analyzed using stress sweeps, creep/recovery, torsional fracture with non-linear analysis, and adhesive tack tests. The second set of cheeses, which used a refined set of rheological tests, was tested using stress sweeps, temperature controlled frequency sweeps, torsional fracture, and a twin cycle compression test designed to assess percent recoverable energy. The results can be divided

into three distinct regions of material behavior, linear, non-linear, and fracture. These regions represent the stress/strain response from low to high magnitude respectively. These results were then compared to sensory to determine relationships.

The first set of cheeses showed strong relationships between sensory terms and the critical stress and strain and the BST model related non-linear curve shape. Some correlation was seen with fracture values, but these were not as high as terms related to the non-linear region of the cheeses. These results showed that the strain weakening behavior of the non-linear region is affected by the fat content, with higher fat cheeses breaking down more as strain increases than lower fat cheeses. Using this information, the second set of cheeses was evaluated with a focus on the non-linear region. Percent recoverable energy, which measures breakdown within the non-linear region, showed strong relationships with all of the sensory terms, with critical point and fracture values showing lower, but still significant correlations. These relationships, coupled with knowledge about oral processing, leads to the conclusion that the non-linear, strain weakening behavior of Cheddar cheese is the key structural region in understanding texture.

Determining how fat causes these differences in the non-linear region was another key point of this study. Mechanical spectra, measured across a range of temperatures showed that fat in cheese behaved as an active filler component of the filled gel model. At lower temperatures (10ºC to 15ºC), fat appeared to play the dominant role in the overall structure of the cheese. Once the temperature was increased (>15ºC), the fat became more liquid and the protein network became the dominant component. This information along with fracture and non-linear data painted a picture of fat as the weakening point in the structure, and as fat content increased the cheeses became weaker and would breakdown more. This suggests that a suitable replacement filler for fat would have to produce similar weakening effects to be able to match full fat texture.

The Effect of Fat Content and Aging on the Texture of Cheddar Cheese

by
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BIOGRAPHY

Neal Rogers was born and raised on a small dairy farm in Ionia, MI run by his grandparents and parents. He spent much of his childhood around dairy cows and had several of his own as 4-H projects. At the age of 16 his family moved to Richfield, NC. There he attended his last two years of high school at North Stanly High School where he was very active in the band. During this time he also played for the Pfeiffer University wind ensemble as a Bassoonist as well as their jazz band where he played tenor and baritone saxophone. Upon completion of high school, Neal started college at Pfeiffer as a music student, where he stayed for one year before transferring to North Carolina State University for computer science. After one year of computer science, he changed his major to food science. As an undergraduate, Neal began working for a professor in the food science department, Dr. Allen Foegeding. He worked for Dr. Foegeding for two years before graduating in May 2006. Upon graduation he applied to the graduate school and was accepted and became a masters student under Dr. Foegeding. During his graduate career, Neal continued training in karate, which he began as an undergraduate, was active in the food science club as the web master, and also spent one summer at Kraft foods as a global technology and quality intern working in their long term research section. During his graduate career he also got engaged to an Israeli student in the department, Yifat.

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Introduction

Cheese in one form or another has existed throughout most of human history. Archeologists have found evidence to suggest that cheese existed as far back as the Sumerian empire (Scott, 1986). These first cheeses were likely discovered while storing sheep or goats milk in animal stomachs. The acidification of milk due to the naturally present bacteria, combined with the enzymes present in the stomach would result in curds and whey (Fox, 2004). This early form, through years of regional development, has evolved into the diverse spectrum of cheeses found today.

While Europe is where many of the cheeses commonly consumed today originated, the largest cheese producing country is the United States (Fox, 2004). In the U. S., milk product consumption has been consistently increasing over the last thirty years. While products such as whole milk have decreased dramatically in consumption over this time period, the enormous growth in the cheese sector, tripling in availability since 1970, has more than made up the difference. Within the cheese sector, the recent growth of low fat cheese products has renewed interest in the research of low fat cheese for a substitute for the health minded consumer (Wells and Buzby, 2007).

Cheese Production

While much of what makes a particular cheese variety different depends on the production process of the cheese, the general underlying procedure remains the same. The basic procedure begins with standardization of the ingredient milk by adding skim milk or removing cream (skimming off the top) to adjust the final casein to fat ratio followed by a heat treatment to eliminate unwanted microbial components (Scott, 1986). In modern cheese making, a Lactic Acid Bacteria starter is commonly added to replace the bacteria inactivated by the heat treating of the cheese milk, this bacterial culture is responsible for the acidification of the milk used to make cheese. This acidification affects several critical aspects of cheese production such as the coagulation properties of the protein, syneresis properties of the protein gel, and control of microorganisms (Fox, 2004). Once the milk is acidified to the pH required for the specific cheese being produced, the rennet is added (Scott, 1986). Chymosin, or Rennin (the primary component of rennet) as it is commonly known, is a protease that hydrolyzes casein (the predominant protein found in milk) in cheese. When enough of the κ-casein (the specific casein that is affected by Chymosin) is hydrolyzed, the surface stability of the proteins is compromised and in the presence of calcium, aggregation occurs (McSweeney, 2007b). Once the gel is set for a predetermined time, depending on the cheese variety, the gel is cut into curds and the cheese begins it dehydration process as the liquid whey component drains away (Fox, 2004). The rate of this gel syneresis is affected by several factors including calcium content, whey pH, and curd size (Holsinger et al., 1995). Depending on the final moisture target of the cheese, a light curd stirring process followed by an added cooking step to continue driving moisture out of the curds is performed (Fox, 2004). This moisture is driven out due to the protein structure of the curds contracting from the heat and forcing out the liquid whey; also due to the increased temperature, microbial activity is increased and with it the amount of lactic acid thus decreasing the pH of the cheese contracting the protein structure more, forcing out more whey. This is followed by the draining off of the whey from the cheese curds (Scott, 1986). Once the cheese reaches its desired pH (approximately 5.2 for Cheddar cheese), salt is added to the cheese to stop the microbial activity in the cheese and prevent the pH from dropping further. This is done through the lowering the water activity of the cheese and thus, dehydrates the bacterial cells. This also directly effects the resulting texture and flavor of the final cheese by stopping the bacteria present which generate flavor and texture properties (Guinee, 2007). This is followed by a pressing process to allow the curds to begin to fuse together as well drives out any remain liquid whey (Fox, 2004). Variations occur to this process depending on the cheese variety, but the overall process remains very similar.

Cheddar Cheese

Cheddar cheese originated and is named for the village of Cheddar in Somersetshire, England where it was produced as far back as the 16^{th} century (United States. Agricultural Research Service. Dairy Products Laboratory. and Sanders, 1969). The name Cheddar actually refers to the process of Cheddaring this cheese undergoes following the stirring and cooking stages. This process involves taking the drained curds and cutting them into sheets and piling the sheets on top of each other (Scott, 1986). This piling and repiling of curd blocks causes the curds to fuse together, resulting in Cheddar cheese's distinctive texture. During this time the pH of the cheese continues to drop, once it reaches the target pH of 5.4, the curd blocks are milled, which involves a machine that tears the blocks into small pieces, and salt is added to stop microbial activity (Scott, 1986). This is followed by pressing of the milled curds into a block for ageing (McSweeney, 2007a). Traditionally, the cheese is pressed for approximately 12-24 hours, this is followed by ageing at 4-10ºC for a minimum of 60 days for a young cheese or 3-6 months for aged examples (United States. Agricultural Research Service. Dairy Products Laboratory. and Sanders, 1969).

Low and Reduced Fat Cheeses

The concept of low and reduced fat cheeses is not a new one, but due to increasing interest in healthy eating, these cheeses have enjoyed renewed interest (Mistry, 2001). A normal full fat cheese has a legally required 30.5% fat minimum to be called Cheddar cheese (Johnson and Chen, 1995). According to the FDA/CFSAN (1999), a reduced fat food must have an overall fat content that is 25% less than the standard product, and to be classified as a low fat product, it must have less than 3g of fat per serving, these classifications allow for the labeling of "reduced fat cheddar cheese" and "low fat cheddar cheese." Consumer perception of these low and reduced fat cheeses has not necessarily been positive; often the cheeses have off flavors and a rubbery texture (Mistry, 2001).

These sensory differences could be due to the higher moisture content present in the cheeses that replaces the displaced fat affecting the microbial cultures in the case of the flavor and the protein/fat structure in the case of the texture (Mistry, 2001). The differences in the lower fat content cheese start with the milk used in the cheese making, which is the source of the fat in the cheese; this is standardized to the desired fat content. This greatly increases the casein to fat ratio over that in regular full fat versions, which makes the protein network in the final cheese much stronger and increases the firmness (Johnson and Chen, 1995). To offset this, moisture is added back into cheese using a curd washing step where the curds, after the whey is drained, are washed or soaked again in water to increase their moisture content and remove excess lactose (Scott, 1986). If this excess lactose is not removed, the cheeses can become increasingly acidic, causing undesired sourness. This washing step does have some disadvantages; it is believed that the lack of strong flavors in these cheeses commonly found in full fat varieties is due to this washing step. This additional moisture can not fully compensate for the fat, and thus reduced and low fat cheeses are still firmer in texture than their full fat counterparts (Johnson and Chen, 1995).

Cheese Texture

Delahunty and Drake (2004) define sensory characteristics of a cheese as “human responses to perceptions of stimuli that are experienced with the cheeses, and can generally be described using terms defined within the categories of appearance, flavor, and texture.” Texture, being a large part of the overall sensory characteristic of a cheese, is made up of several different physical sensory inputs such as touch, appearance, auditory responses, and mouth response during consumption (Delahunty and Drake, 2004). The final texture of cheese is affected by several aspects from both production and ripening. One of the primary influences on final texture of cheese relates to how the curds are treated. Initial cutting size of curd, cooking temperature, and other additional processes affect the moisture content of the curd which affects the texture of the curds and thus the final cheese.

Once the cheese enters the aging stage, the texture of the cheese is primarily affected by how the protein network, composed primarily of casein, is formed and then changed over time. Changes during the aging process involves several biochemical reactions taking place within the cheese, such as proteolysis, lipolysis, and lactose fermentation (Fox, 2004). Lipolysis involves an enzymatic hydrolysis of the triglycerides present in the cheese into fatty acids, which contributes primarily to flavor development of a cheese (Collins et al., 2004). Lactose fermentation contributes slightly during the aging process as residual lactose in the cheese (Cheddar contains 0.8-1% lactose at milling) is converted into lactic acid by the cheese culture present. This conversion is completed at a rate dependant on salt concentration in the cheese which inhibits the cultures activity (McSweeney and Fox, 2004). This slight pH shift over the initial aging process helps to offset an tendency for a pH increase in cheese as it ages, thus keeping the overall pH relatively stable (Lucey et al., 2003). Proteolysis of the casein structure is the primary contributor to texture changes, this happens as a result of the proteases from the rennet degrading the casein structure over time (Banks, 2007). This proteolysis translates into a reduction in the sensory firmness and an increase in the deformability of a cheese as it ages (Tunick et al., 1990). The hydrolysis of casein can be divided into two stages, an initial stage with high proteolysis followed by a more gradual change. The initial stage occurs within the first 14 days of aging where around 20% of the casein is hydrolyzed, the aging after this period involves a much more gradual breakdown. The Chymosin hydrolyzes the protein structure preferentially in these stages. A large portion of the α_{s1} casein is hydrolyzed in the first stage of aging leaving most of the β casein intact, the second stage involves hydrolysis of the remaining α_{s1} as well as the breaking down some of the other forms of casein (Lawrence et al., 1987). As these protein bonds are broken, ionic groups are exposed to the remaining moisture in the cheese; this free water is then tied up by the ionic groups. This has the effect of firming up the texture of a cheese and makes small changes in final moisture content to casein important to the final texture of the cheese (Lawrence et al., 1987).

Calcium found in the system is also a major contributor to cheese structure. The calcium in the cheese can either be free or associated with casein, as the cheese ages the percent of calcium present that is associated with casein tends to decrease (Cheddar cheese drops from 64% to 56%), this has the effect of weakening cheese structure over time (Lucey et al., 2003).

As fat is decreased in a cheese, the moisture and protein contents increase. The higher protein content results in a more dense protein matrix, this coupled with smaller more uniform fat globules, due to the lower aggregation, results in the more firm and elastic textures commonly found in lower fat cheeses (Green et al., 1981, Mistry and Anderson, 1993). The filled gel model has been used to describe the role of fat in Gouda and other hard and semi-hard cheeses. This model involves the concept of a network, in the case of cheese the protein, and filler, the fat. The filler can either interact with the network, which changes the rheological behavior based on the material properties of the filler and how these compare to the properties of the network, or the filler can be non-interacting which decreases firmness of a material as filler content increases (Visser, 1991). Work by Rudan et al (1999) attempted to relate this concept to mozzarella cheeses, but neglected to take the temperature effect of the fat in the cheese into account. At a higher temperature (around room temperature), the fat in cheese is in a liquid form and results in a decrease in firmness as the fat in the cheese increases. At lower temperatures such as refrigeration, the fat tends to become more solid and influences the filled model by making the materials more firm with higher filler fat. Moisture also plays a part in this picture as a higher moisture content in the cheese results in a more deformable material (Visser, 1991).

Sensory Measurement of Texture in Cheese

The ability to characterize the human texture response is a valuable tool in understanding what aspects of texture differentiate cheeses. Many aspects of texture are assessed by the consumer before the material is consumed. Initial appearance of a product (surface sheen, surface geometry), physical sensations from tactile interaction with the product, and auditory response during first bite all provide the consumer with an initial impression of the product texture that can then combine with the actual mastication texture impression to provide an overall texture impression (Wilkinson et al., 2000). Over the years, many terms have been used to describe different aspects of these texture responses, often these terms were vague, contradictory, or redundant. Szczesniak (1963) took commonly used texture terms that had been used previously and grouped them into three classes: mechanical, geometrical which are related visual responses to the product, and other characteristics such as moisture content and oily textures. Mechanical characteristics, which deal with sensory responses due to applied force either from the mouth or the fingers, are the primary terms that represent the overall texture of a product; this includes such aspects as hardness, cohesiveness, viscosity, elasticity, and adhesiveness along with secondary factors such as brittleness, chewiness, and gumminess (Szczesniak, 1963). Further research by Szczesniak et al (1963) dealt with determining standards for texture terms. It was found that a good standard contained the desired characteristic at the desired intensity and this characteristic is not overshadowed by other aspects of the standard; it is also important that the material chosen is consistent. Using both standards and defined sensory terms it possible to properly assess the texture of a product form a sensory perspective.

Sensory methods involved in determining overall quality of cheeses have existed for many years; one of the most widely used grading methods was developed by the United States Department of Agriculture (USDA). The texture aspect of this grading system is used, not to differentiate cheeses, but to detect flaws in the cheese. The American Dairy Science Association (ADSA) also maintains a similar ballot used to assess quality of cheeses. This ballot (Table 1) contains terms for both flavor and texture that are considered negative such as bitter and rancid for flavor and crumbly and pasty for texture (Delahunty and Drake, 2004).

While methods such as these are useful for quality assurance, they do not provide a complete profile of the texture of the cheese. Utilizing the texture terms and standards developed by Szczesniak (1963, Szczesniak et al., 1963), several studies have conducted sensory tests on different types of cheeses (Chen et al., 1979, Lee et al., 1978). These studies utilized the descriptive analysis method for texture profiling, which was adapted from the flavor profiling method. This method utilizes reference scales and panelist training to establish product references which allows for the distinguishing of minute differences in a specific product (Civille and Szczesniak, 1973). There are several methods available to conduct descriptive analysis, such as the Texture Profile method, the Quantitative Descriptive Analysis (QDA) method, and the most recent method, the Spectrum method. In all of the methods, a panel must be formed and trained in texture evaluation. While the older Texture Profile method involves using a universal set of sensory terms, the QDA and Spectrum method both involve panel development of texture terms or lexicon (Kilcast, 2004).

Mouth terms such as firmness, cohesiveness, stickiness to teeth, elasticity, and toothpull coupled with hand evaluation terms springiness, firmness, brittleness, stickiness, and slipperiness of film are used on a 15 point scale to determine differences in cheeses (Brown et al., 2003). Work done by Drake et al (1999a) concluded that many of these terms were correlated with each other and that both can be used to discriminate cheese texture. Using hand and mouth evaluation methods, a standard texture lexicon with descriptive terms was developed for use with a trained panel (Table 2). This lexicon for cheese has been used to assess several kinds of cheese including Gouda, Mozzarella, and Cheddar (Brown et al., 2003, Carunchia Whetstine et al., 2007, Yates and Drake, 2007).

Rheological Measurement of Texture

While sensory evaluation of texture is a good method for determining differences between samples, in order to understand why these differences exist, rheological tests must be conducted to determine the material properties of the samples. Steffe (1996) defines rheology as "the study of the manner in which materials respond to applied stress or strain." The primary aspects of viscosity, elasticity, and the area between these two extremes, viscoelasticity, are measured by applying a stress and measure the strain or vice versa, or how far the material deforms under a certain set of parameters. This force can be applied either in the normal mode (force applied in the vertical direction of the material) or shear mode (force is applied to the material across the sample). As stress or strain on a material is increased, three regions of material behavior can be seen. At the lowest levels of stress and strain a linear relationship is seen between the two. This level of stress and strain is used for small strain testing which is dependant on the linear relationship of stress to strain. This transitions to a non linear relationship between stress and strain where the material is actually disturbed and slightly damaged. This breakdown continues until the sample actually breaks, this region is known as fracture (Foegeding et al., 2003). The results from these tests reflect both the microstructure of the cheese as well as the macrostructure, which involves larger scale inconsistencies with the cheese such as cracks and weak point related to the cheese making process and curd structure (O'Callaghan and Guinee, 2004). Many tests have been used to determine the microstructure and texture of different food materials including cheese.

There has been much work over the years in developing instrumental tests to determine the texture of a food. Many of the tests developed and used early on were designed to imitate the chewing forces of the mouth; such is the case with one of the original texture instruments developed by Friedman et al (1963). This instrument utilized a plate and a plunger that applies a normal force to the sample once, and then applies the same force again. The response to this test produces two force curves with two separate peaks. Aspects of each curve, such as peak force and area are graphed by using the voltage demand for the motor compressing the sample, the harder the sample is to compress the more voltage is required to do the work. This test evolved into the commonly used Texture Profile Analysis (TPA), which utilizes the same twin compression/decompression cycles but the equipment (Instron testing equipment) allows for compression of the sample at a constant speed as opposed to the original General Foods Texturometer which due to the rotational movement of the instrument plunger changes compression speed depending on the position of the mechanism (Bourne, 2002). The TPA method has often been used to match with sensory texture data (Antoniou et al., 2000, Bryant et al., 1995, Casiraghi et al., 1989, Chen et al., 1979, Drake et al., 1999b, Drake et al., 1999c, Jack et al., 1993a, Jack et al., 1993b, Lee et al., 1978, Xiong et al., 2002), and shown to be highly correlated with sensory texture terms. While there is a high correlation with these empirical type tests, they can be very instrument specific and do not provide fundamental information about the physical properties of the material.

In order to better understand the materials properties, fundamental rheological measurements of foods have recently become a more common instrumental testing method

(Foegeding et al., 2003). Early testing of fundamental cheese properties involved using a compression test where the sample was compressed between parallel plates until it fractured; the stress and strain at fracture could then be calculated using equations related to sample geometry changes (Hort et al., 1997, Hort and Grys, 2000). Fracture testing is also performed in torsion utilizing the method developed by Diehl and Hamann (1979). This allows samples to be fractured without any changes in its geometry.

While fracture testing looks at failure of a material, small strain rheological tests are used to look at samples without damaging the structure, making it a non-failure environment. A commonly used example of this is the creep test, which involves applying a force and measuring the deformation of the sample (Foegeding et al., 2003). Tests such as these provide a good insight into to structural properties of a food material.

SMALL STRAIN RHEOLOGY

To understand the overall structure of the cheese, the protein and fat structure in the system needs to be probed to ascertain each components effect on the network. Small strain oscillatory measurements utilize small forces in a sinusoidal pattern, these tests put the structural network of the material under a known stress or strain and measure its response, and this provides information on a fundamental level about the behavior of a materials structure (Steffe, 1996). Stress and Strain sweeps are often used to characterize the linear viscoelastic region of a material; this end of this region is the critical stress and strain. These sweeps are conducted by maintaining constant frequency and varying the applied stress or strain on the sample. This results in a range of stresses that follow a linear pattern followed by a region that deviates from the linear pattern, the point at which the pattern transition is the critical point (Gunasekaran and Ak, 2003). The critical stress and strain of a material is a good indicator of overall strength of material, the longer the linear region (higher critical point) the stronger the material (Steffe, 1996).

Once the linear viscoelastic region is determined, tests can be conducted using a constant stress or strain and varying the frequency, or the rate at which the force oscillates. This test gives insight into how the viscous and elastic components (ideal liquid and ideal solid) are affected as frequency changes, providing a kind of material fingerprint (Steffe, 1996). Frequency sweeps result in four specific values at each frequency tested: G′, G″, G*, and phase angle (δ). The values of G′ (storage modulus) and G" (loss modulus) represent the elastic and viscous components of a material respectively, where the elastic component involves the energy stored and released during each oscillation and the viscous component deals with the energy lost during each oscillation (Foegeding and Drake, 2007). The ratio of the viscous component to the elastic component is represented by the phase angle of the material (δ), this value is a numerical representation of the viscoelastic nature of a material with a phase angle of 0º being fully elastic and 90º being totally viscous (Foegeding et al., 2003). G* is the stress applied divided by the strain measured or vice versa for each oscillation (Foegeding and Drake, 2007).

$$G^* = \frac{\sigma_0}{\gamma_0}$$

Where σ_0 is the amplitude of the stress and γ_0 is the amplitude of the strain (Steffe, 1996).

Another method commonly used (Kahyaoglu et al., 2005, Nagano and Nishinari, 2001) in food rheology to determine the overall firmness and elasticity of a material is the creep/recovery test. This test involves applying a constant stress to a material and measuring the change in strain over time, the stress is then removed and the amount of recovery of the original shape is measured (Fig. 1) (O'Callaghan and Guinee, 2004). This is often described using Burgers model, this model uses representations of ideal elastic behavior (springs) and ideal viscous components (dashpots). These ideal models are arranged in such a way to represent the materials behavior as a force is applied. In the case of the Burgers model for creep, it is represented by a spring followed by a spring and dashpot in parallel followed by a single dashpot. This model fits well to the first curve (Fig. 1) (force applied) of a creep recovery test, the initial spring compares to the high initial change in J (stress divided by the strain), the parallel spring and dashpot is associated with the decreasing slope in the middle portion of the curve, and the final viscous component represents the final slope of the curve which remains fairly constant (Steffe, 1996).

Creep measurements are reported as compliance (J) at a given time (t), which is related to the deformation of the sample or the strain (γ) at the same time over the constant stress applied ($\sigma_{constant}$).

$$J(t) = \frac{\gamma(t)}{\sigma_{cons\tan t}}$$

Using information gathered from this test, the extent of a material's viscous and elastic components can be determined. Thus a higher maximum (J_{max}) compliance is related to the material being more elastic and less viscous (Steffe, 1996). A retardation time for a material can also be calculated, this value is a representation of the viscoelastic nature of a material. This value represents the time taken for a material to reach its maximum strain when the constant stress of the test is applied, in the case of a fully elastic material this time would be zero (Steffe, 1996). Looking at the amount of recovery of a material also relates to the extent of a viscoelastic materials elastic component. A fully elastic material would have 100% recovery of its shape, while a fully viscous material would have 0% recovery (O'Callaghan and Guinee, 2004).

Large Strain Fracture Rheology

While small strain rheological tests deal with a material's linear behavior region, large strain tests deal primarily with the non-linear region of a material. This region involves strains in which the network is permanently deformed or at higher strain ranges, fracture of the sample occurs (O'Callaghan and Guinee, 2004). Tests can be performed in compression using two plates that can press the samples until fracture and measure the stress applied to the sample as well as the distance of the cross head travel which is then converted into strain (Bot et al., 1996). Materials can also be tested by forces in shear, where the sample is twisted (strain) on its horizontal axis. This method, unlike compression, does not change the sample volume, and thus the fracture is in "pure shear (Gunasekaran and Ak, 2003, Hamann, 1983)." In order to maintain this pure shear condition and to reduce any normal stresses from the twisting action, the middle portion of the sample is ground down to form a capstan shape (Fig. 2).

The testing instrument then turns the sample at a constant shear rate and measures torque and time. The torque (τ) is then converted to stress (σ) using the equation (Brown et al., 2003, Diehl and Hamann, 1979, Hamann, 1983):

$$\sigma = \frac{2K\tau}{\pi r_{\min}^{3}}$$

Where K is a shape constant determined by Diehl and Hamann (1979) and r_{min} is the radius at the smallest point of the capstan shape. Determining the materials true corrected strain (γ_{true}) at a time point can be determined using the equations (Brown et al., 2003, Diehl and Hamann, 1979, Hamann, 1983, Nadai, 1937):

$$\gamma_t = \frac{2K\phi_s}{\pi r_{\min}^{3} Q}$$

$$\gamma_{true} = \ln\left[1 + \frac{\gamma_t}{2} + \gamma_t\left(1 + \frac{\gamma_t^2}{4}\right)^{1/2}\right]$$

Where γ_t represents the sample strain, ϕ_s represents the angular deformation of the sample (Brown et al., 2003) and Q is a shape constant determined by Diehl and Hamann (1979).

Data from both the compression and torsion tests can be graphed as stress versus strain and the shape of this curve reflects what type material is being tested (Bot et al., 1996). The shape of the curve can be modeled to reflect deviations from a mathematical model using equations such as the BST model (Blatz et al., 1974) and the polynomial model (Barrangou et al., 2006). Through mathematical shape factors present in each equation, comparisons can be made between the shapes of the non-linear curves of different materials.

Pressure Sensitive Adhesion

Adhesion has been described in two forms, fundamental adhesion which relates to forces between two atoms, and practical adhesion, which relates to the force of cling between two surfaces, a combination of these two forms create overall adhesive force (Packham, 2005). An adhesive force called "tack" is a distinguishable resistance to the separation of two materials brought briefly into contact with each other (Aubrey, 2005). Tack response is made up of components related to both chemical and physical properties on the surface of the material, these properties result in weak temporary bonds being formed between the material and the adhering surface. A number of methods have evolved over the years to determine the tack force of materials such as rolling ball tests, peel tests, and probe tests. All of these tests involve measuring energy required to break the adhesive bonds on the surface of the material. These tests relate to the sensory aspect of feeling the stickiness of a material with a panelists finger (Hammond, 1989). The probe test is the most commonly used of these three for food materials (Childs et al., 2007, Heddleson et al., 1993, Steiner et al., 2003). The probe test looks at how changes in contact time and contact force affect tack bond formation and thus adhesiveness of a material (Hammond, 1989).

Materials that adhere to a foreign surface when they are lightly pressed and can be easily removed from that surface with no damage to the material and no residue left are considered a pressure sensitive adhesive (Dahlquist, 1989). A practical example of this behavior is bread dough adhering on contact to metal surfaces such as mixers and other metal processing equipment (Heddleson et al., 1993). For a material to be considered a pressure sensitive adhesive, it must fulfill certain rheological criteria; the material must be more elastic and resistant to flow; this can be determined by looking at a materials creep/recovery properties (Dahlquist, 1989). Surface energy of the material also plays a major role in the pressure sensitive adhesion of a material which relates to bond formation of the surfaces and thus overall adhesive work (Hammond, 1989).

Sensory and Rheology Correlation

While rheological tests, both empirical and fundamental, provide an excellent insight into the texture of a material, they by no means provides a complete picture of the texture of a cheese. Many rheological tests involve testing one “bite,” however materials change while being broken down in the mouth and thus every time a bite is taken a new material is formed and thus the texture changes. Chewing also involves several factors that are not measured such as temperature changes and saliva interactions in the mouth (Bourne, 1975).

Using aspects of both sensory and TPA testing have long been a popular approach to look at cheese texture. The empirical TPA test measures of mechanical force have often been compared with sensory terms to look for correlations, these correlations would mean the TPA would provide a mechanical analog to the sensory panel and could be used to replace the texture panel (Friedman et al., 1963). Sensory terms such as firmness or hardness, cohesiveness, and adhesiveness have been used when comparing to TPA parameters. Firmness or hardness have shown to be highly correlated with instrumental hardness (Casiraghi et al., 1989, Drake et al., 1999b, Lee et al., 1978), cohesiveness is not usually correlated to instrumental terms (Bryant et al., 1995), and adhesiveness varied from study to study being positively correlated in some studies (Bryant et al., 1995) and negatively correlated in others (Chen et al., 1979). While these tests showed strong correlation between certain terms, the empirical nature means that they have no specific structural meaning. On the other hand, fundamental tests measure properties that can be linked to structural elements (Foegeding et al., 2003).

Fundamental rheological tests, unlike their empirical counterparts are used to assess physical properties in a way in which they can be referred to using basic engineering terminology such as stress and strain (Foegeding et al., 2003). One of the earliest uses of these types of tests on cheese was in compression fracture testing (Green et al., 1985, Hort and Grys, 2000). Xiong et al (2002) found that higher correlations were seen with sensory firmness when samples were compressed to higher percentages (70% and 90% compression), which would be more likely to result in sample fracture rather than the lower compressions found in some TPA tests. Hort et al (1997) found strong relationships between fracture stress and strain for a variety of Cheddar cheeses and several of the sensory terms such as springiness and firmness. Torsional fracture is also used in determining fracture properties of materials and has shown good correlations with springiness and hardness (firmness) as well as several sensory breakdown terms (Brown et al., 2003, Carunchia Whetstine et al., 2007, Gwartney et al., 2002). Small strain rheology tests such as frequency sweeps also tend to correlate with sensory firmness, both hand and mouth terms. Brown et al (2003) found that G', G^*, and phase angle all correlated with both sensory firmness terms in young cheeses, and Drake et al (1999b) has shown strong correlations between G' and G'' with sensory firmness, cohesiveness, and stickiness in a variety of cheeses. Creep/recovery tests, another small strain fundamental test, has also shown strong correlations between sensory firmness and J_{max}, which is related to the maximum deformation of the sample under a constant stress (Brown et al., 2003, Drake et al., 1999c). Brown et al (2003) also found that sensory adhesiveness was correlated to percent recovery, and fracturability was correlated with retardation time. This study did not find any significant correlations with certain breakdown terms relating to cohesiveness and smoothness, Brown suggests that the lack of correlations is a result of the cannon of rheological tests used are not measuring these sensory sensations (Brown et al., 2003). While many fundamental rheological tests do correlate with sensory terms, they may not correlate as well as the TPA terms that they often replace, but the combination of the correlation along with the knowledge of structural properties provide a more complete picture of a food product (Foegeding et al., 2003).

Conclusion

Determining the differences, both rheological and sensory, of different fat contents of Cheddar cheeses is important in both developing a model for the role of fat in the cheese as well as understanding how those material properties affect the sensory texture. Sensory tests provide a numerical representation of the human response to a texture; this is the best way to understand a food texture from a consumer standpoint. Rheological tests provide an understanding of the material structure and thus give an idea as to what can be changed or affected to change the structure in order to improve the sensory texture. The sensory deficiencies often associated with low and reduced fat cheeses are often textural in nature. Understanding what causes these differences is valuable in being able to change the final texture of a cheese and thus improve the consumer opinion of low and reduced fat cheeses.

References

Antoniou, K. D., D. Petridis, S. Raphaelides, Z. Ben Omar, and R. Kesteloot. 2000. Texture assessment of french cheeses. J. Food Sci. 65(1):168-172.

Aubrey, D. W. 2005. Tack. Pages 527-529 in Handbook of adhesion. 2nd ed. D. E. Packham, ed. John Wiley & Sons, West Sussex, England.

Banks, J. M. 2007. What general factors affect the texture of hard and semi-hard cheeses? Pages 200-201 in Cheese problems solved. P. L. H. McSweeney, ed. Woodhead, Boca Raton.

Barrangou, L. M., C. R. Daubert, and E. A. Foegeding. 2006. Textural properties of agarose gels. I. rheological and fracture properties. Food Hydrocolloids 20:184-195.

Blatz, P. J., S. C. Sharda, and N. W. Tschoegl. 1974. Strain energy function for rubberlike materials based on a generalized measure of strain. Transactions of the society of rheology 18(1):145-161.

Bot, A., I. vanAmerongen, R. Groot, N. Hoekstra, and W. Agterof. 1996. Large deformation rheology of gelatin gels. POLYMER GELS AND NETWORKS 4(3):189-227.

Bourne, M. C. 1975. Is rheology enough for food texture measurement? J. of Texture Studies 6:259-262.

Bourne, M. C. 2002. Principles of objective texture measurements. Pages 107-187 in Food texture and viscosity: concept and measurement. 2nd ed. S. L. Taylor, ed. Academic Press, San Diego.

Brown, J. A., E. A. Foegeding, C. R. Daubert, M. A. Drake, and M. Gumpertz. 2003. Relationships among rheological and sensorial properties of young cheese. 86(10):3054-3067.

Bryant, A., Z. Ustunol, and J. Steffe. 1995. Texture of cheddar cheese as influenced by fat reduction. J. Food Sci. 60(6):1216-1236.

Carunchia Whetstine, M. E., P. J. Luck, M. A. Drake, E. A. Foegeding, and P. D. Gerard. 2007. Characterization of flavor and texture development within large (291 kg) blocks of cheddar cheese. J. of Dairy Sci. 90(7):3091-3109.

Casiraghi, E., M. Lucisano, and C. Pompei. 1989. Correlation among instrumental texture, sensory texture and chemical composition of five italian cheeses. Italian journal of food science 1(1):53-64.

Chen, A., J. Larkin, C. Clark, and W. Irwin. 1979. Textural analysis of cheese. J. of Dairy Sci. 62(6):901-907.

Childs, J. L., C. R. Daubert, L. Stefanski, and E. A. Foegeding. 2007. Factors regulating cheese shreddability. J. Dairy Sci. 90:2163-2174.

Civille, G. V. and A. S. Szczesniak. 1973. Guidelines to training a texture profile panel. J. of Texture Studies 4:204-223.

Collins, Y. F., P. L. H. McSweeney, and M. G. Wilkinson. 2004. Lipolysis and catabolism of fatty acids in cheese. Pages 373-389 in Cheese: Chemistry, physics and microbiology. Vol. 1. 3rd ed. P. F. Fox, P. L. H. McSweeney, T. M. Cogan, and T. P. Guinee, ed. Elsevier, Amsterdam.

Dahlquist, C. A. 1989. Creep. Pages 97-114 in Handbook of pressure sensitive adhesive technology. 2nd ed. D. Satas, ed. Van Nostrand Reinhold, New York.

Delahunty, C. M. and M. A. Drake. 2004. Sensory character of cheese and its evaluation. Pages 455-487 in Cheese: Chemistry, Physics and Microbiology. 3rd ed. P. F. Fox, P. L. H. McSweeny, T. M. Cogan, and T. P. Guinee, ed. Elsevier, Amsterdam.

Diehl, K. C. and D. D. Hamann. 1979. Structural failure in selected raw fruits and vegetables. Journal of Texture Studies 10:371-400.

Drake, M., P. Gerard, and G. Civille. 1999a. Ability of hand evaluation versus mouth evaluation to differentiate texture of cheese. JOURNAL OF SENSORY STUDIES 14(4):425-441.

Drake, M. A., P. D. Gerard, V. D. Troung, and C. R. Daubert. 1999b. Relationship between instrumental and sensory measurements of cheese texture. J. of Texture Studies 30:451-476.

Drake, M. A., V. D. Truong, and C. R. Daubert. 1999c. Rheological and sensory properties of reduced-fat processed cheeses containing lecithin. J. Food Sci. 64(4):744-747.

FDA/CFSAN. 1999. FDA backgrounder: the food label. Vol. 2008. US Department of Health and Huamn Services.

Foegeding, E. A., J. Brown, M. A. Drake, and C. R. Daubert. 2003. Sensory and mechanical aspects of cheese texture. International Dairy Journal 13:585-591.

Foegeding, E. A. and M. A. Drake. 2007. Sensory and mechanical properties of cheese texture. J. of Dairy Sci. 90(4):1611-1624.

Fox, P. F. 2004. Cheese: chemistry, physics, and microbiology. 3rd ed. Elsevier, Amsterdam ; Boston.

Friedman, H. H., J. E. Whitney, and A. S. Szczesniak. 1963. The texturometer-a new instrument for objective texture measurement. J. Food Sci. 28:390-396.

Green, M. L., R. J. Marshall, and B. E. Brooker. 1985. Instrumental and sensory texture assessment and fracture mechanisms of cheddar and cheshire cheeses. J. of Texture Studies 16:351-364.

Green, M. L., A. Turvey, and D. G. Hobbs. 1981. Development of structure and texture in cheddar cheese. J. of Dairy Research 48:343-355.

Guinee, T. P. 2007. Salt in cheese. Pages 80-81 in Cheese problems solved. P. L. H. McSweeney, ed. Woodhead, Boca Raton.

Gunasekaran, S. and M. M. Ak. 2003. Cheese rheology and texture. CRC Press, Boca Raton.

Gwartney, E. A., E. A. Foegeding, and D. K. Larick. 2002. The texture of commercial full-fat and reduced-fat cheese. J. Food Sci. 67(2):812-816.

Hamann, D. D. 1983. Structural failure in solid foods. Pages 351-383 in Physical properties of foods. M. Peleg and E. B. Bagley, ed. AVI, Westport, Connecticut.

Hammond, F. H. 1989. Tack. Pages 38-60 in Handbook of pressure sensitive adhesive technology. 2nd ed. D. Satas, ed. Van Nostrand Reinhold, New York.

Heddleson, S. S., D. D. Hamann, and D. R. Lineback. 1993. The Dahlquist criterion: applicability of a rheological criterion to the loss of pressure-sensitive tack in flour-water dough. Cereal Chem. 70(6):744-748.

Holsinger, V. H., P. W. Smith, and M. H. Tunick. 1995. Overview: Cheese Chemistry and Rheology. Pages 1-6 in Chemistry of structure-function relationships in cheese. E. L. Malin and M. H. Tunick, ed. Plenum press, New York [etc].

Hort, J., G. Grys, and J. Woodman. 1997. The relationships between the chemical, rheological and textural properties of cheddar cheese. Lait 77:587-600.

Hort, J. and G. L. Grys. 2000. Rheological models of cheddar cheese texture and their application to maturation. J. of Texture Studies 31:1-24.

Jack, F. R., A. Paterson, and J. R. Piggott. 1993a. Relationships between rheology and composition of cheddar cheese and texture as perceived by consumers. International journal of food science and technology 28:293-302.

Jack, F. R., J. R. Piggott, and A. Paterson. 1993b. Relationships between electromyography, sensory and instrumental measures of cheddar cheese texture. J. Food Sci. 58(6):1313-1317.

Johnson, M. E. and C. M. Chen. 1995. Technology of manufacturing reduced-fat cheddar cheese. Pages 331-337 in Chemistry of structure-function relationships in cheese. E. L. Malin and M. H. Tunick, ed. Plenum press, New York.

Kahyaoglu, T., S. Kaya, and A. Kaya. 2005. Effects of fat reduction and curd dipping temperature on viscoelasticity, texture and appearance of gaziantep cheese. Food science and technology international 11(3):191-198.

Kilcast, D. 2004. Measuring consumer perceptions of texture: an overview. Pages 1-32 in Texture in food: solid foods. Vol. 2. D. Kilcast, ed. CRC Press, Boca Raton.

Lawrence, R. C., L. K. Creamer, and J. Gilles. 1987. Texture development during cheese ripening. J. of Dairy Sci. 70(8):1748-1760.

Lee, C., E. Imoto, and C. Rha. 1978. Evaluation of cheese texture. J. Food Sci. 43(5):1600-1605.

Lucey, J. A., M. E. Johnson, and D. S. Horne. 2003. Perspectives on the basis of the rheology and texture properties of cheese. J. of Dairy Sci. 86(9):2725-2743.

McSweeney, P. L. H. 2007a. Cheddar cheese: introduction. Pages 214-216 in Cheese problems solved. Woodhead, Boca Raton.

McSweeney, P. L. H. 2007b. Conversion of milk to curd. Pages 50-51 in Cheese problems solved. P. L. H. McSweeney, ed. Woodhead, Boca Raton.

McSweeney, P. L. H. and P. F. Fox. 2004. Metabolism of residual lactose and of lactate and citrate. Pages 361-371 in Cheese: Chemistry, physics and microbiology. Vol. 1. 3rd ed. P. F. Fox, P. L. H. McSweeney, T. M. Cogan, and T. P. Guinee, ed. Elsevier, Amsterdam.

Mistry, V. 2001. Low fat cheese technology. INTERNATIONAL DAIRY JOURNAL 11(4-7):413-422.

Mistry, V. V. and D. L. Anderson. 1993. Composition and microstructure of commercial full-fat and low-fat cheeses. Food Structure 12:259-266.

Nadai, A. 1937. Plastic behavior of metals in the strain-hardening range part I. JOURNAL OF APPLIED PHYSICS 8(3):205-213.

Nagano, T. and K. Nishinari. 2001. Rheological studies on commercial egg white using creep and compression measurements. Food Hydrocolloids 15:415-421.

O'Callaghan, D. J. and T. P. Guinee. 2004. Rheology and texture of cheese. Pages 511-540 in Cheese: chemistry, physics and microbiology. 3rd ed. P. F. Fox, P. L. McSweeney, T. M. Cogan, and T. P. Guinee, ed. Elsevier, Amsterdam ; Boston.

Packham, D. E. 2005. Adhesion. Pages 14-16 in Handbook of adhesion. 2nd ed. D. E. Packham, ed. John Wiley & Sons, West Sussex, England.

Rudan, M. A., D. M. Barbano, J. J. Yun, and P. S. Kindstedt. 1999. Effect of fat reduction on chemical composition, proteolysis, functionality, and yield of mozzarella cheese. J. of Dairy Sci. 82(4):661-672.

Scott, R. 1986. Cheesemaking practice. 2nd ed. Elsevier Applied Science Publishers ; sole distributor in the USA and Canada, Elsevier Science Pub. Co., London ; New York New York, NY, USA.

Steffe, J. F. 1996. Rheological methods in food process engineering. Freeman press, East Lansing, MI.

Steiner, A. E., E. A. Foegeding, and M. Drake. 2003. Descriptive analysis of caramel texture. Journal of sensory studies 18:277-289.

Szczesniak, A. S. 1963. Classification of textural characteristics. Journal of food science 28:385-389.

Szczesniak, A. S., M. A. Brandt, and H. H. Friedman. 1963. Development of standard rating scales for mechanical parameters of texture and correlation between the objective and the sensory methods of texture evaluation. J. Food Sci. 28:397-403.

Tunick, M. H., E. J. Nolan, J. J. Shieh, J. J. Basch, M. P. Thompson, B. E. Maleeff, and V. H. Holsinger. 1990. Cheddar and chesire cheese rheology. J. of Dairy Sci. 73(7):1671-1675.

United States. Agricultural Research Service. Dairy Products Laboratory. and G. P. Sanders. 1969. Cheese varieties and descriptions. Slightly rev. ed. United States. Dept. of Agriculture. Agriculture handbook. No. no 54. [For sale by the Supt. of Docs., Washington;.

Visser, J. 1991. Factors affecting the rheological and fracture properties of hard and semi-hard cheese. Pages 49-61 in Rheological and fracture properties of cheese. P. Walstra, ed. International Dairy Federation, Brussels, Belgium.

Wells, H. F. and J. C. Buzby. 2007. Americans' Dairy Consumption Below Recommendations. in Amberwaves. USDA/ERS.

Wilkinson, C., G. B. Dijksterhuis, and M. Minekus. 2000. From food structure to texture. Trends in food science & technology 11:442-450.

Xiong, R., J.-F. Meullenet, J. A. Hankins, and W. K. Chung. 2002. Relationship between sensory and instrumental hardness of commercial cheeses. J. Food Sci. 67(2):877-883.

Yates, M. D. and M. A. Drake. 2007. Texture properties of gouda cheese. J. Sensory Studies 22:493-506.

Table 1-1. ADSA Scorecard Cheese Texture Terms (Drake et al., 1999a)

Term	Description
Corky	Described as dry, hard, or tough. When worked, the cheese plug may have a rubber-like consistency and a smooth silky texture is lacking. When worked, the cheese tends to curl up under the thumb and is distributed in irregular patches.
Crumbly	Described as friable. A crumbly cheese falls apart when sliced and a plug of such a cheese will be extremely friable.
Curdy	Described as rubbery. The cheese plug will resist finger pressure. Cheese, when pressed will have a tendency to spring back to original shape. Curdy cheeses are usually firm.
Mealy	When worked, the cheese will feel like cornmeal and will spread in irregular patches under the thumb.
Pasty	Upon working, the cheese will break down easily into a sticky mass which easily sticks to the fingers.
Short	Also described as flaky. The cheese will show a distinct lack of elasticity and may be associated with a lack of homogeneity. The cheese consistency may appear loose-knit.
Weak	Also described as soft. A small amount of finger pressure will penetrate the cheese plug.

Table 1-2. Descriptive sensory texture lexicon for cheese (Brown et al., 2003).

Term	Definition	Technique	Reference
Hand Firmness	The amount of force required to completely compress the sample.	Press completely through the sample using the thumb and first two fingers.	3 = Process Cheese 7 = Muenster 10 = Sharp Cheddar 14 = Parmesan
Hand Springiness	The total amount of recovery of the sample.	Press the sample between the thumb and first two fingers until it is depressed 30%.	1 = Parmesan 4 = Process Cheese 7 = Sharp Cheese 13 = Muenster
Hand Rate of Recovery	The rate at which the sample recovers (i.e. the speed at which the sample returns to its original shape).	Press the sample between the thumb and first two fingers until it is depressed 30%.	1 = Feta 4 = Process Cheese 7 = Muenster
First Bite Firmness	The amount of force required to completely bite through the sample.	Completely bite through the sample using the molars.	3 = Process Cheese 7 = Muenster 10 = Sharp Cheddar 14 = Parmesan
First Bite Fracturability	The amount of fracturability in the sample after biting.	Completely bite through the sample using the molars.	1 = Process Cheese 5 = Sharp Cheddar 14 = Feta
Chewdown 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 five times and evaluate the chewed mass.	1 = Parmesan 10 = Sharp Cheddar 14 = Process Cheese
Chewdown Cohesiveness	The degree to which the chewed mass holds together.	Chew the sample five times and evaluate the chewed mass.	1 = Pamesan 3 = Feta 9 = Muenster 14 = Process Cheese
Chewdown Adhesivness	The degree to which the chewed mass sticks to mouth surfaces.	Chew the sample five times and evaluate the chewed mass.	1 = Parmesan 7 = Muenster 12 = Feta
Chewdown Smoothness of Mass	The degree to which the chewed mass surface is smooth (i.e. evaluation for gritty or grainy particles).	Chew the sample five times and evaluate the chewed mass	1 = Parmesan 3 = Feta 8 = Muenster 14 = Process Cheese
Residual Smoothness of Mouth Coating	The degree of smoothness felt in the mouth after expectorating the sample.	Chew the sample five times expectorate, and evaluate the residual in the mouth.	1 = Parmesan 5 = Feta 10 = Muenster 14 = Process Cheese

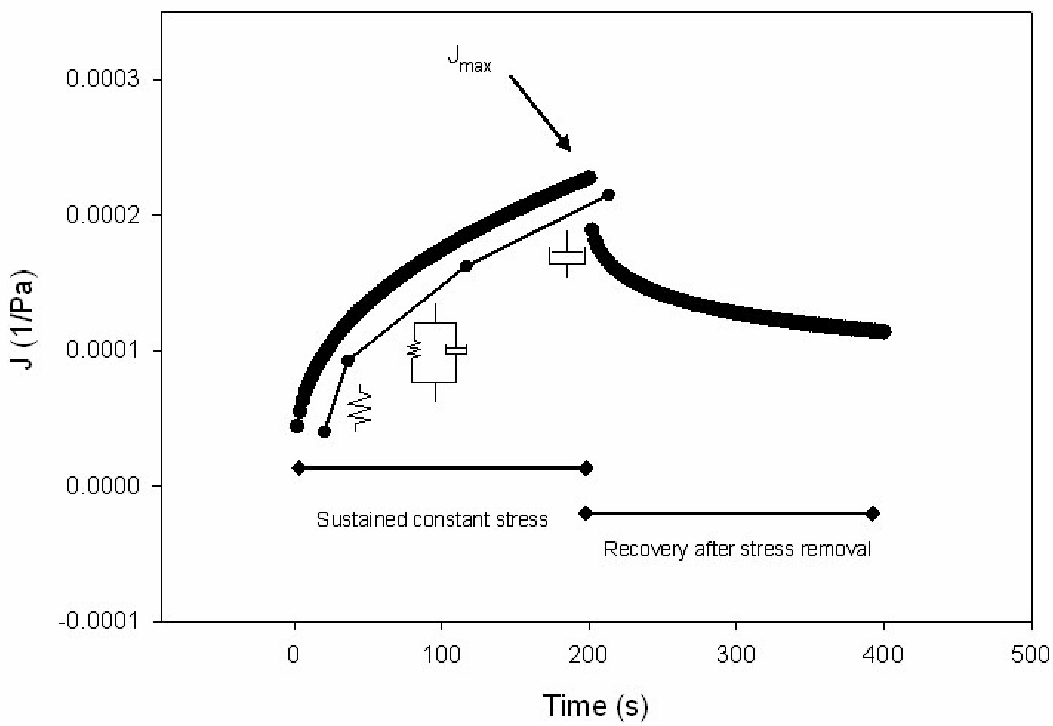

Figure 1-1. Creep/Recovery test curve with Burgers model

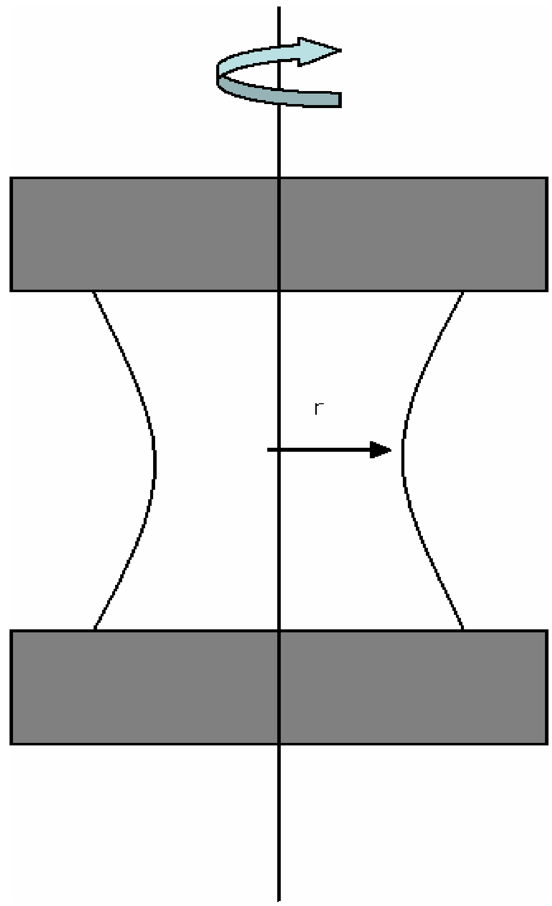

Figure 1-2. Torsion sample (Capstan)

2. The Effect of Aging on Low, Reduced, and Full Fat Cheddar Cheese Texture

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Introduction

Cheese is a very popular food in the United States; the cheese industry has experienced rapid growth with product availability tripling since 1970 (Wells and Buzby, 2007). Trends towards healthier eating have provided an increased interest in low fat cheeses. However, consumer perception of low and reduced fat cheese has not necessarily been positive as these cheeses often have off flavors, different appearance, and rubbery texture (Mistry, 2001).

Lower fat cheeses are made from lower fat milks and thus have higher protein to fat ratios than full fat cheeses; this causes the lower fat cheeses to have a more dense protein networks and thus are more firm. To try to compensate for the increased protein concentration, water is added back into the cheeses to offset some of the fat but the texture is still firmer than full fat cheeses (Johnson and Chen, 1995). Water addition is done through a curd washing step in the processing of the cheese, which involves the curds being washed or soaked in water after the whey draining step (Scott, 1986).

The aging of cheese also contributes to the final texture due to the chemical and structural changes that happen over time, which are primarily related to the hydrolysis of proteins. This degrades the casein network over time and results in a less firm and more deformable cheese (Banks, 2007, Tunick et al., 1990). Proteolysis occurs in two stages, the initial stage being within the first 14 days of aging where around 20% of the casein in the network is hydrolyzed, and a second period occurs during long term aging, where a more gradual breakdown takes place. Lawrence et al (1987) have suggested that moisture present in the cheese also has an effect on texture as the proteolysis takes place, as the bonds are broken the ionic groups are exposed and tie up the free water in the cheese, increasing cheese firmness.

The ability to characterize human texture response is a valuable tool in understanding what aspects of texture differentiate cheese. Utilization of descriptive sensory panels and texture terminology (lexicon) specifically designed for cheese have been used in the past to probe the texture of many varieties of cheese (Brown et al., 2003, Carunchia Whetstine et al., 2007, Drake et al., 1999a, Yates and Drake, 2007). This sensory testing looks at several aspects of cheese texture including tactile, first bite, and breakdown during chewing. The use of a consistent descriptive lexicon of terms provides a “textural fingerprint” for a cheese that can be compared to other cheeses analyzed with the same lexicon and standards.

While sensory evaluation is the main method for determining perception of cheese texture, in order to better understand why these texture differences exist, fundamental rheological tests are needed to probe the cheese structure. The earliest measurements of these properties determined fracture stress and strain under compression (normal force) (Hort et al., 1997, Hort and Grys, 2000). Tests that apply a normal (compressive) force to cause fracture correlate well with sensory lexicon terms related to firmness. Tests have also been conducted in torsion, where the sample is twisted rather than compressed until fracture (Diehl and Hamann, 1979). Torsion testing correlates with sensory springiness and firmness (Brown et al., 2003, Carunchia Whetstine et al., 2007, Gwartney et al., 2002). Fracture testing provides information about how a material breaks down. Alternatively, determining mechanical properties of a material without damaging it is often desired to probe the basic nature of a material. Small strain rheological tests can achieve this goal. Small strain tests are conducted within the linear viscoelastic region (LVR). This means that material properties such as the storage modulus (G′ or measure of the energy stored by elastic component) and the loss modulus (G″ or the energy dissipated by the viscous component) are not dependant on level of stress or strain (Steffe, 1996). These small strain terms have been shown to correlate well with certain sensory term relating to the breakdown of the cheese during mastication as well as the firmness of both hand evaluation and during the first bite of the sample (Brown et al., 2003, Drake et al., 1999b).

The purpose of this study was to determine how cheeses with differing contents of fat are affected by aging. This is part of a multi-university investigation looking at low fat cheese. Manufacturing and chemical analysis was conducted at Utah State University. The specific goals of this research were to determine the sensory and rheological differences between Cheddar cheeses at different fat contents as they age, and to see how these differences are related to the structure of the cheeses.

Materials and Methods

Cheddar Cheese Production

Five Cheddar cheeses were produced with differing fat contents at the Utah State University Dairy Plant. Two cheeses were produced with a target fat content of 32%; one of these cheeses was made using the standard stirred curd method and referred to as the *full fat standard*, the other cheese was made utilizing a stirred/washed curd method and was identified as *full fat washed*. Three more cheeses were made using the same stirred/washed curd method, a cheese with a target fat content of 16% identified as *reduced fat* and two cheeses with target fat content of 6%, one being identified as *low fat standard* and the other being identified as *low fat special* which used a different cheese culture than the other cheeses. Two replications of each cheese were produced for this study.

The cheeses were kept at Utah State University for aging at 8ºC for 9 months. Sample blocks were shipped to North Carolina State University at 2 weeks, 3 months, 6 months, and 9 months of age for texture testing.

Rheological Analysis

Determination of the Linear Viscoelastic Region. Stress sweeps of cheeses were done using a Stress Tech controlled stress rheometer (ATS Rheosystems, Bordentown, NJ) fitted with a 20 mm smooth parallel plate geometry. Temperature was controlled using an integrated, induction heating device set at 25ºC. Cheese samples were cut 4 mm thick, and trimmed to the size of the plate. Samples were glued to both plates to prevent slipping using cyanoacrylate glue (Loctite 401: Loctite Corp. Rocky Hill, CT). Once the plates were glued, the exposed edges of the samples had a thin layer of synthetic lubricant applied (SuperLube: Synco Chemical Bohemia, NY) to prevent sample dehydration. Tests were conducted at 10 Hz with a stress range from 1 to 1000 Pa on each cheese for each replication. The critical stress and strain were calculated by determining when G* values begin to regularly decrease; the stress and strain on the sample at that point were used as the critical stress and critical strain.

Creep/Recovery Analysis. Creep/Recovery tests were conducted using a Stress Tech controlled stress rheometer (ATS Rheosystems, Bordentown, NJ) as described above. Tests were conducted at 100 Pa and 150 Pa, which were determined to maintain the strain within the linear viscoelastic region. Forces were applied to the sample for 200 seconds, removed, and the recovery of the sample was measured for an additional 200 seconds. Tests at each force were conducted twice for each replication. The values of maximum compliance (J_{max}), instantaneous compliance (J_0), retardation time (λ_{ret}), and percent recovery (crp) were determined from the creep/recovery data. Maximum compliance was the maximum compliance reached before the force was removed. Instantaneous compliance was the compliance as time approached zero. Retardation time was calculated as the time it takes for the strain to reach 63.2% of its final value. The percent recovery was calculated using the equation:

$$crp = \frac{(J_{\max}) - (J_r)}{J_{\max}} \qquad \text{(Eq. 1)}$$

Where J_{max} is the maximum compliance and J_r is the compliance after the sample has been allowed to fully recovered (Brown et al., 2003).

Large Strain Torsion analysis. Non-linear and fracture analysis were conducted using the torsion method adapted from Brown et al (2003). Cheese blocks were set out on the counter in sealed plastic bags for 8 hours to allow them to come to room temperature (25ºC ±4ºC). Cheese samples were taken from sample blocks using an 18 mm diameter cork borer and cut to a length of 28 mm. These samples had notched, plastic disks (Gel Consultants. Raleigh, NC) glued to each end of the sample using cyanoacrylate glue (Loctite 401: Loctite Corp.

Rocky Hill, CT). Samples were then ground into a capstan shape using a precision grinding machine (Model GCPM92 US, Gel Consultants. Raleigh, NC). Samples were tested using a Haake VT-550 rotational viscometer (Gerbruder Haake GmbH, Karlsruhe, Germany) fitted with an attachment designed to facilitate torsion testing (Truong and Daubert, 2000), five samples were tested for each replication at three strain rates, 0.045, 0.45, and 4.5 s^{-1}.

The torsion test measured torque and time for materials until they fractured. The point at which the material fractured was determined as the point (torque and time) where the torque values began to decrease. These values were used to calculate shear stress (σ) and true shear strain (γ_{true}) using the following equations (Diehl and Hamann, 1979, Hamann, 1983, Nadai, 1937).

$$\sigma = \frac{2KM}{\pi r_{\min}^3} \qquad \text{(Eq. 2)}$$

$$\gamma_t = \frac{2K\phi}{\pi r_{\min}^3 Q} \qquad \text{(Eq. 3)}$$

$$\gamma_{true} = \ln\left[1 + \frac{\gamma_t^2}{2} + \gamma_t\left(1 + \frac{\gamma_t^2}{4}\right)^{1/2}\right] \qquad \text{(Eq. 4)}$$

Where K is a shape factor constant, 1.08, M is the torque value from the torsion test, r_{min} is the radius at the minimum of the capstan-shaped sample, was used to calculate shear stress (σ) (Diehl and Hamann, 1979, Nadai, 1937). True strain (γ_{true}) was calculated using the uncorrected strain value (γ_t), which was calculated using angular deformation of the sample

(ϕ) and a curvature section constant (8.45×10^{-6} m^{-3}) Q (Diehl and Hamann, 1979, Nadai, 1937). Fracture modulus (G_f) was calculated using the shear stress and strain at the fracture point (Brown et al., 2003).

$$G_f = \frac{\sigma}{\gamma_{true}} \quad \text{(Eq. 5)}$$

The nonlinear region of the fracture curves was analyzed using a nonlinear curve fitting technique using the BST model proposed by Blatz et al (1974),

$$\sigma = \frac{2G_{BST}}{n}\left(\lambda^{n} - \lambda^{-n}\right) \quad \text{(Eq. 6)}$$

$$\lambda = \frac{\gamma + \left(\gamma^{2} + 4\right)^{1/2}}{2} \quad \text{(Eq. 7)}$$

where G_{BST} refers to the initial slope of fracture curve, n is a curve shape constant referring to its deviation from the ideal and λ is a stretch ratio (Barrangou et al., 2006a). Fracture stress (σ) and strain (γ) between time zero and fracture was used as the data to fit the model. The equation was fit to the data using the Taylor-Newton-Gauss method for nonlinear regression using Maple 10 computer software (Maplesoft. Waterloo, Ontario, Canada) and output values of G_{BST} and n were compiled. This data was compared to the initial slope ($G_{initial}$) of the torsion curve. $G_{initial}$ was calculated by fitting a linear equation to the first five data points of each torsion curve and determining the slope (Barrangou et al., 2006a).

Instrumental Adhesion Testing. Instrumental surface adhesion of the cheese was conducted using a Brookfield LFRA texture analyzer (Brookfield Engineering, Middleboro, MA) with an attached dental composite probe with a circular contact surface 12.5 mm in diameter utilizing a method modified from Steiner et al (2003). Cheese samples were cut, to provide a fresh surface for adhesion, into cubes of 17 mm x 17 mm x 17 mm. Tests were conducted with a probe speed of 0.1 mm/s, samples were loaded with a force of 200 g and this force was held on the sample for 5 seconds, and then the force was removed at the same rate. Five samples from each replication were tested. Peak adhesion and area under the adhesion curve were calculated for each sample by taking the absolute value of all force values less than zero, these values were then integrated using Simpson's rule.

Sensory Analysis

Descriptive sensory analysis was conducted using the methods of Brown et al (2003) and Yates and Drake (2007). Analysis was conducted using an experienced texture panel consisting of seven panelists with approximately 100 hours of experience in descriptive texture analysis utilizing the Spectrum method (Yates and Drake, 2007). Samples were characterized on a 15 point scale anchored on the right by the term "very" and on the left by term "not" using terms from the texture lexicon laid out by Brown et al (2003) (Table 1). Panelists were given 8 cubes (1.27 cm^3) of each cheese to be used throughout testing at the discretion of the panelist in lidded 4oz. plastic cups labeled with three digit codes. Panelists were given deionized water to clean their palettes between each sample, and reference cheeses were made available for each session. Samples were evaluated in triplicate for each replication.

Statistical Analysis

All statistical analysis was conducted using SAS statistical software (version 9.1, SAS Institute Inc., Cary, NC). Sensory data was analyzed for variance using a mixed model (PROC MIXED). This model looked at effects due to aging, fat content, and combined effects from the two variables. Relationships between sensory terms and rheological values were determined using correlation analysis (PROC CORR).

Results and Discussion

Descriptive Sensory Analysis

Main Effects and Interactions for Sensory Results. Mixed model statistical analysis for determination of differences in sensory result is summarized in Table 2. All of the sensory terms were differentiated by age and all but smoothness of mouth feel by fat content. All but the firmness and fracturability terms had interactions between these two variables, meaning that the effects of age and fat content are interrelated.

Descriptive Sensory Terms. Results from the sensory testing of the cheese were grouped into three categories based on rheological considerations; these groupings are supported by correlations between sensory and mechanical terms shown by Brown et al (2003). Sensory terms for firmness, both hand evaluated (Fig. 1b) and first bite (Fig. 1a), as well as fracturability (Fig. 1c), were grouped together because they all were evaluated during the initial deformation to fracture. These terms all show similar changes as the cheese aged, with a high initial decrease between 0.5 and 3 months, followed by a more gradual decrease. This decrease in firmness is expected as the proteolysis that occurs during the aging of cheese has been shown to decrease firmness (Tunick et al., 1990). The higher initial change in firmness terms between 0.5 and 3 months has been attributed to the higher rate of proteolysis known to exist during the first 14 days of aging (Lawrence et al., 1987). These differences were not seen consistently in all of the cheeses for this study, with the full fat cheeses showing this behavior and the low and reduced fat cheeses showing a steady decrease across all time points.

Sensory terms hand springiness (Fig. 2a) and hand rate of recovery (Fig. 2b) were grouped together as they both probe the cheese at non-fracture deformations (30% of initial height) and thereby relate to the elastic/plastic nature of a material. These terms show clear distinctions between full, reduced, and low fat cheese, with the two full fat cheeses being grouped closely together and the two low fat cheeses also being grouped the same. All cheeses did show a decrease in springiness and rate of recovery over time, but the low fat cheeses did not loose much of their springiness as they aged. The full fat cheeses on the other hand, lost much of their initial springiness consistently as they aged. The reduced fat cheese showed behavior in between the two extremes. This clearly points to structural differences in the protein-fat network due to level of fat. Reducing fat in the cheese resulted in an increase in total protein (protein, water and water-soluble compounds) (Table 3); however, it did not cause any differences in protein network composition. This can be described using the filled gel model, where the filler (fat) in the cheese is being removed and thus replaced by more network. This creates a more homogeneous and connected network in the lower fat cheeses with less weak points caused by the fat. This more connective structure caused the lower fat cheeses to have higher initial springiness and recovery and, over time, could reduce the effect of proteolysis on the texture.

Sensory terms degree of breakdown (Fig. 3a), cohesiveness (Fig. 3b), adhesiveness (Fig. 3c), smoothness of mass (Fig. 4a), and smoothness of mouth feel (Fig. 4b) have been grouped together as the show similar trends and are correlated with each other (Brown et al., 2003, Drake et al., 1999a). The breakdown terms, which are evaluated after several chewing cycles, showed similar separations based on fat content as the other sensory terms, with the full fat and the low fat cheeses being very similar and the reduced fat in between the two. All cheeses showed the same high initial change between 0.5 and 3 months followed by a gradual increase; similar to what was observed for the initial deformation. All of the fat contents start at relatively the same level for each of these terms and within the first three months the differences in breakdown between the differing fat contents became apparent and these differences were maintained throughout the rest of the aging. These terms are interrelated as the degree of breakdown of a material determines the particle size distribution, and particle size is related to cohesiveness, adhesiveness, and the coating left in the mouth. Higher adhesiveness results in greater mouth coating, as the cheeses have higher cohesive properties and thus stick together more forming a smoother surface of the chewed mass which translates to smoothness of mouth coating (Brown et al., 2003).

Overall, low fat Cheddar cheeses did not change as much over a 9 month period as compared to full fat cheeses. The textures of low fat cheeses were firm and springy initially and did not loose springiness over time as compared to the full fat cheeses. In addition, full fat cheeses broke down more as they aged becoming more cohesive and adhesive than the low fat cheeses. These results provide valuable insight into how the cheeses vary, but to understand why these differences exist, structural analysis through rheological measurements were also conducted.

Viscoelastic properties

Stress Sweeps. Critical strain (Fig. 5a) and stress (Fig. 5b) values from linear viscoelastic region determination provide the point where a material deviates from its linear stress and strain relationship; these points show where network properties of the material change on a nano scale. This test probes a material on small time scale (one cycle is completed in 0.1 seconds) and thus looks at the more instantaneous response of a material. There was a strong difference between the low and reduced fat cheeses and the full fat cheeses. Full fat cheeses had lower critical stress and strain and thus a shorter linear viscoelastic region than the lower fat cheeses. This means that the full fat cheeses structure broke down at a lower force and deformation making them weaker than their low and reduced fat counterparts. These tests are likely probing when the structure of the protein network begins to breakdown. This coming apart translates into a critical stress and strain at which the cheese begins to break the weak bonds holding the protein network together. The full fat cheeses showed no real changes in critical point values as they aged. The low and reduced fat cheeses showed no general trends over aging times with no real change in critical values at 0.5 and 9 months. Higher fat cheeses are dominated by the higher fat to protein ratio and thus the measurement of the protein network is consistently lower and less prone to change over time. The more a protein network dominates a material, the greater effect hydrolysis has on this network and thus as the protein network is broken down, the structure becomes more deformable, and values for critical stress and strain increase.

Creep/Recovery. While the stress sweep looks at material responses on a very small time scale, creep/recovery tests look at the response on a much larger time scale (200 seconds). Values for maximum compliance (J_{max}), initial compliance (J_{min}), retardation time, and percent recovery for the cheeses are shown in Fig. 6. J_{max} (Fig. 6a) values showed similar trends as the critical stress and strain data. The low fat cheeses had higher J_{max} over time, which means that these cheeses were more deformable than full fat cheeses. Brown et al (2003) found that there was a strong relationship between J_{max} values and sensory firmness of cheeses with a higher J_{max} indicating a less firm texture. J_{min} (Fig. 6c) shows similar trends as

J_{max}, differentiating the full fat and the low fat cheeses and showing the same low fat aging effects. The reduced fat cheese behavior appears to follow the full fat behavior in both compliance terms. This indicates that within the linear region, the cheese network structure behaves in a very similar fashion as the full fat cheeses and that the fat is present in sufficient quantities in the material as to properly emulate the behavior of the higher fat cheese. Percent recovery (Fig. 6b) and retardation time (Fig. 6d) did not show any significant difference in either age or fat content.

Fracture and non-linear properties

Non-linear curve fitting. Data for mathematical curve fitting utilizing the BST model and the initial modulus ($G_{initial}$) determined directly from the stress strain curves are listed in Table 4. The non-linear data showed no consistent aging effect in any of the cheeses. $G_{initial}$ show no discernable changes or trends across either time or fat content. This indicates that the stress-strain relationship at low levels of deformation (strain) is very similar between all of the cheeses. When a mathematical model is applied, modulus (G_{BST}) values for low fat cheeses were consistently lower than the full fat cheeses, with the reduced fat cheese being more closely related to the low fat values than the full fat values, however since the measured value related to G_{BST} ($G_{initial}$) showed no differences, differences seen in G_{BST} should not be weighted to heavily. The shape of the non-linear stress strain relationship is important in understanding how the material behaves in this region. Fig. 7 shows examples for each cheese showing the raw data and an example of the raw data and the fitted BST curve (Fig.

8). The mathematical representation of these shapes is represented by the shape factor constant (n) in the BST model. These n values share the same trends as the G_{BST} values, with low and reduced fat cheese showing slightly higher values than the full fat cheeses. A value of n=2 is considered an ideal elastic material, thus deviation from this gives an idea to the relative elasticity of a material with a value lower than two being less elastic and thus more viscous in behavior (Barrangou et al., 2006a). This means that the low and reduced fat cheeses with their higher n values are more rubbery and elastic in texture than their full fat counterparts. The shape of the curves (Fig. 7) reveals a strain weakening behavior of all of the cheeses.

Torsional fracture. Fracture stress, strain, and modulus (determined at 0.41 1/s) are presented in Fig. 9. While all cheeses showed some decrease in fracture stress (Fig. 9b) over time, the low fat cheeses had the highest change as they aged, while the full fat cheeses exhibited a very small decrease. Fracture strain (Fig. 9a) only showed a small amount of aging effects trending slightly downward over time. Fracture strain did show differences due to fat content, with the full fat cheeses grouped together and at lower fracture strains than the low fat cheeses; this behavior was also seen with the critical strain measurements. These trends mean that the low fat cheeses were less firm than the full fat cheeses; this is the opposite of what was seen with the sensory firmness. This is possibly due to sensory firmness measuring several different structural parameters up to the fracture point. This relationship is likely represented by the behavior in the non-linear region before fracture (Fig. 7). Fracture modulus (Fig. 9c), being the fracture stress divided by the fracture strain, represents the combination of the stress and strain terms and thus provides one term that can relate the data from both. This data fit the sensory firmness well with a good inverse relationship.

Many studies have been conducted looking at ideal materials such as gelatin and agarose and how their structure is related to sensory properties. In the case of agarose, torsional fracture was conducted along with small strain tests and it was found that these fracture terms were more related to the assessed sensory terms than the small strain data (Barrangou et al., 2006b). These relationships can not be expected at the same level for cheeses. Under normal conditions, weak spots or cracks in the material are present; in ideal gels such as agarose these cracks are few and small but still contribute to the failure of a material (van Vliet and Walstra, 1995). In the case of cheese however, these cracks and imperfections are much larger and more numerous, affecting the way the material fractures. Thus, comparing and applying sensory information on structure gleaned from polymer gel models to cheese structure is not always consistent. Because of this, it is important to understand not only why the simpler, ideal, systems work, but also to understand how more complex structures, such as cheese, behave.

Time dependency studies were conducted to see how rate of deformation affects the fracture of cheese. Time dependencies were seen in all cheeses over strain rates of 0.041 to 4.1 1/s in both the fracture stress (Fig. 10) and strain (Fig. 11) with little to no aging effect. Cheddar cheese showed the same time dependant behavior as was observed for Mozzarella and Monterey Jack by Brown et al (2003) as well as Cheddar tested under different compression rates by Xiong et al(2002). This rate effect was described by vanVliet and Walstra (1995) as being attributed to how bonds in a material “unzip.” At low strain rates, the materials are allowed unzip at a rate closer to the deformation rate meaning less energy is needed to fracture a material and thus a lower fracture stress. The fracture stresses of all of the cheeses appear to follow this pattern, showing increasing fracture stress as strain rate increases. The strain on the other hand shows no significant trends. This behavior is possibly due to a combination of energy dissipation mechanisms in fracture, frictional dissipation where the energy is dissipated by frictional creation of heat and the viscous dissipation of energy due to the viscous flow of the material.

Surface adhesion. Results for total adhesive force are presented in Fig. 12. This property showed the same large initial change between 0.5 and 3 months seen in many of the sensory results combined with a similar starting adhesive force for all the cheeses. After the 3 months, the low fat cheeses had more surface adhesion than the full fat cheeses with the reduced fat cheese falling in between the two. This trend follows the rheological tenets of pressure sensitive materials laid out by Dahlquist (1989), which involves materials with a storage modulus (G') less than 10^5 Pa; this refers to more deformable cheeses. Low fat cheeses, which were shown to have higher J_{max} (lower G') with the creep/recovery test, are also shown to have the highest adhesion area in this test. Pressure sensitive adhesion also involves an aspect of material surface energy, which relates to how the temporary bonds between the material and the interacting surface are formed (Hammond, 1989), though surface energies were not assessed in this study. It can be speculated that the fat at higher concentrations has the effect of dominating these surface forces and when at lower concentrations the protein dominates these interactions.

Correlation among sensory texture terms and Rheological properties determined in the linear and non-linear viscoelastic regions. Correlation among sensory terms and Creep/recovery, stress sweep, adhesion, $G_{initial}$, G_{BST}, and n are presented at 0.5 months, 3 months, 6 months, and 9 months (Table 5). Maximum compliance (J_{max}) showed strong correlations with both sensory hand and mouth firmness, this is due to higher J_{max} values referring to more deformable cheeses which is one aspect of what the sensory firmness measures as the cheese is compressed by the teeth or between the fingers. As the cheese aged, critical stress and strain values became more and more related to breakdown sensory terms. Correlation analysis showed a strong negative correlation between critical stress and critical strain and breakdown terms degree of breakdown, cohesiveness, adhesiveness, smoothness of mass and smoothness of mouth feel at 6 and 9 months of aging, therefore as the structure of the cheese network broke down to a greater extent, the length of its linear viscoelastic region decreased. This means that the cheese networks were weaker and thus would breakdown at lower stresses and deformations. Critical strain also showed strong correlations with springiness and rate of recovery terms; because of this, the extent of deformation of the linear region can be related to the springiness of a material. While the initial modulus determined from the BST model (G_{BST}) did not show consistent strong correlations, the shape factor for the model (n) did show strong negative correlations to the sensory breakdown terms. As this value decreased, it indicated more strain weakening in the cheese that could result in a greater degree of breakdown in the mouth resulting in higher smoothness, cohesiveness and adhesiveness. This behavior was shown by the full fat cheeses which were less deformable than the low fat cheeses (lower J_{max}), had higher cohesiveness, adhesiveness and degree of breakdown, and lower n values. Instrumental adhesion was highly negatively correlated with the breakdown terms. At first thought this may seem odd as adhesion is one of the sensory terms tested. One possibility why this relationship was negative is that interactions in the mouth, involving higher temperatures and saliva, are different than the direct measure of adhesion. This was proposed by Steiner et al (2003) concerning sensory and tack of caramel. Another possible explanation for this inverse relationship is the difference in the unchewed adhesion (surface adhesion on the unchewed cube) and sensory breakdown adhesion (adhesion after cheese has been chewed). There is also a high positive correlation seen between adhesion area and the sensory firmness terms; the opposite of what is assumed in the Dahlquist criterion. This could mean that adhesion is surface energy dependant, which has been shown in other cheeses such as Mozzarella (Childs et al., 2007) or that the correlation could just be picking up compositional differences.

Correlation between sensory and fracture properties. Statistical correlations between torsional fracture at the three strain rates and sensory terms were determined at 0.5 months, 3 months, 6 months, and 9 months (Table 6). Looking across all strain rates and aging times, correlations are consistently seen with firmness terms, springiness and rate of recovery, and most of the breakdown terms. Fracture modulus, being a combined term for the stress and strain, is the fracture term most correlated with sensory terms. Fracture modulus is negatively correlated with hand and first bite terms and positively correlated with the breakdown terms. Correlations involving fracture stress and strain can be used to better understand the fracture modulus. Fracture stress values showed negative relationships with the hand and first bite terms. This means that a decrease in fracture stress translates into a firmer cheese as perceived by sensory analysis. Fracture modulus, being fracture stress divided by fracture strain, is affected by this negative relationship. However, stress-strain curves (Fig. 9) suggest that sensory panelists may be evaluating the entire deformation curve rather than just the point of fracture. The negative correlations between springiness and rate of recovery and fracture modulus have been noted by Brown et al (2003) and Carunchia Whetstine et al (2007). Breakdown terms were positively correlated with fracture stress and negatively correlated with fracture strain; this means that as cheeses became more brittle, the degree of breakdown increased. The lowest strain rate showed the highest number of correlations between the torsion terms and the sensory terms. Logic suggests that the higher strain rate terms, which are closer to the strain rates seen in the mouth during chewing, would correlate better with the sensory terms, but as Xiong et al (2002) found that lower strain rates correlate better with sensory hardness.

Conclusion

Overall, full fat cheeses behaved similar as did the two low fat cheeses with reduced fat cheeses falling in between in a stepwise fashion. Washed curd versus stirred curd production methods did not appear to affect the structure significantly, nor did the alternate culture affect the low fat cheese significantly in texture. Much of the changes seen in all the cheeses occur in the first three months of aging.

In the cheeses investigated in this study, it was found that the small strain tests such as critical point values and creep recovery values seemed to show the clearest relationship to many of the sensory terms, especially terms associated with breakdown during chewing. The probing of the cheese in these minimally destructive fashions provided information on the protein network associated with the nano scale of the structure. It was from this scale that the differences in low and full fat cheese could be realized as this, most likely, is either due to fat simply causing weakness in the protein network or differences in the structure of the protein network when fat is removed. Understanding on how the volume reduction in fat affects the overall cheese network structure is an important key into unlocking a consumer palatable low fat cheese.

References

Banks, J. M. 2007. What general factors affect the texture of hard and semi-hard cheeses? Pages 200-201 in Cheese problems solved. P. L. H. McSweeney, ed. Woodhead, Boca Raton.

Barrangou, L. M., C. R. Daubert, and E. A. Foegeding. 2006a. Textural properties of agarose gels. I. rheological and fracture properties. Food Hydrocolloids 20:184-195.

Barrangou, L. M., M. A. Drake, C. R. Daubert, and E. A. Foegeding. 2006b. Textural properties of agarose gels. II. Relationships between rheological properties and sensory texture. Food Hydrocolloids 20:196-203.

Blatz, P. J., S. C. Sharda, and N. W. Tschoegl. 1974. Strain energy function for rubberlike materials based on a generalized measure of strain. Transactions of the society of rheology 18(1):145-161.

Brown, J. A., E. A. Foegeding, C. R. Daubert, M. A. Drake, and M. Gumpertz. 2003. Relationships among rheological and sensorial properties of young cheese. 86(10):3054-3067.

Carunchia Whetstine, M. E., P. J. Luck, M. A. Drake, E. A. Foegeding, and P. D. Gerard. 2007. Characterization of flavor and texture development within large (291 kg) blocks of cheddar cheese. J. of Dairy Sci. 90(7):3091-3109.

Childs, J. L., C. R. Daubert, L. Stefanski, and E. A. Foegeding. 2007. Factors regulating cheese shreddability. J. Dairy Sci. 90:2163-2174.

Dahlquist, C. A. 1989. Creep. Pages 97-114 in Handbook of pressure sensitive adhesive technology. 2nd ed. D. Satas, ed. Van Nostrand Reinhold, New York.

Diehl, K. C. and D. D. Hamann. 1979. Structural failure in selected raw fruits and vegetables. Journal of Texture Studies 10:371-400.

Drake, M., P. Gerard, and G. Civille. 1999a. Ability of hand evaluation versus mouth evaluation to differentiate texture of cheese. JOURNAL OF SENSORY STUDIES 14(4):425-441.

Drake, M. A., V. D. Truong, and C. R. Daubert. 1999b. Rheological and sensory properties of reduced-fat processed cheeses containing lecithin. J. Food Sci. 64(4):744-747.

Gwartney, E. A., E. A. Foegeding, and D. K. Larick. 2002. The texture of commercial full-fat and reduced-fat cheese. J. Food Sci. 67(2):812-816.

Hamann, D. D. 1983. Structural failure in solid foods. Pages 351-383 in Physical properties of foods. M. Peleg and E. B. Bagley, ed. AVI, Westport, Connecticut.

Hammond, F. H. 1989. Tack. Pages 38-60 in Handbook of pressure sensitive adhesive technology. 2nd ed. D. Satas, ed. Van Nostrand Reinhold, New York.

Hort, J., G. Grys, and J. Woodman. 1997. The relationships between the chemical, rheological and textural properties of cheddar cheese. Lait 77:587-600.

Hort, J. and G. L. Grys. 2000. Rheological models of cheddar cheese texture and their application to maturation. J. of Texture Studies 31:1-24.

Johnson, M. E. and C. M. Chen. 1995. Technology of manufacturing reduced-fat cheddar cheese. Pages 331-337 in Chemistry of structure-function relationships in cheese. E. L. Malin and M. H. Tunick, ed. Plenum press, New York.

Lawrence, R. C., L. K. Creamer, and J. Gilles. 1987. Texture development during cheese ripening. J. of Dairy Sci. 70(8):1748-1760.

Mistry, V. 2001. Low fat cheese technology. INTERNATIONAL DAIRY JOURNAL 11(4-7):413-422.

Nadai, A. 1937. Plastic behavior of metals in the strain-hardening range. Part I. J. Appl. Physics 8:205-213.

Scott, R. 1986. Cheesemaking practice. 2nd ed. Elsevier Applied Science Publishers ; sole distributor in the USA and Canada, Elsevier Science Pub. Co., London ; New York New York, NY, USA.

Steffe, J. F. 1996. Rheological methods in food process engineering. Freeman press, East Lansing, MI.

Steiner, A. E., E. A. Foegeding, and M. Drake. 2003. Descriptive analysis of caramel texture. Journal of sensory studies 18:277-289.

Truong, V. D. and C. R. Daubert. 2000. Comparative study on large strain methods in assessing failure characteristics of selected food gels. J. of Texture Studies 31:335-353.

Tunick, M. H., E. J. Nolan, J. J. Shieh, J. J. Basch, M. P. Thompson, B. E. Maleeff, and V. H. Holsinger. 1990. Cheddar and chesire cheese rheology. J. of Dairy Sci. 73(7):1671-1675.

van Vliet, T. and P. Walstra. 1995. Large deformation and fracture behavior of gels. Faraday Discussion 101:359-370.

Wells, H. F. and J. C. Buzby. 2007. Americans' Dairy Consumption Below Recommendations. in Amberwaves. USDA/ERS.

Xiong, R., J.-F. Meullenet, J. A. Hankins, and W. K. Chung. 2002. Relationship between sensory and instrumental hardness of commercial cheeses. J. Food Sci. 67(2):877-883.

Yates, M. D. and M. A. Drake. 2007. Texture properties of gouda cheese. J. Sensory Studies 22:493-506.

Table 2-1. Descriptive sensory lexicon used for texture analysis on a 15 point scale anchored on the left by the term "not" and on the right by term "very."

	Term	Definition	Technique	Reference
Hand Terms	Hand Firmness	The amount of force required to completely compress the sample.	Press completely through the sample using the thumb and first two fingers.	3 = Process Cheese 7 = Muenster 10 = Sharp Cheddar 14 = Parmesan
	Hand Springiness	The total amount of recovery of the sample.	Press the sample between the thumb and first two fingers until it is depressed 30%.	1 = Parmesan 4 = Process Cheese 7 = Sharp Cheese 13 = Muenster
	Hand Rate of Recovery	The rate at which the sample recovers (i.e. the speed at which the sample returns to its original shape).	Press the sample between the thumb and first two fingers until it is depressed 30%.	1 = Feta 4 = Process Cheese 7 = Muenster
First Bite Terms	First Bite Firmness	The amount of force required to completely bite through the sample.	Completely bite through the sample using the molars.	3 = Process Cheese 7 = Muenster 10 = Sharp Cheddar 14 = Parmesan
	First Bite Fracturability	The amount of fracturability in the sample after biting.	Completely bite through the sample using the molars.	1 = Process Cheese 5 = Sharp Cheddar 14 = Feta
Breakdown Terms	Chewdown 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 five times and evaluate the chewed mass.	1 = Parmesan 10 = Sharp Cheddar 14 = Process Cheese
	Chewdown Cohesiveness	The degree to which the chewed mass holds together.	Chew the sample five times and evaluate the chewed mass.	1 = Pamesan 3 = Feta 9 = Muenster 14 = Process Cheese
	Chewdown Adhesivness	The degree to which the chewed mass sticks to mouth surfaces.	Chew the sample five times and evaluate the chewed mass.	1 = Parmesan 7 = Muenster 12 = Feta
	Chewdown Smoothness of Mass	The degree to which the chewed mass surface is smooth (i.e. evaluation for gritty or grainy particles).	Chew the sample five times and evaluate the chewed mass	1 = Parmesan 3 = Feta 8 = Muenster 14 = Process Cheese
	Residual Smoothness of Mouth Coating	The degree of smoothness felt in the mouth after expectorating the sample.	Chew the sample five times expectorate, and evaluate the residual in the mouth.	1 = Parmesan 5 = Feta 10 = Muenster 14 = Process Cheese

Table 2-2. Main effects (age and fat) and interaction (combined age and fat) for sensory texture attributes hand firmness (HFirm), hand springiness (HSpring), hand rate of recovery (HRecov), first bite firmness (MFirm), first bite fracturability (Frac), degree of breakdown (Deg Break), cohesiveness (Cohes), adhesiveness (Adhes), smoothness of mass (Smooth of mass), and residual smoothness of mouth coating (smooth of mouth) of Cheddar cheese.

	HFirm	HSpring	HRecov	MFirm	Frac	Deg Break	Cohes	Adhes	Smooth of Mass	Smooth of Mouth
Age	*	*	*	*	*	*	*	*	*	*
Fat	*	*	*	*	*	*	*	*	*	-
Interaction	-	*	*	-	-	*	*	*	*	*

* denotes presence of an effect at $p < 0.05$, - denotes absence of effect

Table 2-3. Proximate analysis data for Cheddar cheeses of varying fat contents.

	Actual fat percentage (%)	Moisture content (%)	Protein content (%)	pH
Full Fat Standard	31.8	37.7	24.6	5.2
Full Fat Washed	32.0	37.5	24.7	5.2
Reduced Fat	15.9	48.0	29.6	5.2
Low Fat Standard	5.0	53.8	34.2	5.2
Low Fat Special	not analyzed			

Table 2-4. Non-linear curve fitting to the G_{BST} equation, and calculation of the initial slope ($G_{initial}$) of the non-linear curve for full fat standard, full fat washed, low fat special, low fat standard, and reduced fat Cheddar cheese.

	Age	$G_{initial}$ (Pa)	std. dev.	G_{BST} (Pa)	std. dev.	n	std. dev.	R^2
Full Fat Standard	0.5	55.4	24.7	115	77.8	0.70	0.13	0.99
	3	49.0	13.8	158	49.9	0.60	0.04	1.00
	6	40.6	15.8	166	55.0	0.57	0.05	1.00
	9	36.3	15.0	136	49.0	0.62	0.07	0.99
Full Fat Washed	0.5	61.2	39.8	183	107	0.66	0.08	0.99
	3	74.4	26.9	208	95.5	0.57	0.07	1.00
	6	56.5	17.8	162	36.9	0.59	0.04	1.00
	9	57.6	47.7	182	135	0.63	0.10	0.99
Low Fat Special	0.5	103	17.1	64.2	26.5	0.76	0.09	1.00
	3	72.9	19.8	92.2	62.2	0.73	0.13	1.00
	6	71.5	12.8	66.2	29.1	0.68	0.07	1.00
	9	78.5	11.4	56.6	35.8	0.65	0.10	1.00
Low Fat Standard	0.5	53.9	9.12	69.6	29.4	0.75	0.06	1.00
	3	61.2	15.4	109	43.4	0.65	0.05	1.00
	6	39.7	7.10	42.5	14.3	0.71	0.03	1.00
	9	29.0	51.6	65.3	41.3	0.69	0.05	1.00
Reduced Fat	0.5	53.8	19.0	77.8	40.8	0.75	0.09	0.99
	3	59.8	10.8	78.5	19.6	0.68	0.03	1.00
	6	29.6	12.5	77.9	43.4	0.67	0.05	1.00
	9	55.5	19.0	59.0	32.1	0.71	0.03	1.00

Table 2-5. Correlation values for maximum compliance (J_{max}), area under adhesion curve, critical stress and strain, G_{BST}, and shape factor constant (n) of the nonlinear region with Sensory texture terms of hand firmness (HFirm), hand springiness (HSpring), hand rate of recovery (HRecov), first bite firmness (MFirm), first bite fracturability (Frac), degree of breakdown (Deg Break), cohesiveness (Cohes), adhesiveness (Adhes), smoothness of mass (Smooth of mass), and residual smoothness of mouth coating (smooth of mouth) broke down by months of aging.

	Age	HFirm	HSpring	HRecov	MFirm	Frac	Deg Break	Cohes	Adhes	Smooth of Mass	Smooth of Mouth
Jmax (1/Pa)	0.5	**0.97***	0.90	0.88	0.90	…	-0.94	-0.92	-0.91	…	…
	3	0.93	…	0.89	0.93	…	-0.90	-0.91	-0.92	-0.91	-0.94
	6	0.95	0.89	0.89	**0.97***	**0.96***	-0.96	-0.95	-0.95	-0.94	-0.92
	9	…	0.88	0.90	0.92	…	**-0.99***	**-0.99***	**-0.97***	**-0.99***	**-0.99***
Area under Adhesion curve (gs)	0.5	0.91	…	…	…	…	-0.88	…	…	…	…
	3	0.90	…	…	0.88	…	…	…	…	…	-0.90
	6	**0.96***	…	…	**0.96***	0.95	-0.95	-0.94	-0.96	-0.93	-0.89
	9	0.92	0.94	0.95	**0.98***	…	**-0.98***	**-0.99***	**-0.99***	**-0.99***	**-0.99***
Critical Stress (Pa)	0.5	…	…	…	0.88	…	…	…	…	…	…
	3	…	…	…	…	…	…	…	…	…	…
	6	0.89	0.93	0.94	0.90	0.90	-0.91	-0.92	-0.91	-0.93	-0.93
	9	0.91	0.95	0.95	**0.96***	0.94	**-0.98***	**-0.98***	**-0.96***	**-0.96***	**-0.96***
Critical Strain	0.5	…	0.91	0.94	0.94	…	…	-0.89	-0.90	-0.88	-0.90
	3	0.91	0.95	0.93	0.90	0.88	-0.92	-0.91	-0.91	-0.91	-0.89
	6	0.93	**0.97***	**0.98***	0.95	0.95	-0.96	**-0.97***	-0.95	**-0.98***	**-0.98***
	9	0.92	0.91	0.92	0.96	…	-0.89	-0.93	**-0.96***	-0.93	-0.92
Gbst	0.5	…	-0.88	…	…	…	0.90	0.90	0.91	0.93	…
	3	…	-0.94	-0.94	-0.91	-0.95	0.93	0.91	0.91	0.92	0.89
	6	…	**-0.96***	-0.96	-0.87	-0.92	0.90	0.91	…	0.92	0.95
	9	…	-0.93	-0.94	-0.90	…	…	…	…	…	…
n	0.5	…	0.95	0.94	0.92	…	-0.95	-0.96	**-0.96***	**-0.98***	-0.96
	3	…	…	…	…	…	…	…	…	…	…
	6	…	**0.97***	**0.97***	0.91	0.94	-0.92	-0.93	-0.88	-0.94	**-0.97***
	9	…	…	…	…	0.94	**-0.97***	-0.94	-0.90	-0.93	-0.94

Values on chart represent $p<0.05$, * refers to $p<0.01$.

Table 2-6. Correlation values for torsional fracture at strain rates of 0.04, 0.4 and 4.0 1/s with Sensory texture terms of hand firmness (HFirm), hand springiness (HSpring), hand rate of recovery (HRecov), first bite firmness (MFirm), first bite fracturability (Frac), degree of breakdown (Deg Break), cohesiveness (Cohes), adhesiveness (Adhes), smoothness of mass (Smooth of mass), and residual smoothness of mouth coating (smooth of mouth) broke down by months of aging.

	Age	HFirm	HSpring	HRecov	MFirm	Frac	Deg Break	Cohes	Adhes	Smooth of Mass	Smooth of Mouth
Fracture Stress (0.04 1/s)	0.5	…	…	…	…	…	…	…	…	…	…
	3	…	…	…	…	…	…	…	…	…	…
	6	**-0.96***	**-0.98***	**-0.99***	**-0.98***	**-0.98***	**0.98***	**0.99***	**0.97***	**0.99***	**0.99***
	9	...	-0.89	-0.90	-0.89	-0.89	0.95	0.93	0.90	0.92	0.91
Fracture Strain (0.04 1/s)	0.5	0.94	…	…	…	…	-0.90	…	…	…	…
	3	0.89	0.92	0.92	0.91	**0.96***	-0.92	…	…	…	…
	6	…	…	…	…	…	…	…	…	…	…
	9	…	…	…	…	…	…	…	…	…	…
Fracture Modulus (0.04 1/s)	0.5	**-0.96***	-0.93	-0.91	-0.92	…	**0.97***	0.95	0.94	0.92	…
	3	-0.95	**-0.99***	**-0.98***	**-0.96***	**-0.98***	**0.98***	**0.97***	**0.96***	**0.97***	0.95
	6	…	-0.91	-0.92	…	…	…	0.88	…	0.91	0.91
	9	-0.91	**-0.97***	**-0.98***	-0.95	…	0.88	0.89	0.89	…	…
Fracture Stress (0.4 1/s)	0.5	…	…	…	…	-0.89	…	…	…	…	…
	3	…	…	…	…	…	…	…	…	…	…
	6	**-0.97***	…	…	-0.93	-0.92	0.94	0.92	0.96	0.90	…
	9	…	…	…	…	…	**0.96***	0.94	0.90	0.94	0.94
Fracture Strain (0.4 1/s)	0.5	…	0.94	0.96	0.94	…	-0.89	-0.92	-0.93	-0.93	-0.94
	3	…	…	…	…	…	…	…	…	…	…
	6	…	…	…	…	…	…	…	…	…	…
	9	…	…	…	…	…	…	…	…	…	…
Fracture Modulus (0.4 1/s)	0.5	…	…	…	…	…	0.90	0.88	0.89	0.90	…
	3	…	…	…	…	…	…	…	…	…	…
	6	-0.90	-0.93	-0.93	-0.96	-0.95	0.94	0.95	0.92	0.96	0.95
	9	…	…	…	…	…	…	…	…	…	…
Fracture Stress (4.0 1/s)	0.5	…	…	…	…	…	…	…	…	…	…
	3	…	…	…	…	…	…	…	…	…	…
	6	…	…	…	…	…	…	…	…	…	…
	9	…	…	…	…	…	…	…	…	…	…
Fracture Strain (4.0 1/s)	0.5	0.89	0.94	**0.96***	0.96	…	-0.90	-0.92	-0.93	-0.92	-0.93
	3	**0.99***	**0.99***	**0.99***	**0.99***	0.96	**-0.99***	**-0.99***	**-0.99***	**-0.99***	**-0.99***
	6	…	…	…	…	…	…	…	…	…	…
	9	0.88	0.94	0.95	0.92	…	…	…	…	…	…
Fracture Modulus (4.0 1/s)	0.5	…	…	…	…	…	…	…	…	…	…
	3	-0.96	**-0.97***	**-0.98***	**-0.98***	**-0.97***	**0.98***	**0.98***	**0.98***	**0.99***	**0.97***
	6	…	…	…	…	…	…	…	…	…	…
	9	…	…	…	…	…	…	…	…	…	…

Values on chart represent $p<0.05$, * refers to $p<0.01$.

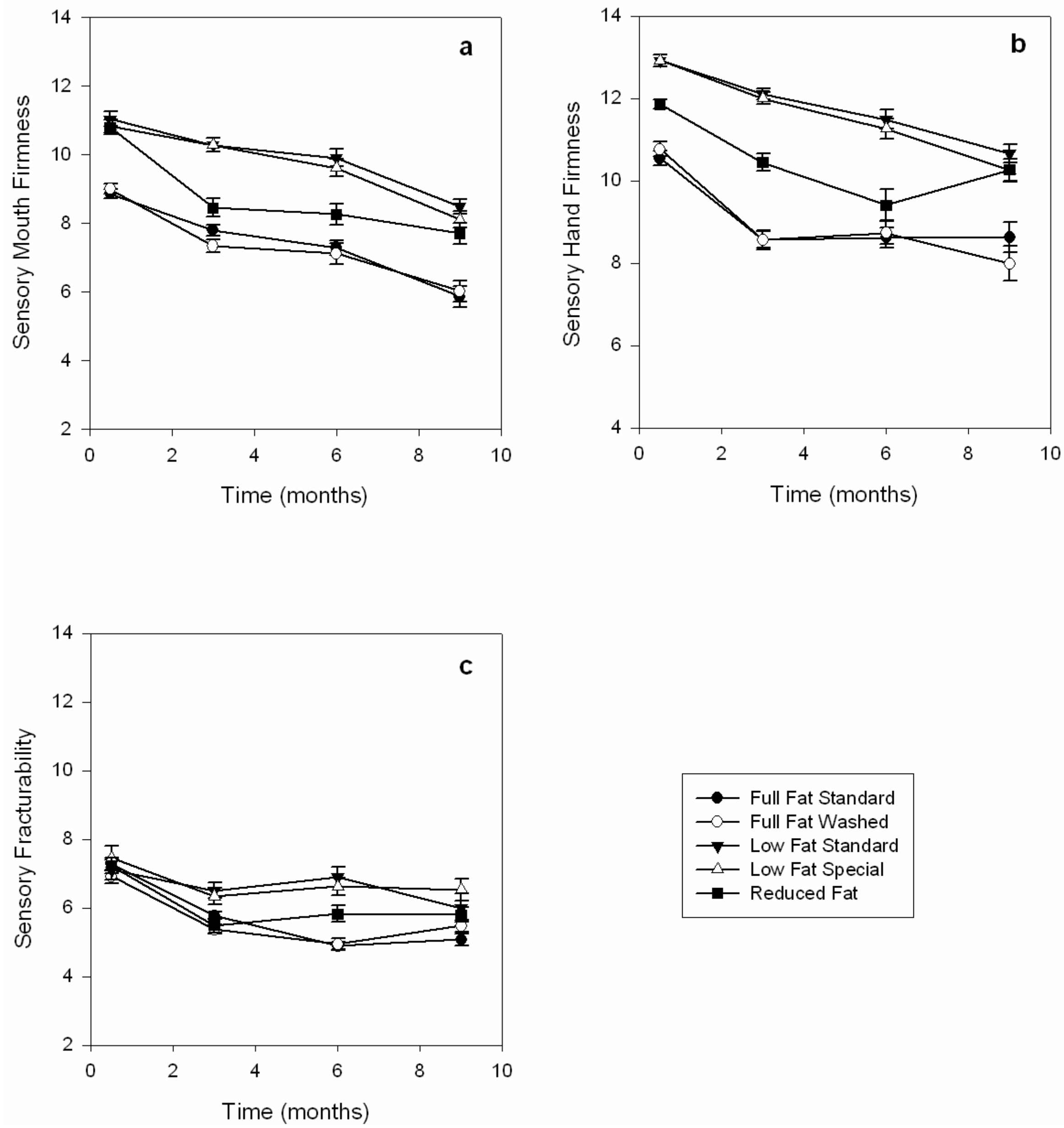

Figure 2-1. Descriptive Sensory analysis of lexicon terms fracturability (a), hand firmness (b), and first bite mouth firmness (c). Error bars represent the standard error of the mean.

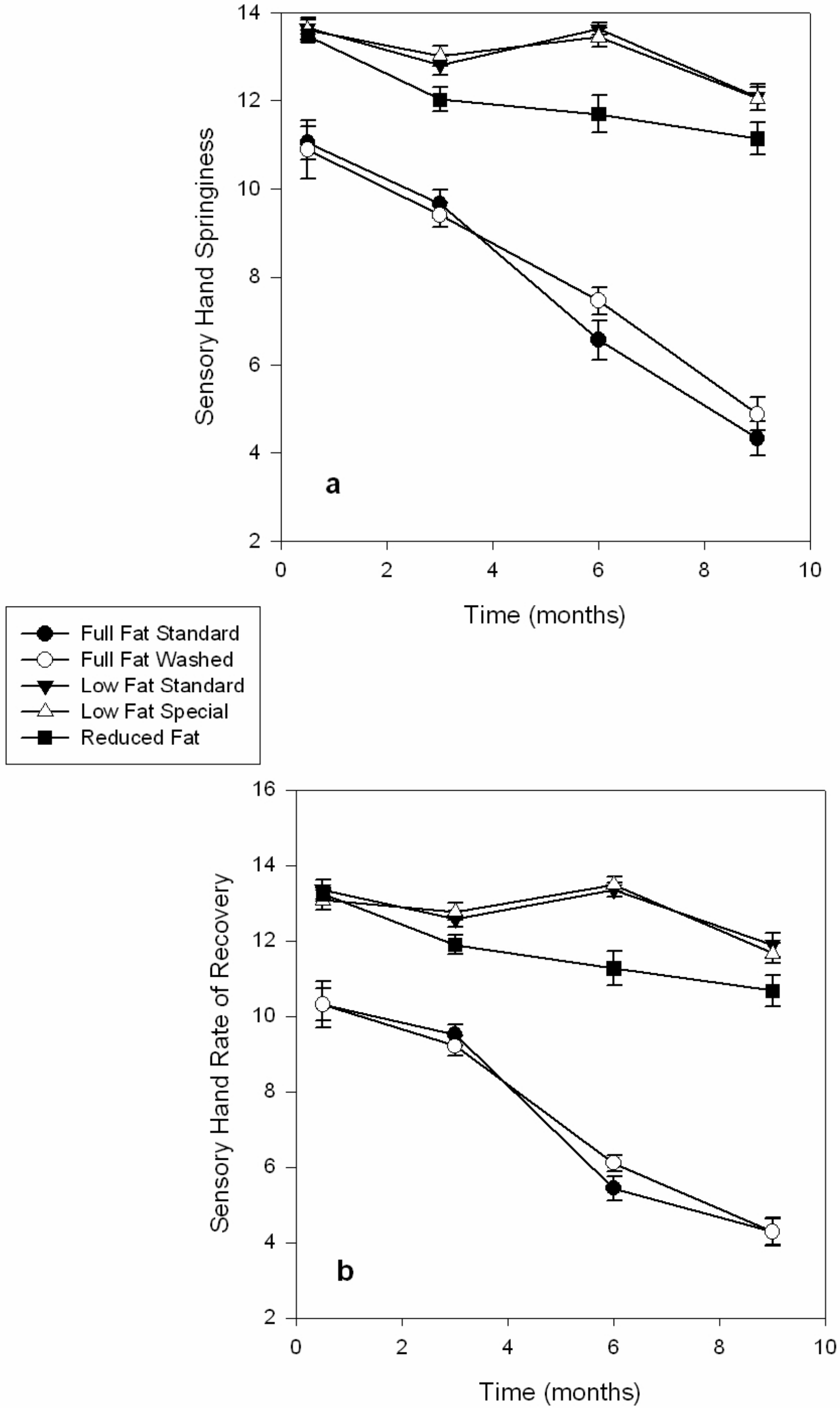

Figure 2-2. Descriptive Sensory analysis of hand measured lexicon terms springiness (a) and rate of recovery (b). Error bars represent the standard error of the mean.

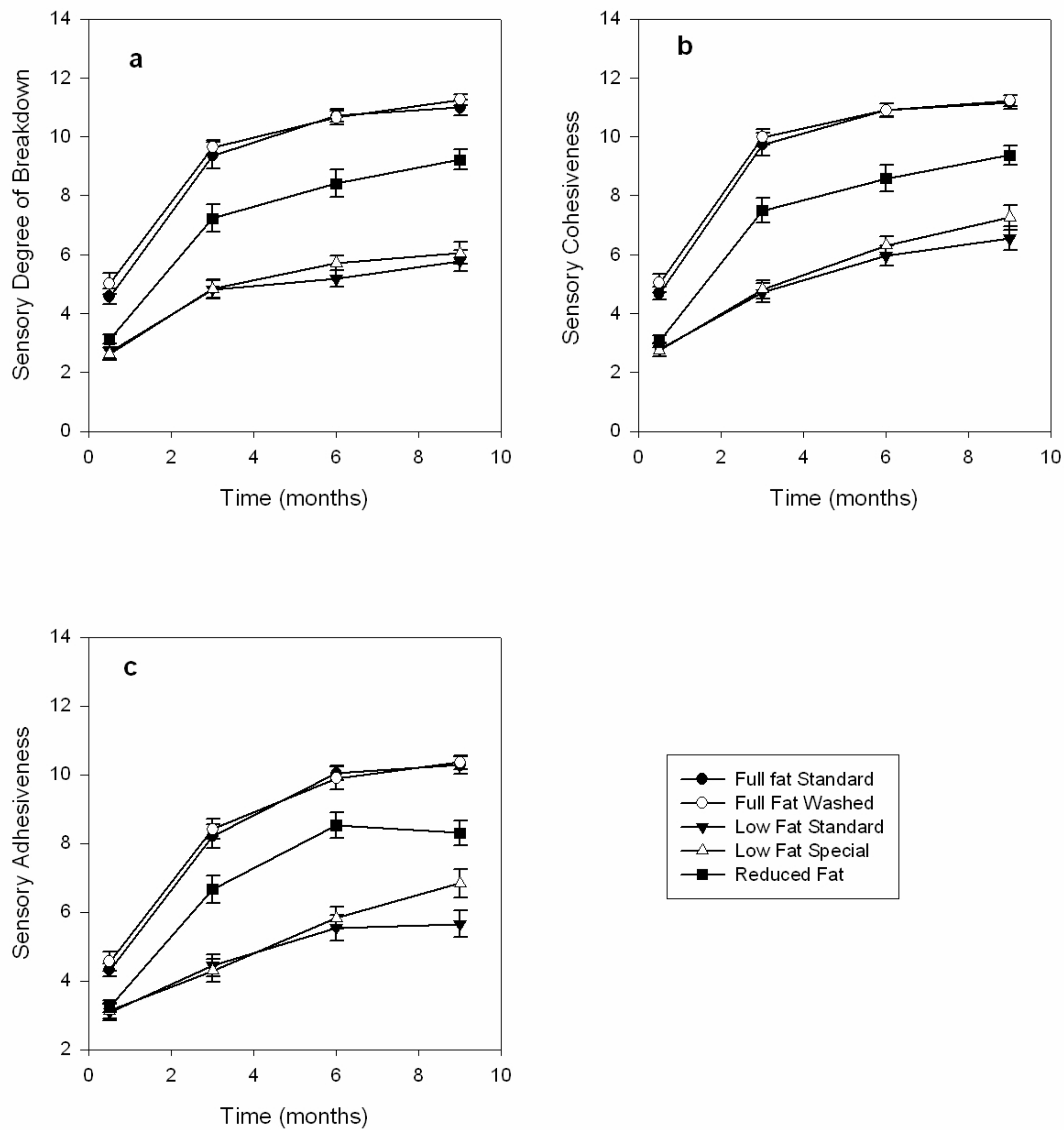

Figure 2-3. Descriptive Sensory analysis of lexicon terms degree of breakdown (a), cohesiveness (b), and adhesiveness (c). Error bars represent the standard error of the mean.

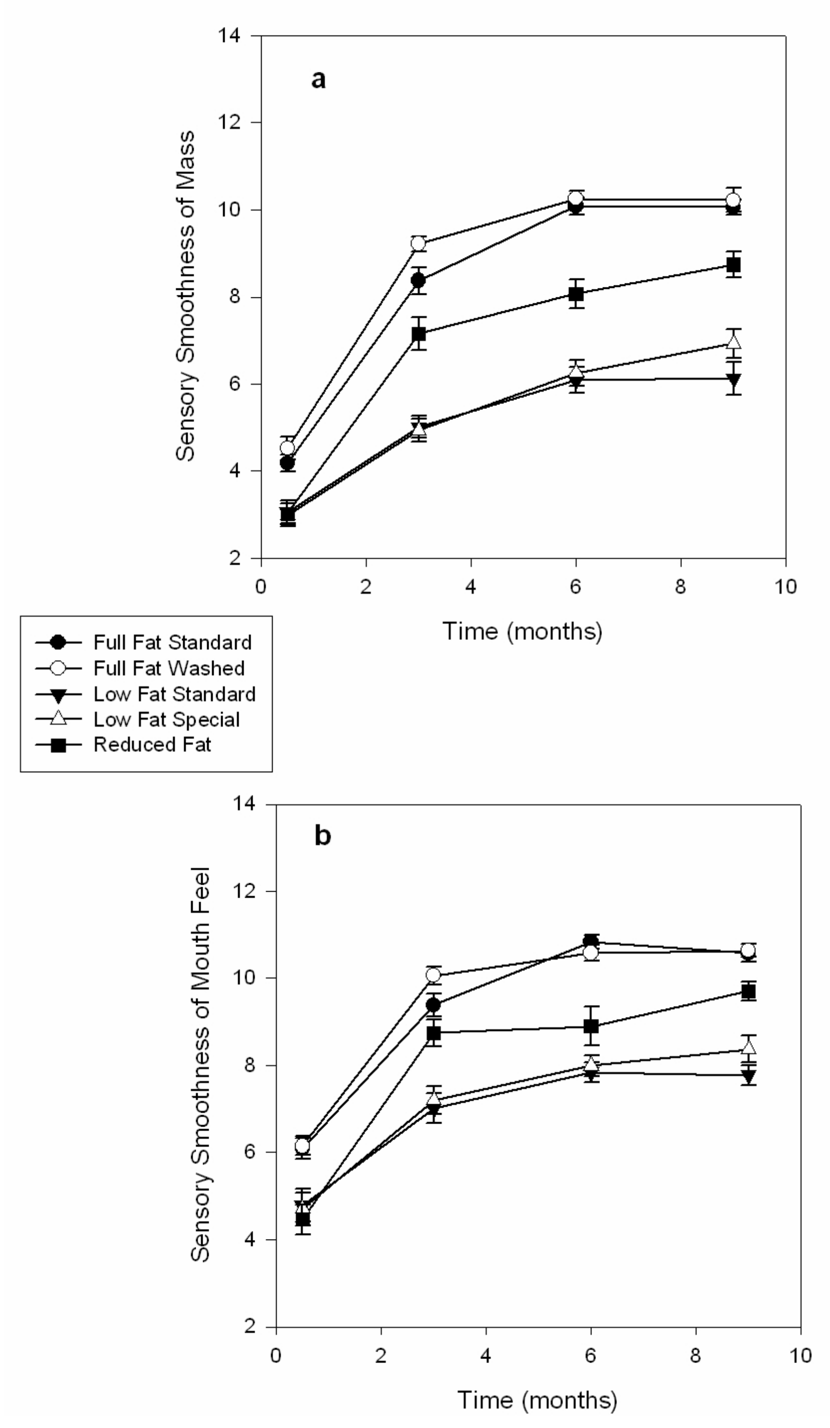

Figure 2-4. Descriptive Sensory analysis of breakdown lexicon terms smoothness of mass (a) and Smoothness of mouth feel (b). Error bars represent the standard error of the mean.

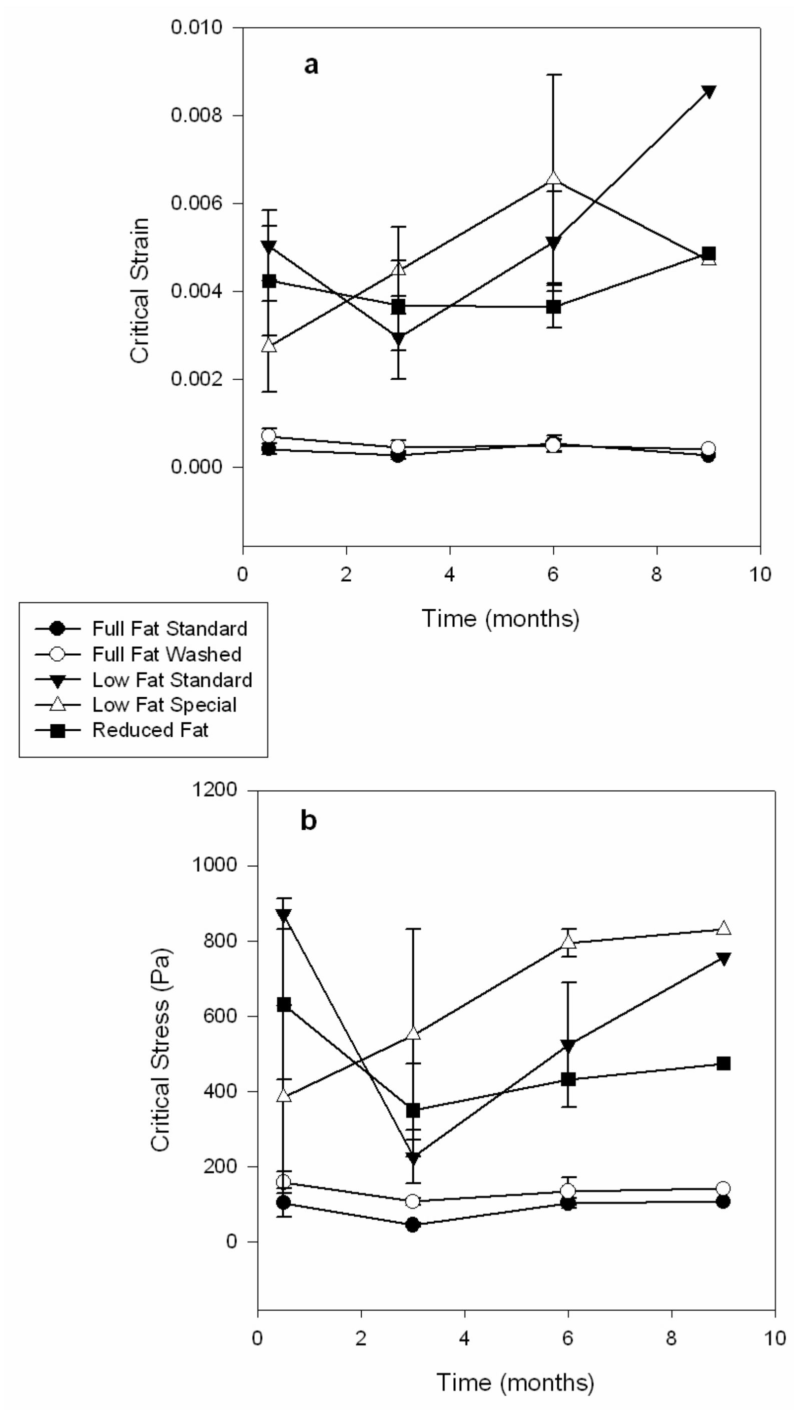

Figure 2-5. Critical Strain (a) and Stress (b) values for stress sweeps conducted at 10 Hz. Error bars represent the standard error of the mean.

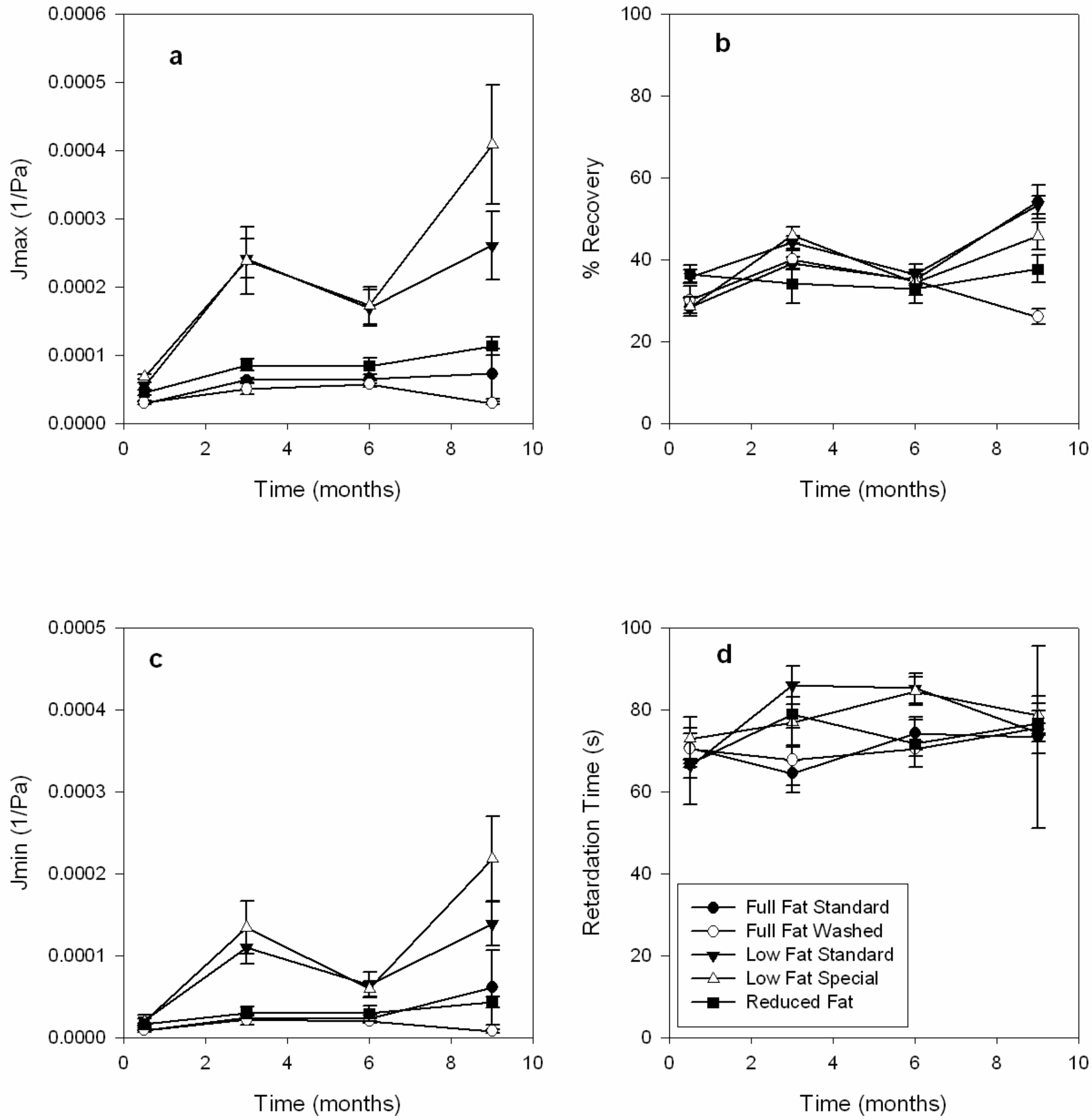

Figure 2-6. Creep/Recovery test conducted at 150 Pa, results of J_{max} (a), percent recovery (b), J_{min} (c), and retardation time (d) were calculated. Error bars represent the standard error of the mean.

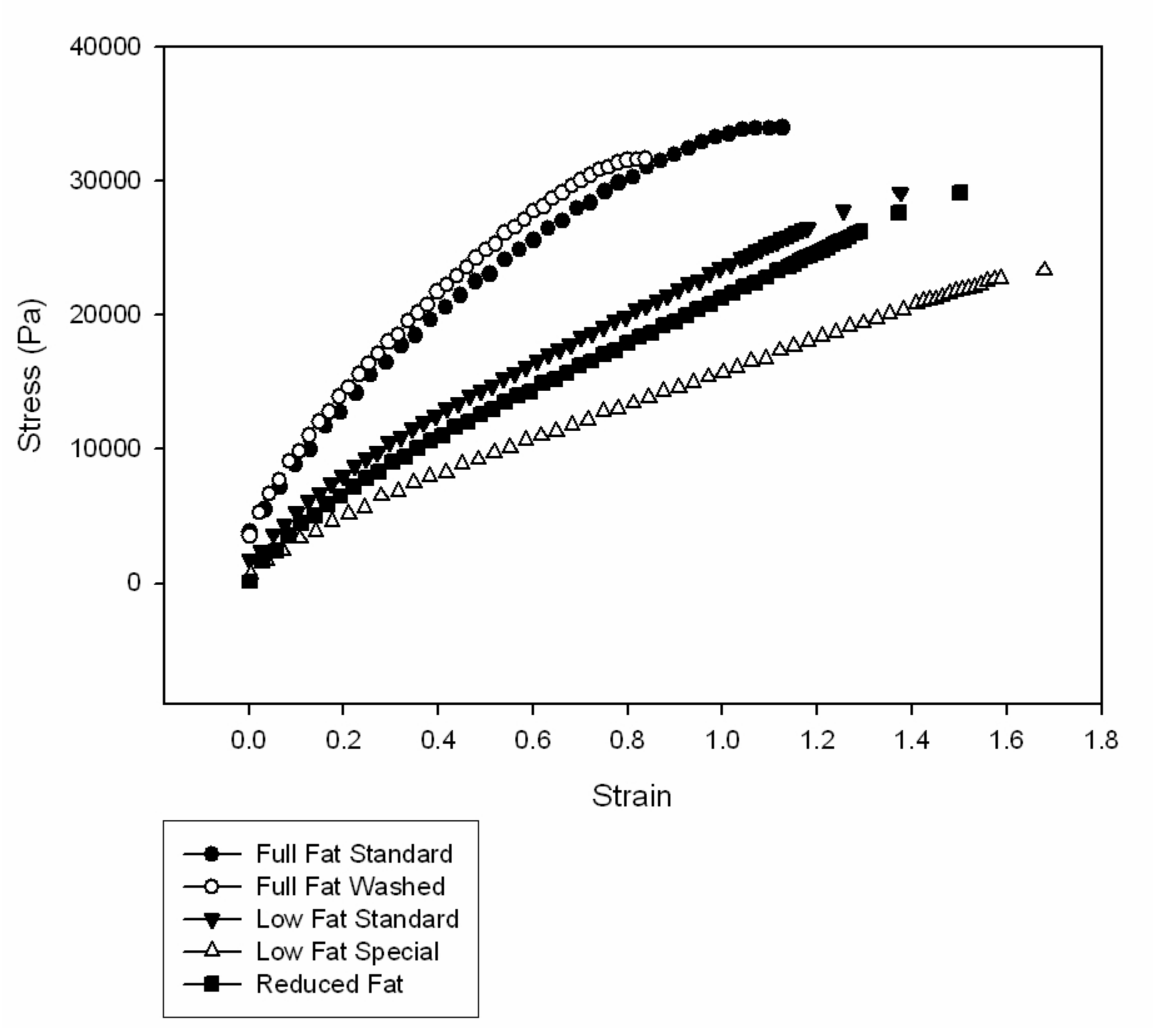

Figure 2-7. Non-linear fracture curves for Cheddar cheeses of varying fat contents at 6 months of age. Curves show every fifth data point improve clarity.

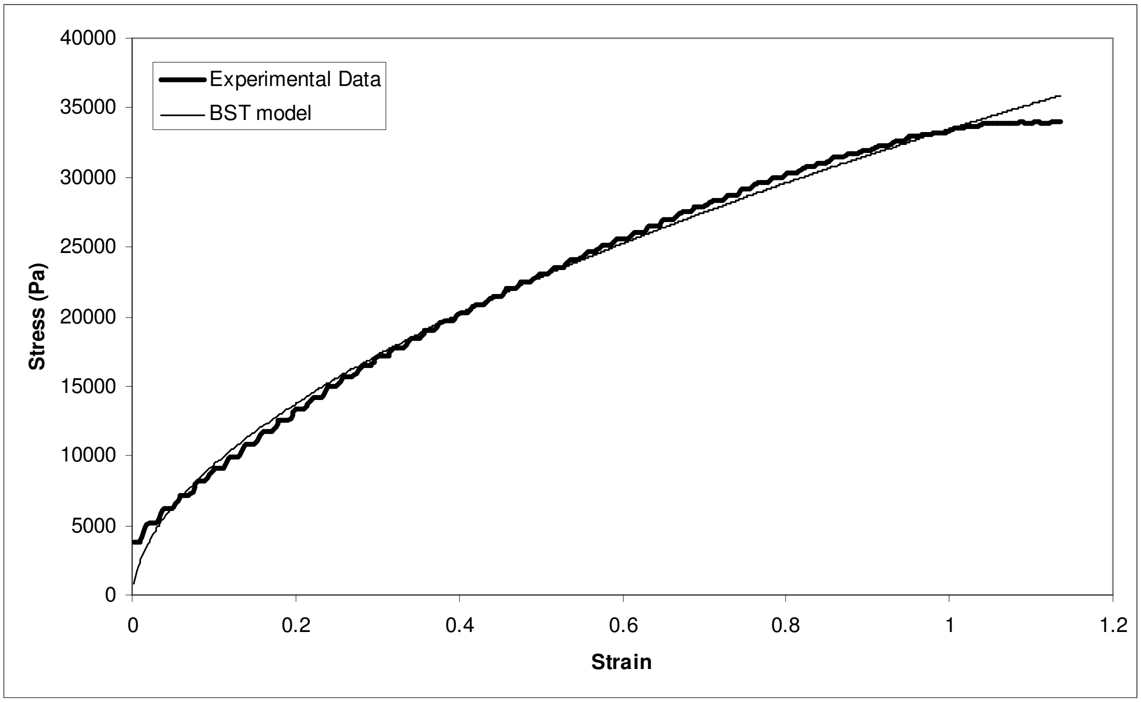

Figure 2-8. Actual data and BST equation fit for full fat standard Cheddar cheese at 6 months of age.

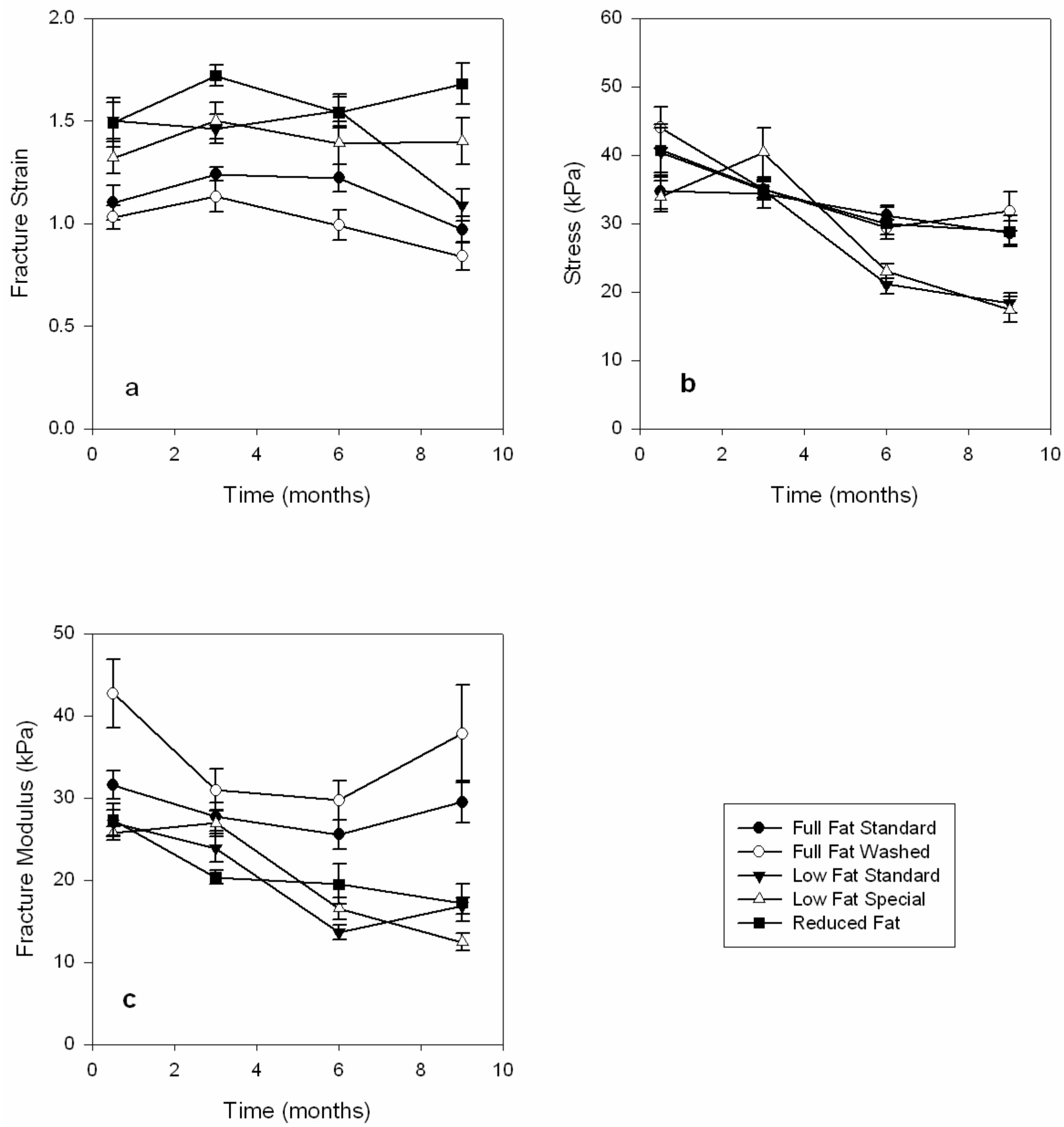

Figure 2-9. Torsional fracture strain (a), stress (b) and modulus (c) for Cheddar cheese tested at a strain rate of 0.41 1/s. Error bars represent the standard error of the mean.

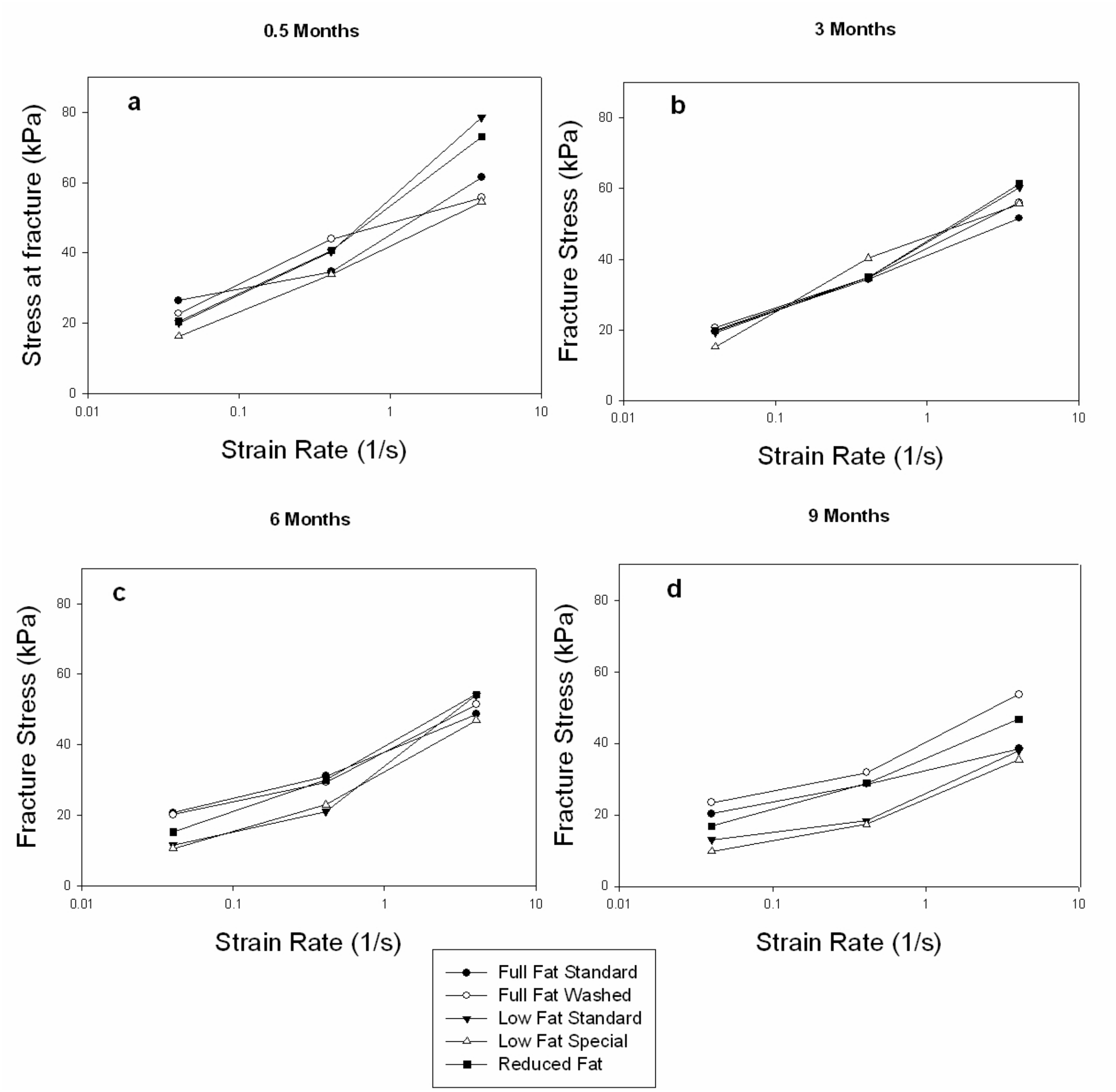

Figure 2-10. Rate effects on torsional fracture stress of Cheddar cheese at 0.5 months (a), 3 months (b), 6 months (c), and 9 months (d) of aging.

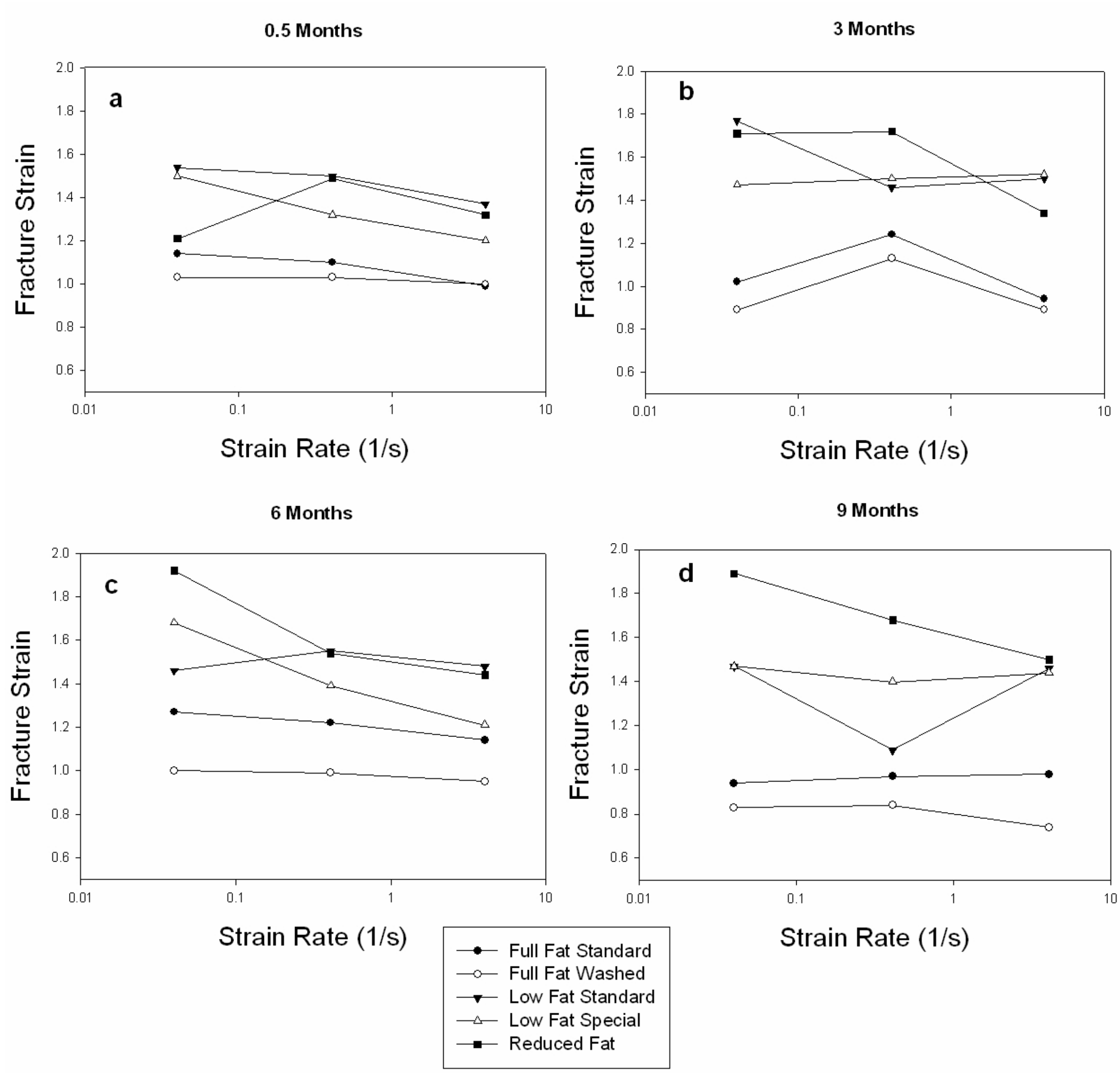

Figure 2-11. Rate effects on torsional fracture strain of Cheddar cheese at 0.5 months (a), 3 months (b), 6 months (c), and 9 months (d) of aging.

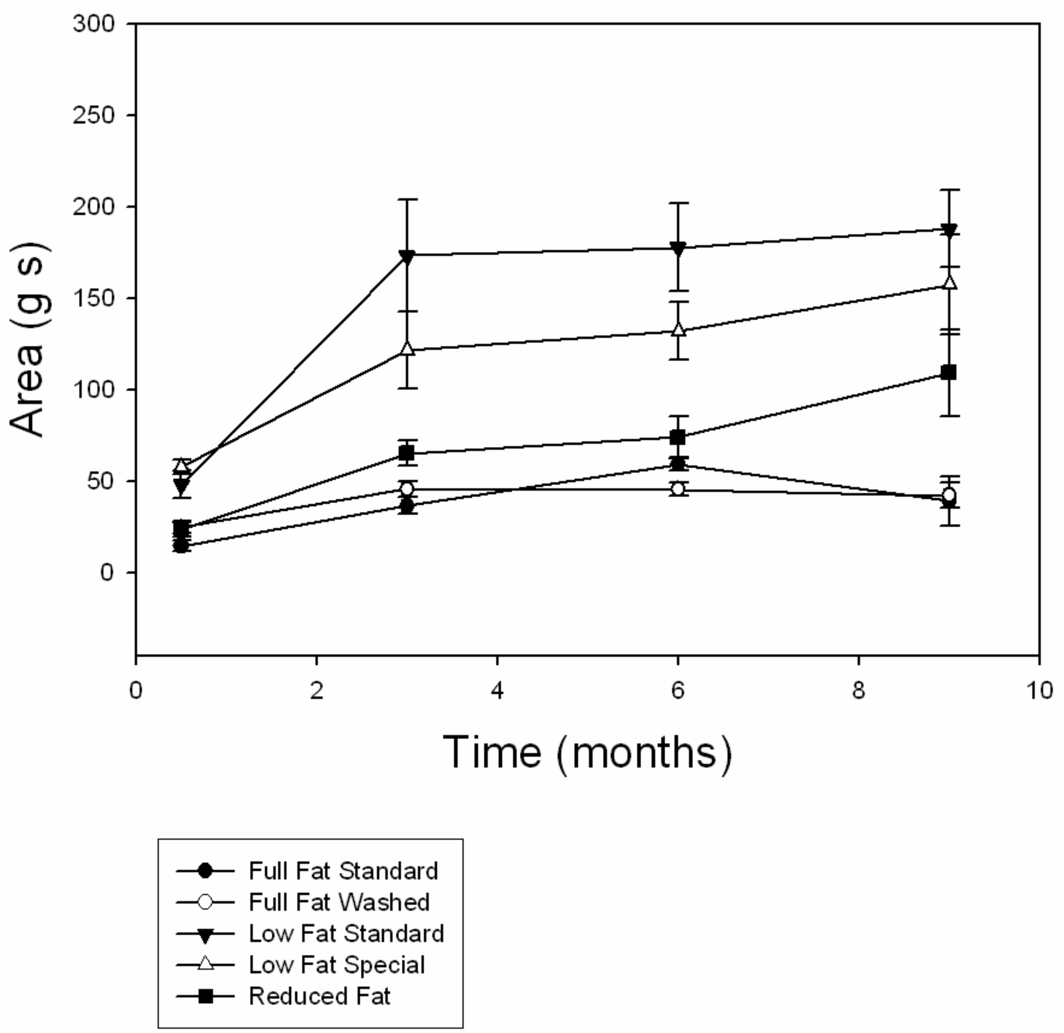

Figure 2-12. Area under the adhesion curve for differing fat contents of Cheddar cheese. Error bars represent the standard error of the mean.

3. Determining the Effect of Fat Content on Cheddar Cheese During the First Three Months of Aging

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Introduction

Fat content reduction in cheese has long been a goal for consumers who desire healthier alternatives to current products. However, many of the current lower fat cheeses available have undesirable aspects such as visual differences and rubbery texture (Mistry, 2001). These differences stem in part from the lower fat to protein ratio resulting in a more dense protein structure making the cheese firmer (Johnson and Chen, 1995). Aging also plays a major role in final texture of a cheese. This occurs as a result of hydrolysis of the protein structure, which results in, as it ages, a more deformable and less firm cheese (Banks, 2007).

Descriptive sensory analysis has often been used to characterize cheese texture differences (Brown et al., 2003, Carunchia Whetstine et al., 2007, Yates and Drake, 2007). Descriptive sensory testing utilizes a sensory language (lexicon) in conjunction with trained panelists to yield information on the textural aspects of cheese relating to hand, first bite, and breakdown (chewing) evaluation. While these tests provide information into the human response, they do not provide direct information on the structure of the cheese.

In order to understand the links among textural properties and cheese structure, fundamental rheological tests must be conducted (Foegeding and Drake, 2007). These tests are conducted in three regions of a materials behavior, the linear region, non-linear region, and fracture point. Non-linear testing involves probing a material at a level low enough that the storage modulus (G') and the loss modulus (G'') are not dependant on stress or strain level (Steffe, 1996). On the opposite end of the spectrum, the fracture point is the stress and strain level at which a material breaks apart. In between these two regions is the non-linear region, which shows a stress/strain dependant behavior but does not go as far as material fracture. All of these regions are important in understanding structural properties of a material and how that is applied to texture.

Determining what role fat content plays in this structure is important in understanding how to improve the texture of low fat cheese. The filled gel model has been used to describe the role of fat in hard and semi-hard cheeses (Visser, 1991). The filled gel model consists of a continuous network with inter-dispersed filler particles. The filler particles can either interact with the network which affects the overall structure of the material depending on the properties of the filler or the filler can not interact which results in a simple relationship where in the material is weakened with increasing filler volume (van Vliet, 1988). A filled gel model with the protein structure interacting with the fat filler has been suggested for Gouda cheese (Visser, 1991). This interaction is also greatly affected by temperature of the cheese. The fat in the cheese is predominantly solid at refrigeration temperatures, but when warmed to room temperature, the fat is predominantly liquid. This has a dramatic effect on the overall texture of the cheese (Visser, 1991). This suggests that temperature of the fat and fat content can influence the texture of the cheese.

The previous study conducted looked at how texture and structure of low, reduced, and full fat Cheddar cheese changed as the aged (chapter 2). Samples of 33%, 16%, and 6% fat were tested at 0.5, 3, 6, and 9 months of age. Descriptive sensory analysis was used to look at the different aspects of texture and how these changed with both fat content and time. Low fat (6% fat) cheeses were firmer and more deformable than full fat (33% fat) cheeses.

Full fat cheeses did breakdown more than lower fat cheeses. Reduced fat (16% fat) cheeses consistently fell in between these cheeses in a stepwise fashion. Many of the sensory terms, primarily terms related to breakdown, showed large changes in the first 3 months of aging, making this age range a primary area of interest. Rheological measurements were conducted in the previous study (chapter 2) using creep/recovery, stress sweeps, torsional fracture and modeling of the non-linear region, as well as adhesion tests. Of these tests, critical stress and strain, which determines the point of deviation from the linear viscoelastic relationship, showed the highest correlation with sensory terms related to breakdown during chewing. These sensory terms have showed very little relation with rheological tests in past studies (Brown et al., 2003). This strong relationship was attributed to these properties probing the cheese structure when it initially starts to breakdown. Fracture values showed correlations with firmness terms, in accordance with other studies of cheese texture (Brown et al., 2003, Carunchia Whetstine et al., 2007, Gwartney et al., 2002). Consistent correlations with sensory breakdown terms and fracture modulus were also seen in the previous study, but only at 6 months of age and older. These correlations were seen with rheological tests that had not been used in the previous studies, such as non-linear curve shape and critical stress and strain.

Taking the above mentioned results into account, the current study was assembled. As was shown in the first study, the most significant changes with regards to age were seen in the first 3 months, so this investigation was for 12 weeks. With this time scale in mind, a more graduated set of fat contents was chosen (3%, 8%, 13%, 18%, 23%, 28%, and 33%), representing the lowest and highest fat contents from the first study. Descriptive sensory analysis, which showed good differentiation of the different fat contents in chapter 2, was used again unchanged. Rheological tests were adjusted to better fit the results found in chapter 2. Torsional fracture was limited to one strain rate for testing. Temperature sweeps were chosen to look at the filled gel temperature effect described by Visser (1991). A two cycle recoverable energy test was added to better understand the non-linear region of the cheeses. Stress sweeps were kept because of their strong relationships with breakdown terms as well as their use in determining the linear viscoelastic region for the frequency sweeps. This study was also undertaken to gain a better understanding as to how the filled gel model can be applied to Cheddar cheese.

MATERIALS AND METHODS

Cheddar Cheese Production

Seven Cheddar cheeses were produced with differing fat contents at the Utah State University Dairy Plant. Cheeses were produced at 3%, 8%, 13%, 18%, 23%, 28%, and 33% fat contents. Two replications of each cheese were produced.

The cheeses were kept at Utah State University for aging at 8ºC for 9 months. Sample blocks were shipped to North Carolina State University at 2, 4, 8, and 12 weeks of age for texture testing.

Sensory Analysis

Descriptive sensory analysis was conducted using the methods laid out by Brown et al (2003) and Yates and Drake (2007) and described in chapter 2.

Rheological Analysis

Determination of the Linear Viscoelastic Region. Stress sweeps of cheeses were done using a Stress Tech controlled stress rheometer (ATS Rheosystems, Bordentown, NJ) as described by chapter 2.

Controlled Temperature Frequency Sweeps. Frequency sweeps for all cheeses were conducted using a Stress Tech controlled stress rheometer (ATS Rheosystems, Bordentown, NJ) with the same instrument geometry and sample fixation as described in chapter 2. Sweeps were conducted from 0.1 to 10 Hz at 150 Pa, which was determined to be within the linear viscoealstic region. All cheeses were tested at 4 temperatures 10ºC, 15 ºC, 20 ºC, and 25 ºC.

Large Strain Torsion analysis. Non-linear and fracture analysis were conducted using the torsion method adapted from Brown et al (2003). Cheese samples were taken from sample blocks using an 18 mm diameter cork borer, were set out on the counter in sealed plastic bags for 8 hours to allow them to come to room temperature (25ºC ±4ºC), and then cut to a length of 28 mm. These samples had notched, plastic disks (Gel Consultants. Raleigh, NC) glued to each end of the sample using cyanoacrylate glue (Loctite 401: Loctite Corp. Rocky Hill, CT).

Samples were then ground into a capstan shape using a precision grinding machine (Model GCPM92 US, Gel Consultants. Raleigh, NC). Samples were tested using a Haake VT-550 rotational viscometer (Gerbruder Haake GmbH, Karlsruhe, Germany) with an attachment designed to facilitate torsion testing (Truong and Daubert, 2000). Ten samples were tested for each replication at a strain rate of $0.45s^{-1}$. Fracture stress, strain, and modulus were calculated using the equations laid out in chapter 2.

Twin cycle compression. Compression of cheeses was conducted in a twin cycle pattern using an Instron 5524 universal testing machine (Norwood, MA) based on tests compression/decompression tests conducted by van den Berg (2008). Sample blocks were placed in sealed plastic bags for 8 hours to allow them to come to room temperature (25ºC ±4ºC). Samples were cut from block using a 15.6 mm diameter cork borer; these cylinders were then cut to a length of 17 mm. Instrument testing surfaces were coated with mineral and samples were placed on the bottom plate and the top plate was brought into contact with the top of the sample. Samples were compressed to 20%, 25%, and 30% of their initial height corresponding to true strains of 0.18, 0.22, and 0.26 respectively. Samples were compressed at a rate of 0.83 mm/s until target strain was reached, then the strain was removed at the same rate then reapplied to the same strain (based on initial height) at the same rate and removed again.

Percent recoverable energy was calculated using the area of the two force-distance curves for compression. Areas of each curve were calculated using Simpson's rule. Percent recoverable energy ($\%energy_{rec}$) was then calculated as a work ratio of the second curve (a_2) and the first curve (a_1).

$$\%energy_{rec} = \frac{a_2}{a_1}(100) \qquad \text{(eq. 1)}$$

Statisical Analysis

All statistical analysis was conducted using SAS statistical software (version 9.1, SAS Institute Inc., Cary, NC) in the method described in chapter 2.

Results and Discussion

Proximate Analysis

Data for proximate analysis of the cheeses conducted at Utah State University is presented in Table 1. The data shows that actual fat contents were very close to their target values. Moisture content increased as fat content decreased, this is consistent with how the washed curd processing method used in making low fat cheese affects final moisture (Scott, 1986). Protein content also increased slightly as fat content decreased; this is consistent with trends known for low fat cheeses (Johnson and Chen, 1995).

Descriptive Sensory Analysis

Main Effects and Interactions for Sensory Results. Mixed model statistical analysis for determination of differences in sensory terms is summarized in Table 2. All of the terms were differentiated by fat content and none of the cheeses were different with respect to age. Only two terms, smoothness of mass and cohesiveness, showed interrelationships between age and fat content changes. The fat content effect seen in the current study was also noted in the previous study (chapter 2). The data from chapter 2 also showed age effects on almost all of the sensory terms as well as age/fat content interaction that were shown on all of the terms with the exception of terms related to sensory firmness. The lack of age effects in the current data means that the cheeses are not differentiated as they age.

Descriptive Sensory Terms. Sensory terms were group in the same fashion as the sensory data from chapter 2, with terms grouped into three categories based on rheological considerations. Sensory terms for firmness, both first bite (Fig. 1b) and hand (Fig. 1a) evaluation, as well as first bite fracturability (Fig. 1c), were grouped. Firmness terms showed decreasing trends with increasing fat content; while this trend is similar to the trend seen in the previous study (chapter 2), cheeses in the current study showed much higher values in firmness with the full fat cheeses around 8 to 12 and lower fat cheeses ranging from 10 to 15. These values in the previous study were approximately 2 units lower for almost all of the cheeses across the board. This means that the current cheeses, due to the variable nature of cheese making, are consistently firmer than the cheeses from the previous study. Sensory fracturability, on the other hand, did not appear to show any difference between the previous study and the current one, with both studies showing little differentiation of the cheeses by fat content. The previous study does show a drop within the first 3 months on all cheeses between 1 and 2 points, the current study shows a similar trend between 2 and 12 weeks. This indicates a decrease in the number of particles a sample breaks into during the first bite of the cheese.

Sensory terms for hand springiness (Fig. 2a) and hand rate of recovery (Fig. 2b) were grouped, as they both probe the deformation of a material at below fracture levels and relate to its elastic nature. Springiness and rate of recovery showed very little separation based on fat content, with all of the cheeses grouping around the very top end of the scale (15). The lower fat cheeses from chapter 2 showed fairly consistent values for both terms (around 13-14). Higher fat cheeses however, were initially around 3 points higher in the current study than they were previously and did not change with age rather than the 1 point drop in both terms within the first three months observed for cheeses in chapter 2.

Descriptive terms related to breakdown of the cheeses during chewing, degree of breakdown (Fig. 3a), cohesiveness (Fig. 3b), adhesiveness (Fig. 3c) and smoothness terms for both the chewed mass (Fig. 4a) and residual mouth coating (Fig. 4b), all showed similar trends. These sensory terms differentiate by fat content, with the full fat cheeses breaking down more than the lower fat cheeses. While these terms had no aging effects, the highest fat content (33% and 28%) cheeses showed trends toward more breakdown as they aged.

The low fat cheeses alternatively, remained relatively constant as they aged. This resulted in cheeses, which all showed roughly the same initial breakdown, becoming more separated by fat content as they aged. While the behavior of these breakdown terms was consistent with what was seen in the previous work (chapter 2), the scale of the differences was not. The cheeses in the current study all started between 0 and 1 for all of the terms with the lower fats showing little change and the higher fats only showing a change of at most 3 point for the 12 week period. The cheeses from the pervious study in contrast, showed changes in the first 3 months more in the 4 to 5 point range with higher starting point in all terms by around 2 points.

Overall, the lower fat cheeses were more firm and broke down less than the full fat cheeses. Differences in firmness among the different fat contents showed that firmness increased as fat content decreased. Breakdown terms showed some differentiation among fat contents as cheeses aged, with the largest differences seen at 12 weeks. Springiness terms did not differentiate the cheeses with respect to fat content, nor did they change with age. In earlier research (chapter 2), it was found that that the sensory terms changed the most over the first three months, while these cheeses showed very little changes during the same amount of time. It is possible that additional time is needed for these cheeses to reflect age differences because they appeared to be starting from a different structure than was observed in the previous study.

Viscoelastic properties

Frequency Sweeps. Mechanical spectra were determined within the linear viscoelastic for a range of temperatures and the storage modulus was used to represent these spectra (Fig. 5). All cheeses showed increasing G′ with increasing frequencies indicating the viscoelastic nature of cheese. The major differences seen were in variations between refrigeration (10ºC) and room temperature (25ºC). These differences are also magnified by fat content, with the difference between the two temperatures increasing as fat content increases. At refrigeration temperature, the cheeses showed differences across the changes in fat content, with fat contents grouping together by frequency dependent behavior. At 2 weeks of age, the two highest fat cheeses showing similar frequency behavior, the three middle range fat cheeses (23%, 18%, and 8% fat), and two lower fat cheeses being grouped (13% and 3% fat). This shifted by 12 weeks, with the cheeses decreasing stepwise from the highest fat cheese to the lowest fat cheese, with the exception of 8% and 13% which follow the same trend. At room temperature, the cheeses showed minor differences at 2 weeks (Fig. 6a) and no major differences at 12 weeks (Fig. 6b), with the lowest fat contents (3% and 8%) having higher G′ values. This behavior was explored further by looking at how G′ changes with temperature at the four different aging times (Fig. 7). There was a drop off in G′ at temperatures above 15ºC and from that point on the fat content differences were continuously diminished to 25ºC, where the differences were not consistent at any of the time points. This temperature behavior can be attributed to the phase change of the fat in the cheese; with fat in a predominantly solid form at 10°C and at 25ºC being predominantly liquid. This behavior was described by Visser (1991), where differences in the range of 14ºC to 26ºC were attributed to change in rigidity of the fat particles due crystallization. This also indicates that the fat was acting as an active filler in the system. Fig. 8 shows that at 10°C (where fat is more firm), the higher the fat content (Fig. 8a) the higher the storage modulus. This corresponds in general with a decrease in protein content (Fig. 8b); thus it is not due to an increase in the protein network. This effect is diminished by the fat becoming less firm at 25°C (Fig.8c,d). This is the same active filler behavior suggested for cheese by Visser (1991).

Stress Sweeps. Critical point values from the end of the linear viscoelastic region were divided into critical stress (Fig. 9a) and critical strain values (Fig. 9b). The two lowest fat content cheeses (3% and 8% fat) showed higher critical stress and strain than the cheeses with higher fat contents, which did not show large differentiations among themselves. There were no consistent aging trends seen with any of cheeses, with the exception of the 3% fat content cheese, which showed decreasing critical stress and strain as the cheese aged. This is possibly due to the extremely low fat content meaning the protein network played a much greater role in the cheese structure due to the lower fat to protein ratio and thus was less affected overall by the proteolysis during the first 14 days or so of aging (Lawrence et al., 1987). These values are consistent with what was seen for critical stress and strain in chapter 2. This test probes a material with progressively higher stresses until the material starts to become damaged on the nano or micro-scale, once this breakdown begins, a non-linear relationship is observed.

Non-linear and fracture properties

Twin cycle compression. In order to probe the non-linear region, which was measured by the BST model related n values in chapter 2, a twin cycle compression of cheeses was conducted at three different strains, 0.18 (Fig. 10a), 0.22 (Fig. 10b), and 0.26 (Fig. 10c) and the percent recoverable energy calculated. This showed similar trends across all compression strains with a magnification of differences as strain increased. This test was used because it relates to how much work is required to compress the sample the second time versus the first, which translates to sample breakdown in the non-linear region. Cheeses showed differences due to fat content, with the higher fat content cheeses having lower recoverable energy than the lower fat cheeses. The separation by fat content was seen with the three highest fat levels, the remaining fat contents showed no real differences at any of the time points. This showed that the full fat cheeses breakdown more since it takes much less work to compress the second sample than the first, meaning the sample lost this through small internal cracks yielding or through dissipation of energy either by viscous or frictional internal components (van Vliet and Walstra, 1995). As the cheeses aged, percent recoverable energy decreased, indicating that all of the cheeses broke down more as they aged. This is consistent with the sensory terms evaluated after five chews which showed an increase in perceived breakdown in the cheeses. Van den Berg et al (2008) used a similar energy loss relationship involving a single compression and decompression to study mixed whey protein polysaccharide gels and concluded that breakdown of a material was related to energy loss and this then affected how the material crumbled.

Torsional fracture. Towards the end of the non-linear region, a material reaches a point where it can no longer cope with the increasing stresses and strains applied and the material fractures. Fracture properties have been shown to relate to aspects of sensory texture of cheese (Brown et al., 2003, Carunchia Whetstine et al., 2007, Foegeding and Drake, 2007, Green et al., 1985, Gwartney et al., 2002, Hort et al., 1997, Xiong et al., 2002). Fracture stress, strain, and modulus determined at 0.41 1/s are seen in Fig. 11 for cheeses of varying fat contents. Fracture stress (Fig. 11a) did show some differences by fat content with the lowest two fat contents (3% and 8% fat) being higher than the remaining, higher fat, cheeses which showed no general trends. Fracture strain (Fig. 11b) and modulus (Fig. 11c) did not appear to show any differences among cheeses, with modulus showing slightly higher values for the two lowest fat contents similar to the fracture stress data.

Protein (Fig. 12a) and fat content's (Fig. 12b) relationships with fracture stress provides information as to how the protein network contributes to the texture properties of the cheeses. The two lowest fat, and highest protein, cheeses appear to show the largest differences in fracture stress, this may indicate a stronger protein network that is dominating structure due to the lack of fat. This is opposite of what was seen with the G′ trends for protein and fat content at 10ºC (Fig. 8a, b). This is likely due to the differences in what is measured between the two tests. G′ values are related to how a materials structure behaves by probing it at very low, non-destructive levels. The fat seems to dominate the structure of the material at 10 ºC, since G′ increases with increasing fat content and decreasing protein content. When temperature is increased to 25 ºC (Fig. 8c, d), these differences disappear, indicating that the firmness of the fat is a major contributor to G′ behavior. This is shown in

Fig. 6, where low fat cheeses showed higher G′ rather than the full fat cheeses, which was the case at 10ºC. This indicates that the protein network, not the fat, is the major contributor to cheese structure at room temperature. This is a major indicator of fat acting as an active filler as described by Visser (1991). Fracture tests, by comparison, relate how much force and deformation is required to break a sample into multiple pieces (Foegeding and Drake, 2007). This appears to be measuring the firmer protein network present when the contribution of the fat filler is reduced. This is consistent with conclusions made in chapter 2 relating to the protein networks role in firmness.

Correlation among instrumental rheological terms and descriptive sensory terms.

Correlations among descriptive sensory lexicon terms and fracture stress, strain, and modulus, critical stress and strain, and storage modulus (G′), loss modulus (G″), and complex modulus (G*) at 0.01 Hz (frequency tested that was closest to torsion strain rate) are shown in Table 3. Very few rheological terms showed strong correlations with sensory terms, with the two firmness terms being the only sensory properties consistently correlated with rheological properties seen for the first 8 weeks of aging. Hort et al (1997) and Gwartney et al (2002) have also shown correlation between sensory firmness and rheological fracture terms in previous work. These correlations were also seen in the previous study (chapter 2) with the two sensory firmness terms correlating with fracture terms. Negative correlations with sensory breakdown terms such as degree of breakdown, cohesiveness, and adhesiveness began to appear at the 12 week time point with rheological terms related to the critical point (critical stress and strain). This was found in the previous study (chapter 2) where strong inverse relationships were seen among these terms. These correlations only began to appear at 12 weeks, indicating that perhaps there is structural change around this point. There were no consistent correlations seen among sensory terms and values of G′, G″, and G*, while previous studies have shown relationships between these values and sensory firmness terms for mozzarella and Monterey jack (Brown et al., 2003) as well as for Cheddar cheese (Drake et al., 1999). This is possibly related to the age of these cheeses, which is still relatively young for Cheddar. These correlations may become more apparent as aging progresses, as these cheeses have been shown with other terms that they have not quite reached the aging level seen in the previous study (chapter 2).

Correlation among descriptive sensory terms and percent recoverable energy at the three strains are seen in Table 4. Strong inverse correlations were seen with some of the breakdown terms in the first 2 weeks of aging and the number of correlations increased to all of the sensory breakdown terms from 4 weeks of age onward. This means that as the cheeses are perceived to breakdown more as the percent recoverable energy decreased. Strong correlations were also seen among percent recoverable energy and first bite and hand evaluation sensory terms developed by 4 weeks of aging, with all sensory terms in these categories being strongly correlated by 8 weeks of age. This means that as springiness and firmness of a cheese increased, the percent recoverable energy increased. These strong relationships support the conclusions made in the first study (chapter 2) that the non-linear regions of Cheddar cheese are the most related aspect of structure with what consumers experience when they assess the texture. This idea of the non-linear region of a material being important is supported by information known about oral processing where it is believed that humans assess the hardness of a material not as it breaks, but just as it begins to weaken before fracture (Lucas et al., 2004). This type of behavior would put the sensory response more towards the end of the non-linear region and less at the fracture point.

Xiong et al (2002) has suggested that compression tests relating to sensory should be conducted at lower rates of deformation and higher peak strains. A correlation study looking at sensory hardness and compression parameters over a variety of cheeses showed that the highest correlations occur after the sample fractures in the 70-90% range of compressive height. While this may be true for single compression tests, it did not hold true for the percent recoverable energy test used in the current study. This test showed strong firmness correlations with compressions only in the range of 20-30% of compressive height (below fracture level). This is the result of a test, not designed to look at the fracture point of a material, but the behavior leading up to fracture, which is suggested to be more important in sensing texture (Lucas et al., 2004). Xiong et al (2002) did note that lower rates of compression did show better correlations , this may explain why correlations in the current study were strong, as the compression rate used (0.83 mm/s) was similar to the optimal rate determined by Xiong et al (2002) of 1.0 mm/s.

Conclusion

This study revealed that some of the most important types of rheological tests for determining texture are those that probe the non-linear region. In chapter 2, it was shown that critical stress and strain have strong relationships with sensory breakdown terms. This point, which marks the deviation from linear to non-linear behavior in a material, plays an important role in perceived texture. It is at this point that the cheese first began to breakdown on a nano or micro-scale, and as strain increased the cheese structure degraded until it reached the fracture point. It is this degradation of cheese structure within the non-linear region that appears to show the strongest relationships with the sensory terms used to describe breakdown while chewing. The percent recoverable energy, which probes the non-linear region, showed the strongest correlations with the breakdown terms of any mechanical properties measured in this study. This not only provided very high relationships with the expected breakdown sensory terms, but also with the hand and first bite terms, which also have demonstrated correlations in the past with fracture terms. This suggests that the non-linear region provides one of the best measures of how humans analyze texture in Cheddar cheese.

This study also showed strong support of the filled gel theory and its application to Cheddar cheese. The temperature dependant behavior of the mechanical spectra, revealing differences at low temperatures and much smaller differences at higher temperatures, demonstrated that the fat behaved like an interacting filler within a protein network. Differences in the protein network are also observed as filler content decreases. This was shown as an increase in fracture stress of the lower fat cheeses as well as mechanical spectra data at 25ºC versus 10ºC. This, combined with the increased breakdown seen in the non-linear structure data, imply that fat is acting as a weakening point in the material, and thus as fat content increased the cheese became weaker and breaks down more. This indicates that a suitable replacement filler for fat would have to produce a similar weakening effect to create a texture similar to full fat Cheddar cheese.

References

Banks, J. M. 2007. What general factors affect the texture of hard and semi-hard cheeses? Pages 200-201 in Cheese problems solved. P. L. H. McSweeney, ed. Woodhead, Boca Raton.

Brown, J. A., E. A. Foegeding, C. R. Daubert, M. A. Drake, and M. Gumpertz. 2003. Relationships among rheological and sensorial properties of young cheese. 86(10):3054-3067.

Carunchia Whetstine, M. E., P. J. Luck, M. A. Drake, E. A. Foegeding, and P. D. Gerard. 2007. Characterization of flavor and texture development within large (291 kg) blocks of cheddar cheese. J. of Dairy Sci. 90(7):3091-3109.

Drake, M. A., P. D. Gerard, V. D. Troung, and C. R. Daubert. 1999. Relationship between instrumental and sensory measurements of cheese texture. J. of Texture Studies 30:451-476.

Foegeding, E. A. and M. A. Drake. 2007. Sensory and mechanical properties of cheese texture. J. of Dairy Sci. 90(4):1611-1624.

Green, M. L., R. J. Marshall, and B. E. Brooker. 1985. Instrumental and sensory texture assessment and fracture mechanisms of cheddar and cheshire cheeses. J. of Texture Studies 16:351-364.

Gwartney, E. A., E. A. Foegeding, and D. K. Larick. 2002. The texture of commercial full-fat and reduced-fat cheese. J. Food Sci. 67(2):812-816.

Hort, J., G. Grys, and J. Woodman. 1997. The relationships between the chemical, rheological and textural properties of cheddar cheese. Lait 77:587-600.

Johnson, M. E. and C. M. Chen. 1995. Technology of manufacturing reduced-fat cheddar cheese. Pages 331-337 in Chemistry of structure-function relationships in cheese. E. L. Malin and M. H. Tunick, ed. Plenum press, New York.

Lawrence, R. C., L. K. Creamer, and J. Gilles. 1987. Texture development during cheese ripening. J. of Dairy Sci. 70(8):1748-1760.

Lucas, P. W., J. F. Prinz, K. R. Agrawal, and I. C. Bruce. 2004. Food texture and its effect on ingestion, mastication and swallowing. J. of Texture Studies 35:159-170.

Mistry, V. 2001. Low fat cheese technology. INTERNATIONAL DAIRY JOURNAL 11(4-7):413-422.

Scott, R. 1986. Cheesemaking practice. 2nd ed. Elsevier Applied Science Publishers ; sole distributor in the USA and Canada, Elsevier Science Pub. Co., London ; New York New York, NY, USA.

Steffe, J. F. 1996. Rheological methods in food process engineering. Freeman press, East Lansing, MI.

Truong, V. D. and C. R. Daubert. 2000. Comparative study on large strain methods in assessing failure characteristics of selected food gels. J. of Texture Studies 31:335-353.

van den Berg, L., A. L. Carolas, T. van Vliet, E. van der Linden, M. A. J. S. van Boekel, and F. van de Velde. 2008. Energy storage controls crumbly perception in whey protein/polysaccharide mixed gels. Food Hydrocolloids 22:1404-1417.

van Vliet, T. 1988. Rheological properties of filled gels. Influence of filler matrix interaction. Colloid Polym Sci. 266:518-524.

van Vliet, T. and P. Walstra. 1995. Large deformation and fracture behavior of gels. Faraday Discussion 101:359-370.

Visser, J. 1991. Factors affecting the rheological and fracture properties of hard and semi-hard cheese. Pages 49-61 in Rheological and fracture properties of cheese. P. Walstra, ed. International Dairy Federation, Brussels, Belgium.

Xiong, R., J.-F. Meullenet, J. A. Hankins, and W. K. Chung. 2002. Relationship between sensory and instrumental hardness of commercial cheeses. J. Food Sci. 67(2):877-883.

Yates, M. D. and M. A. Drake. 2007. Texture properties of gouda cheese. J. Sensory Studies 22:493-506.

Table 3-1. Proximate analysis data conducted at Utah State University for Cheddar cheeses.

		Actual fat percentage (%)	Moisture content (%)	Protein content (%)	pH
Target cheese fat values	3%	3.0	53.0	32.2	5.4
	8%	8.5	49.6	35.2	5.3
	13%	15.5	46.8	29.6	5.6
	18%	20.3	45.4	26.9	5.5
	23%	23.0	43.4	27.8	5.4
	28%	28.8	40.0	26.3	5.5
	33%	33.0	37.5	24.1	5.5

Table 3-2. Main effects and interactions for sensory texture attributes hand firmness (HFirm), hand springiness (HSpring), hand rate of recovery (HRecov), first bite firmness (MFirm), first bite fractuarbility (Frac), degree of breakdown (Deg Break), cohesiveness (Cohes), adhesiveness (Adhes), smoothness of mass (Smooth of mass), and residual smoothness of mouth coating (Smooth of Mouth) of Cheddar cheese.

	HFirm	HSpring	HRecov	MFirm	Frac	Deg Break	Cohes	Adhes	Smooth of Mass	Smooth of Mouth
Age	-	-	-	-	-	-	-	-	-	-
Fat	*	*	*	*	*	*	*	*	*	*
Interaction	-	-	-	-	-	-	*	-	*	-

* denotes presence of an effect at p< 0.05, - denotes absence of effect

Table 3-3. Correlation values for fracture stress, strain, and modulus, critical stress and strain, and modulus (G′), loss modulus (G″), and complex modulus (G*) at 0.01 Hz with descriptive sensory terms of hand firmness (HFirm), hand springiness (HSpring), hand rate of recovery (HRecov), first bite firmness (MFirm), first bite fracturability (Frac), degree of breakdown (Deg Break), cohesiveness (Cohes), adhesiveness (Adhes), smoothness of mass (Smooth of mass), and residual smoothness of mouth coating (smooth of mouth) broke down by weeks of aging.

	Age (weeks)	HFirm	HSpring	HRecov	MFirm	Frac	Deg Break	Cohes	Adhes	Smooth of Mass	Smooth of Mouth
Fracture Stress	2	…	…	…	…	…	…	…	-0.81	…	…
	4	…	…	…	0.76	…	…	…	…	…	…
	8	…	…	…	0.87	…	…	…	…	…	…
	12	0.81	…	…	…	…	…	…	…	…	…
Fracture Strain	2	**0.92***	0.81	0.78	**0.98***	…	…	…	-0.77	…	…
	4	…	…	…	…	…	…	…	…	…	…
	8	…	…	…	…	…	…	…	…	…	…
	12	…	…	…	…	…	…	…	…	…	…
Fracture Modulus	2	…	…	…	…	…	…	…	…	…	…
	4	…	…	…	0.78	…	…	…	…	…	…
	8	…	…	…	0.89	…	…	…	…	…	…
	12	0.87	…	0.77	…	…	…	…	-0.76	…	…
Critical Stress	2	…	…	…	0.77	…	…	…	-0.88	…	…
	4	0.87	…	…	**0.92***	…	…	…	…	-0.83	…
	8	0.78	…	…	**0.91***	…	…	…	…	…	…
	12	0.86	…	…	…	…	-0.76	-0.75	-0.79	-0.76	…
Critical Strain	2	…	…	…	…	…	…	…	-0.82	…	…
	4	0.82	…	…	0.84	…	…	…	…	-0.82	…
	8	0.79	…	…	**0.91***	…	…	…	…	…	…
	12	0.87	…	0.77	…	…	-0.79	-0.78	-0.81	-0.80	…
G*	2	…	…	…	…	…	…	…	…	…	…
	4	0.84	…	…	0.82	…	…	…	…	…	…
	8	…	…	…	…	…	…	…	…	…	…
	12	…	…	…	…	…	…	…	…	…	…
G′	2	…	…	…	…	…	…	…	…	…	…
	4	0.84	…	…	0.82	…	…	…	…	…	…
	8	…	…	…	…	…	…	…	…	…	…
	12	…	…	…	…	…	…	…	…	…	…
G″	2	…	…	…	…	…	…	…	…	…	…
	4	…	…	…	…	…	…	…	…	…	…
	8	…	…	…	…	…	…	…	…	0.83	0.81
	12	…	…	…	…	…	…	…	…	…	…

Values on chart represent $p<0.05$, * refers to $p<0.01$.

Table 3-4. Correlation values for percentage difference for percent recoverable energy at compressive strains of 0.18, 0.22, and 0.26 with descriptive sensory terms of hand firmness (HFirm), hand springiness (HSpring), hand rate of recovery (HRecov), first bite firmness (MFirm), first bite fracturability (Frac), degree of breakdown (Deg Break), cohesiveness (Cohes), adhesiveness (Adhes), smoothness of mass (Smooth of mass), and residual smoothness of mouth coating (smooth of mouth) broke down by weeks of aging.

	Age	HFirm	HSpring	HRecov	MFirm	Frac	Deg Break	Cohes	Adhes	Smooth of Mass	Smooth of Mouth
0.18 strain	2	…	…	…	…	0.82	**-0.90***	**-0.91***	…	-0.81	…
	4	0.88*	0.86	…	0.79	0.79	**-0.93***	**-0.88***	**-0.94***	**-0.96***	**-0.97***
	8	**0.92***	**0.98***	**0.96***	0.78	0.87	**-0.96***	**-0.96***	**-0.91***	**-0.97***	**-0.98***
	12	**0.92***	**0.96***	**0.96***	**0.89***	**0.99***	**-0.97***	**-0.98***	**-0.90***	**-0.98***	**-0.99***
0.22 strain	2	…	…	0.77	…	0.83	**-0.91***	**-0.94***	…	-0.87	…
	4	**0.90***	0.86	…	0.82	0.77	**-0.92***	-0.86	**-0.93***	**-0.96***	**-0.96***
	8	**0.96***	**0.96***	**0.97***	**0.89***	**0.88***	**-0.98***	**-0.97***	**-0.94***	**-0.94***	**-0.95***
	12	**0.94***	**0.98***	**0.97***	0.85	**0.98***	-0.96*	**-0.98***	**-0.90***	**-0.98***	**-0.97***
0.26 strain	2	…	…	0.81	…	0.76	**-0.94***	**-0.96***	…	**-0.90***	…
	4	**0.92***	**0.94***	…	0.82	0.76	**-0.95***	**-0.91***	**-0.96***	**-0.96***	**-0.95***
	8	**0.95***	**0.94***	**0.98***	**0.89***	**0.92***	**-0.97***	**-0.96***	**-0.93***	**-0.92***	**-0.94***
	12	**0.94***	**0.99***	**0.97***	0.85	**0.98***	**-0.97***	**-0.98***	**-0.90***	**-0.98***	**-0.97***

Values on chart represent $p<0.05$, * refers to $p<0.01$.

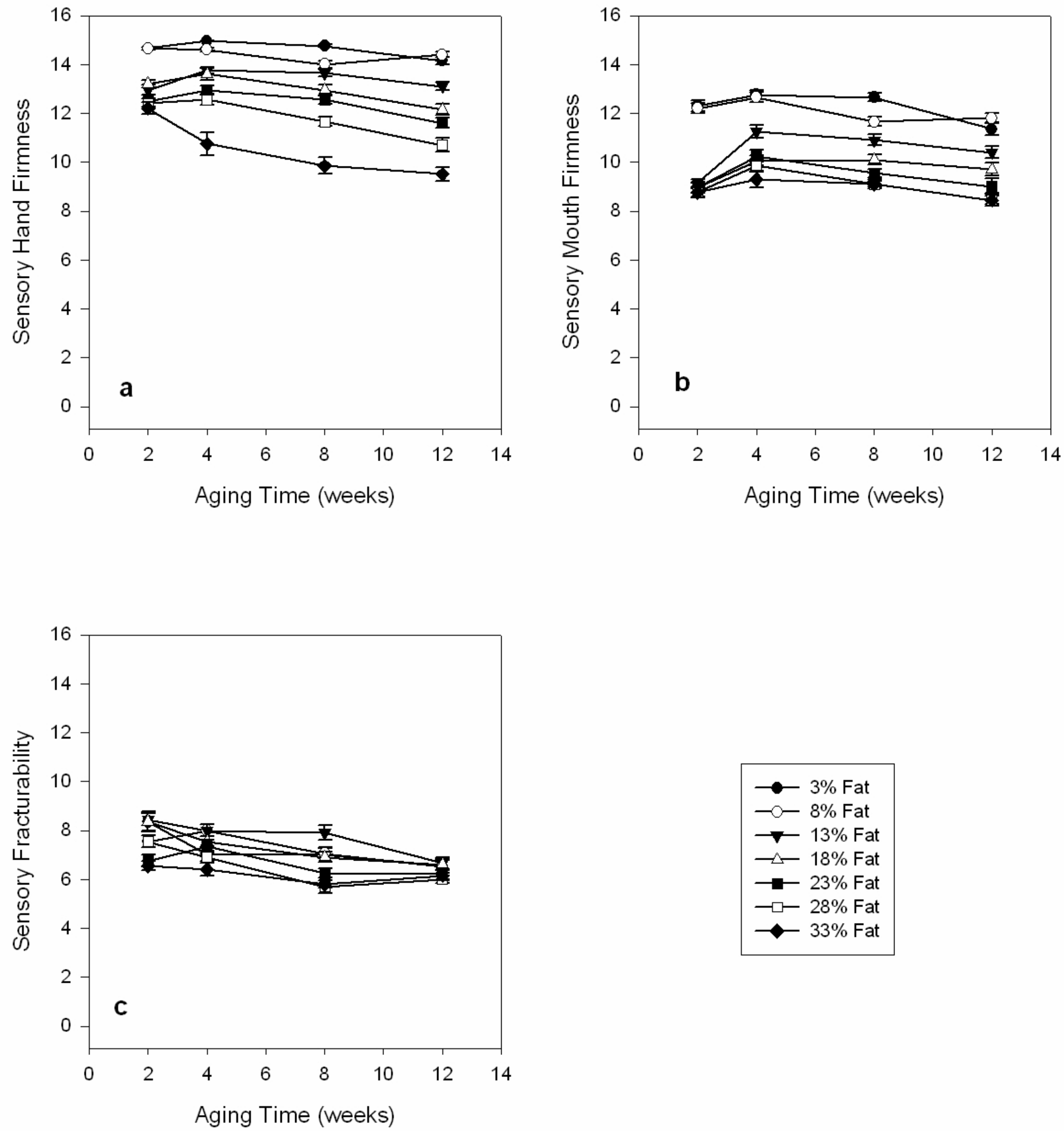

Figure 3-1. Descriptive sensory analysis of hand firmness (a), mouth firmness (b), and fracturabity (c) for Cheddar cheeses. Error bars represent the standard error of the mean.

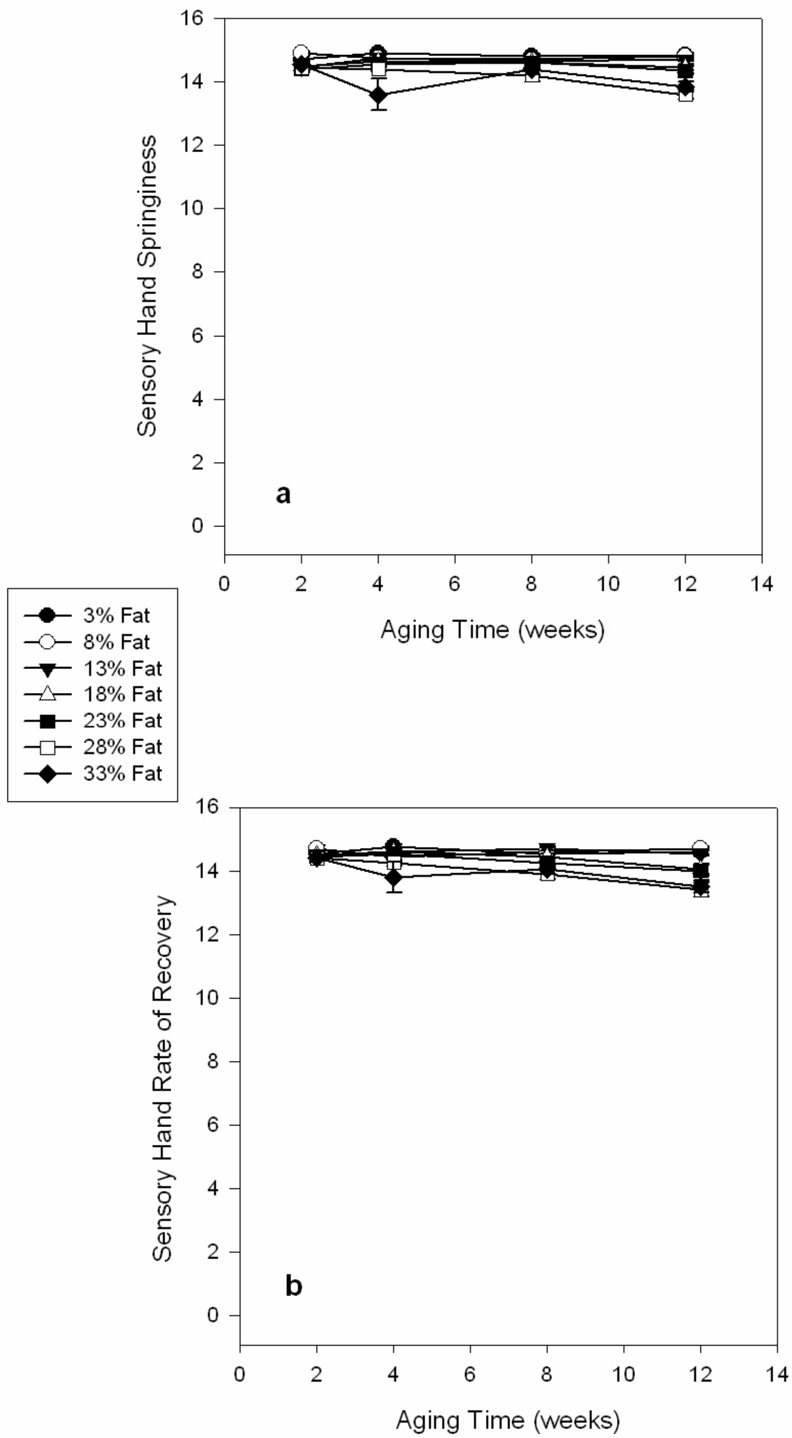

Figure 3-2. Descriptive sensory analysis of hand measured lexicon terms hand springiness (a) and hand rate of recovery (b) for Cheddar cheese. Error bars represent the standard error of the mean.

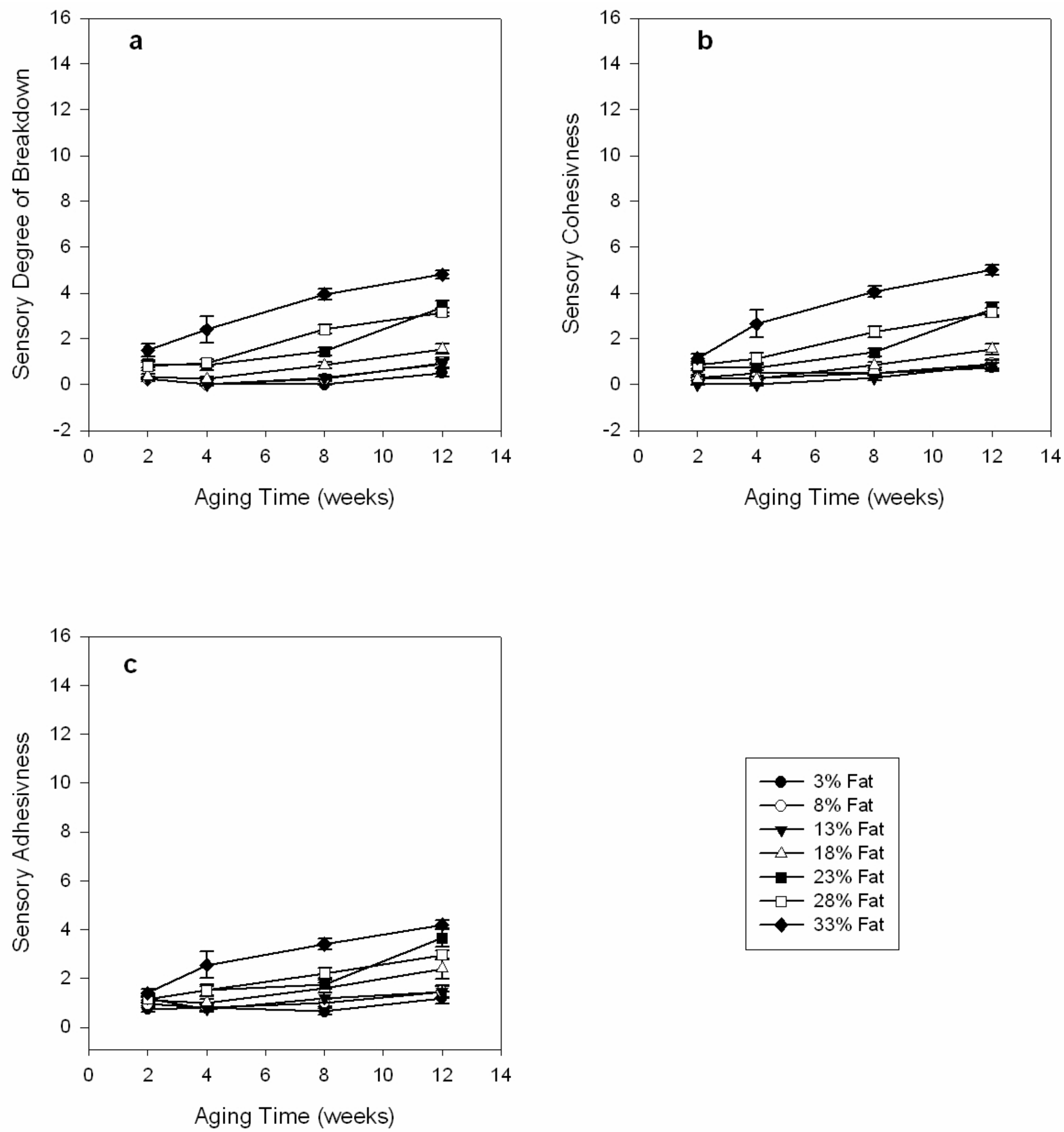

Figure 3-3. Descriptive sensory analysis of degree of breakdown (a), cohesiveness (b), and adhesiveness (c) for Cheddar cheeses. Error bars represent the standard error of the mean.

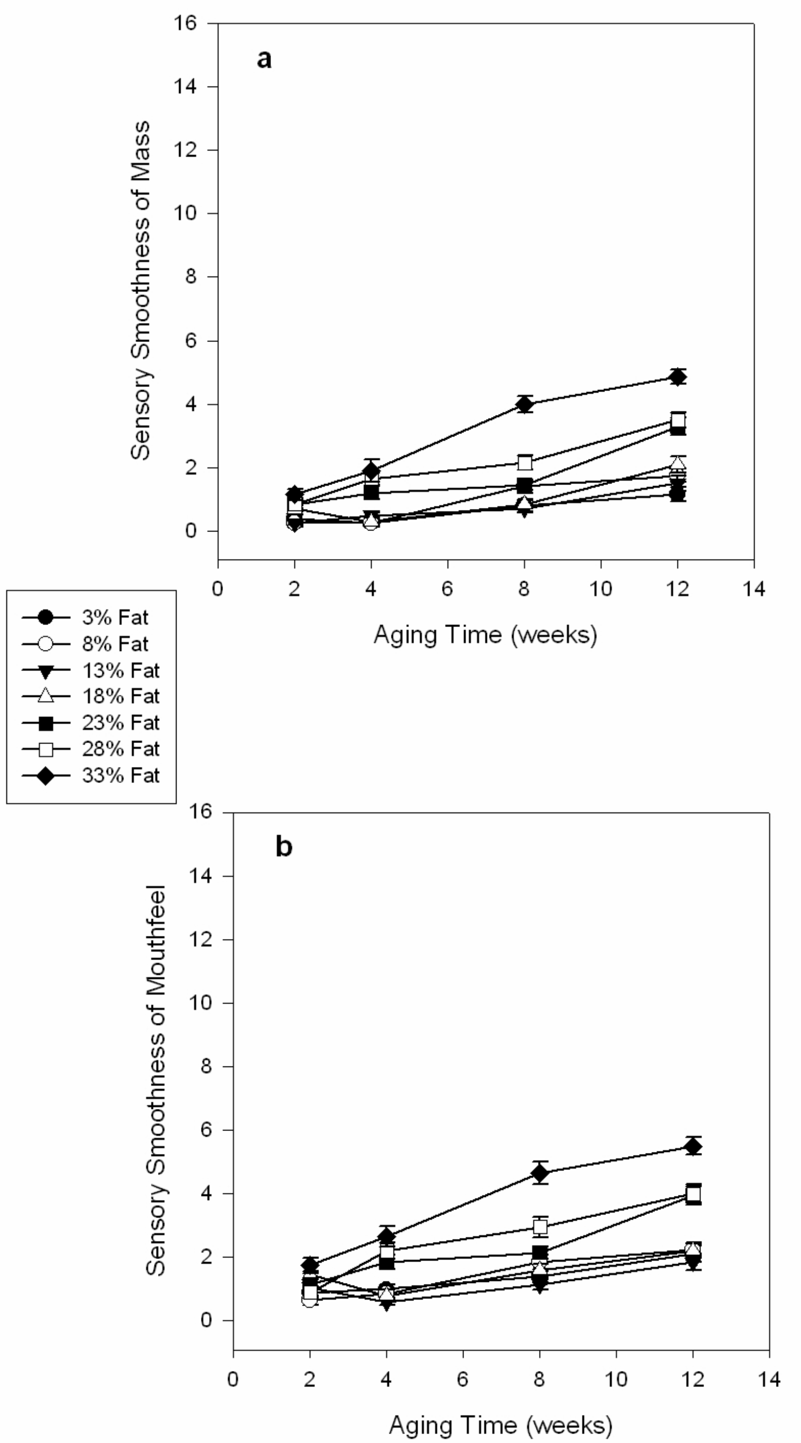

Figure 3-4. Descriptive sensory analysis of smoothness of mass (a) and smoothness of mouth feel for Cheddar cheeses. Error bars represent the standard error of the mean.

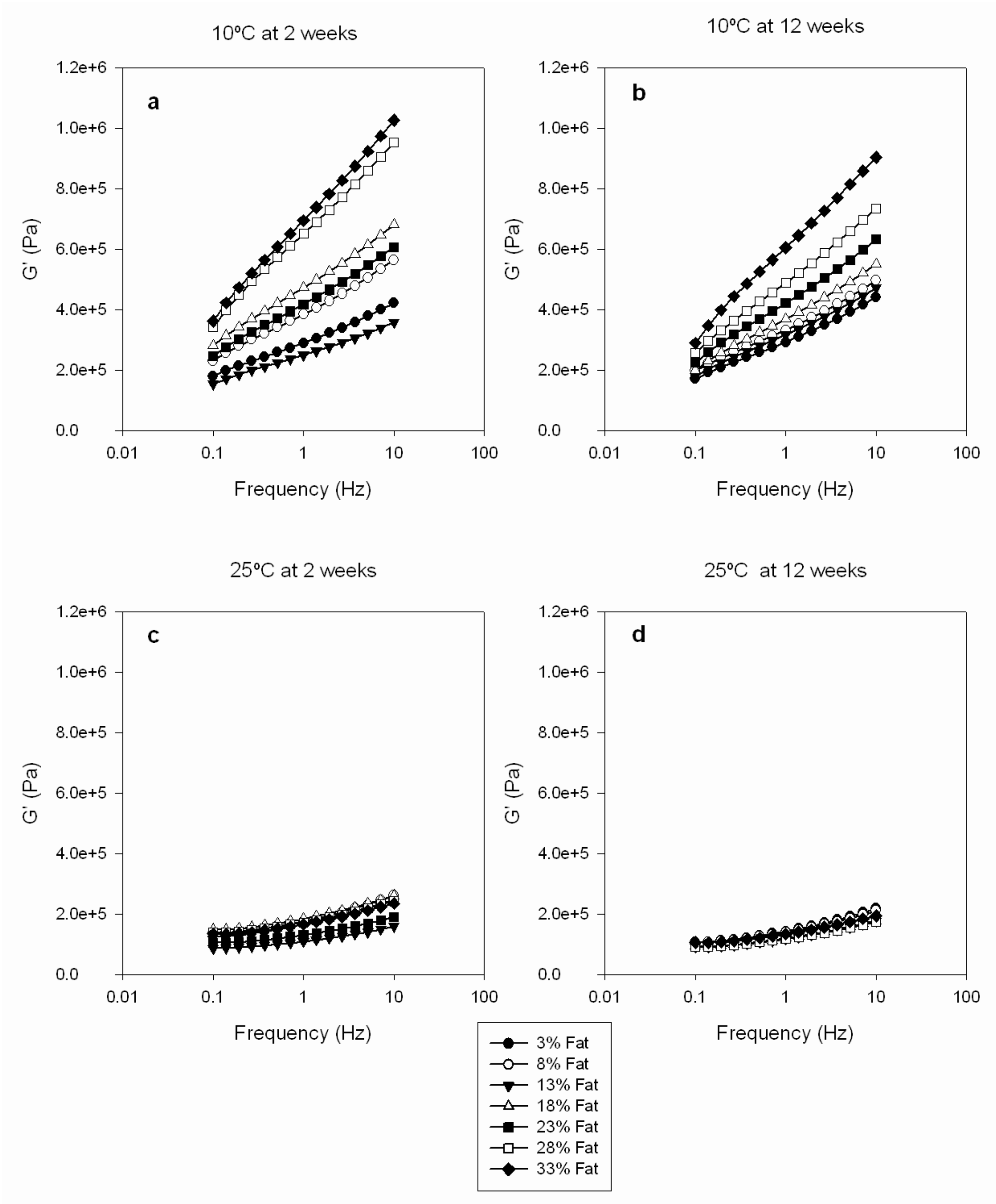

Figure 3-5. Storage modulus (G′) of Cheddar cheeses of various fat contents over a range of frequencies, showing lowest (10ºC) and highest (25ºC) temperature for both 2 weeks (a, 10ºC and c, 25ºC) and 12 weeks (b, 10ºC and d, 25ºC) of aging.

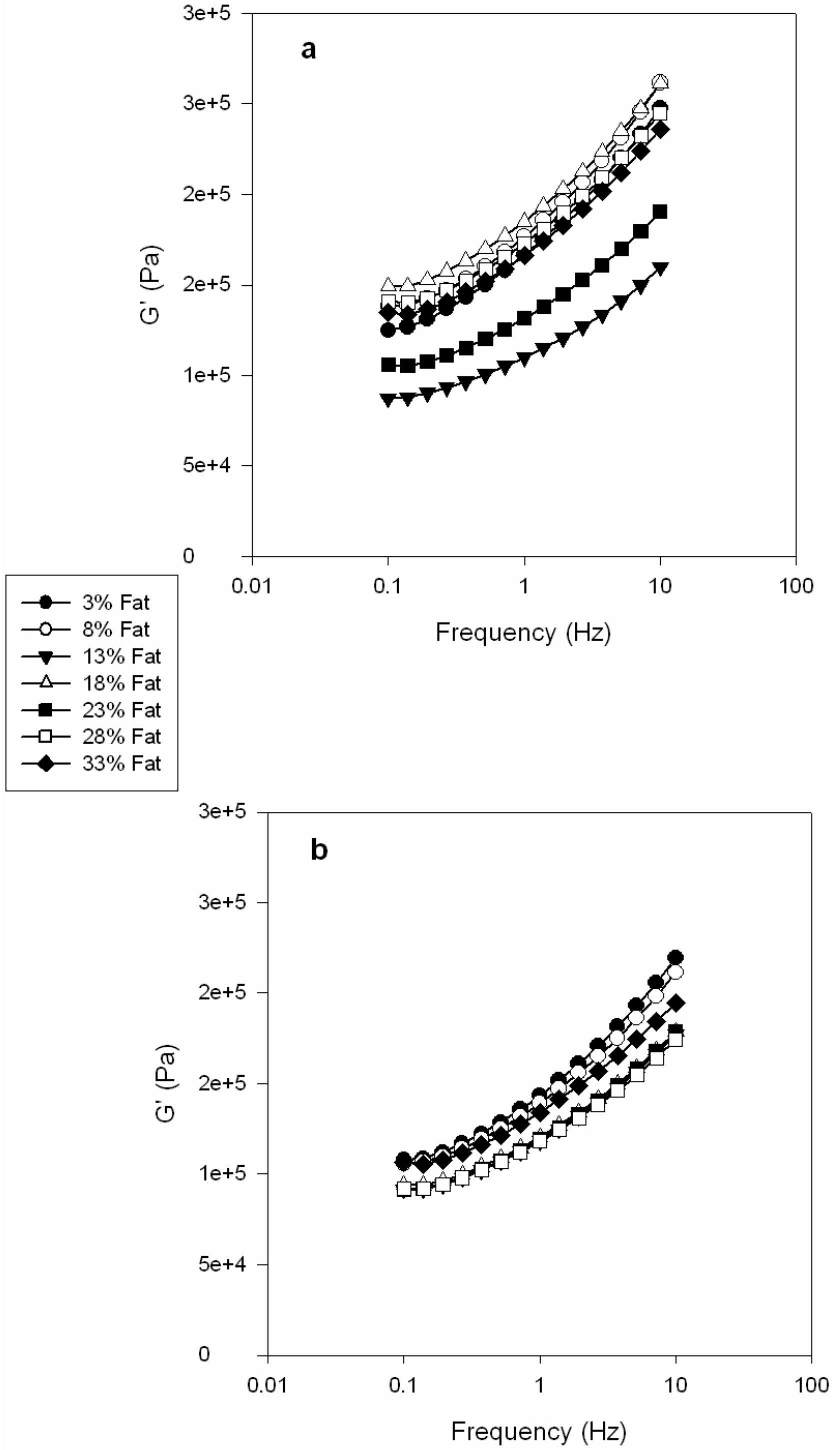

Figure 3-6. Storage modulus (G′) of Cheddar cheeses of various fat contents over a range of frequencies at 25 ºC for 2 weeks (a) and 12 weeks (b) of aging.

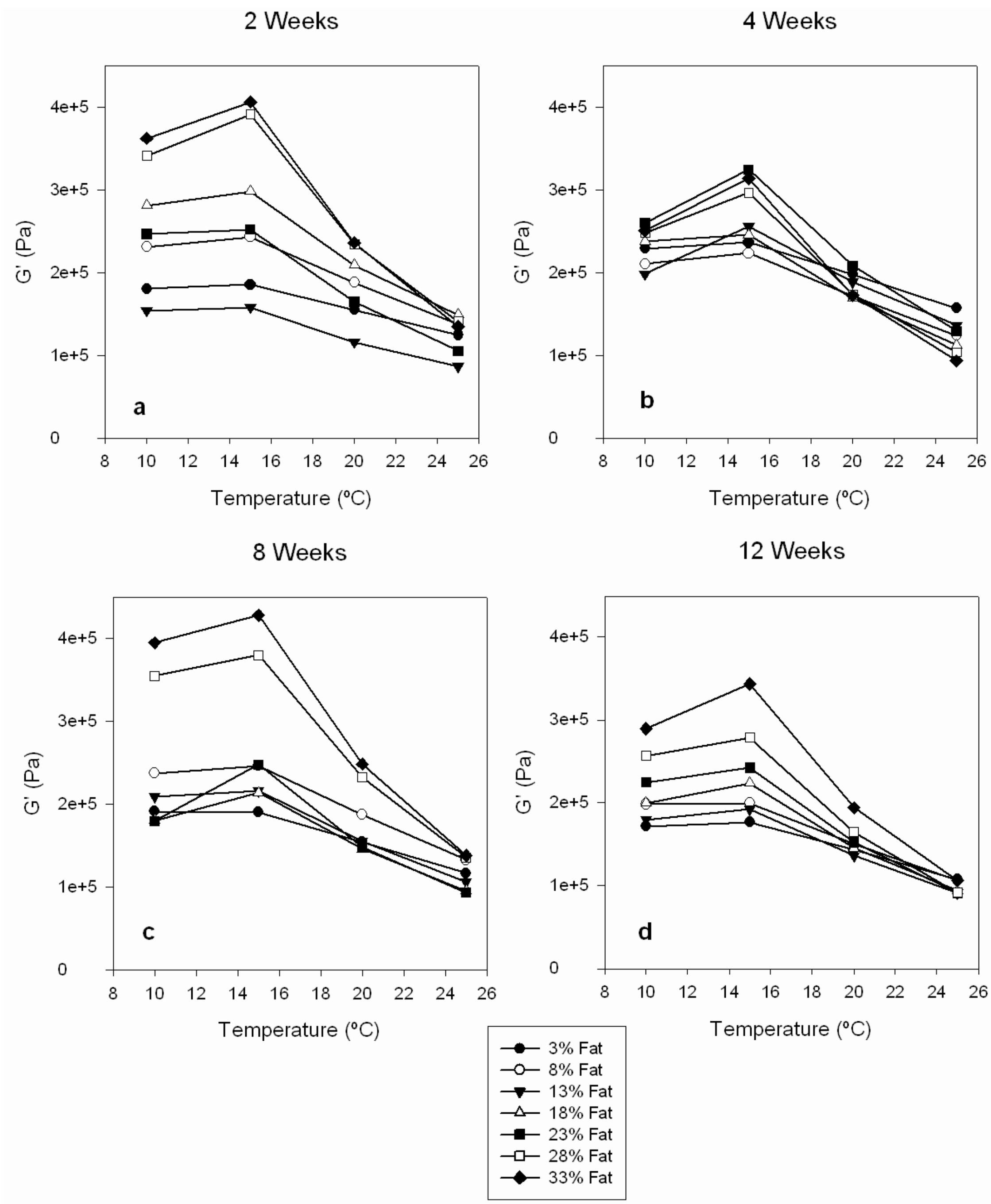

Figure 3-7. Storage modulus (G′) of Cheddar cheeses of varying fat contents and temperatures. Values were determined at 1 Hz at 2 weeks (a), 4 weeks (b), 8 weeks (c), and 12 weeks (d) of aging.

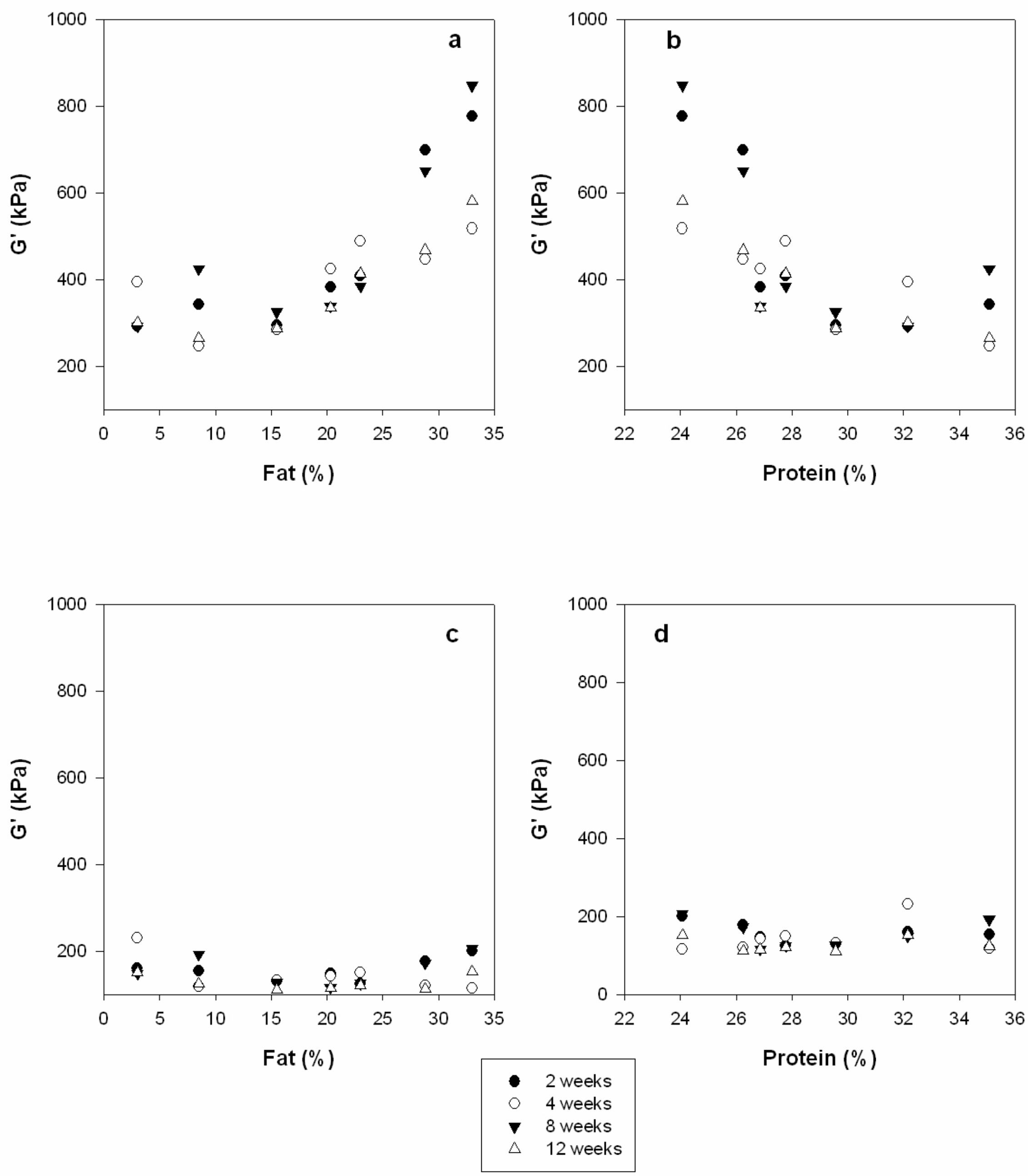

Figure 3-8. Storage modulus (G′) of Cheddar cheeses with respect to fat (a) and protein content (b) at 10°C and with respect to fat (c) and protein content (d) at 25°C and measured at 1 Hz.

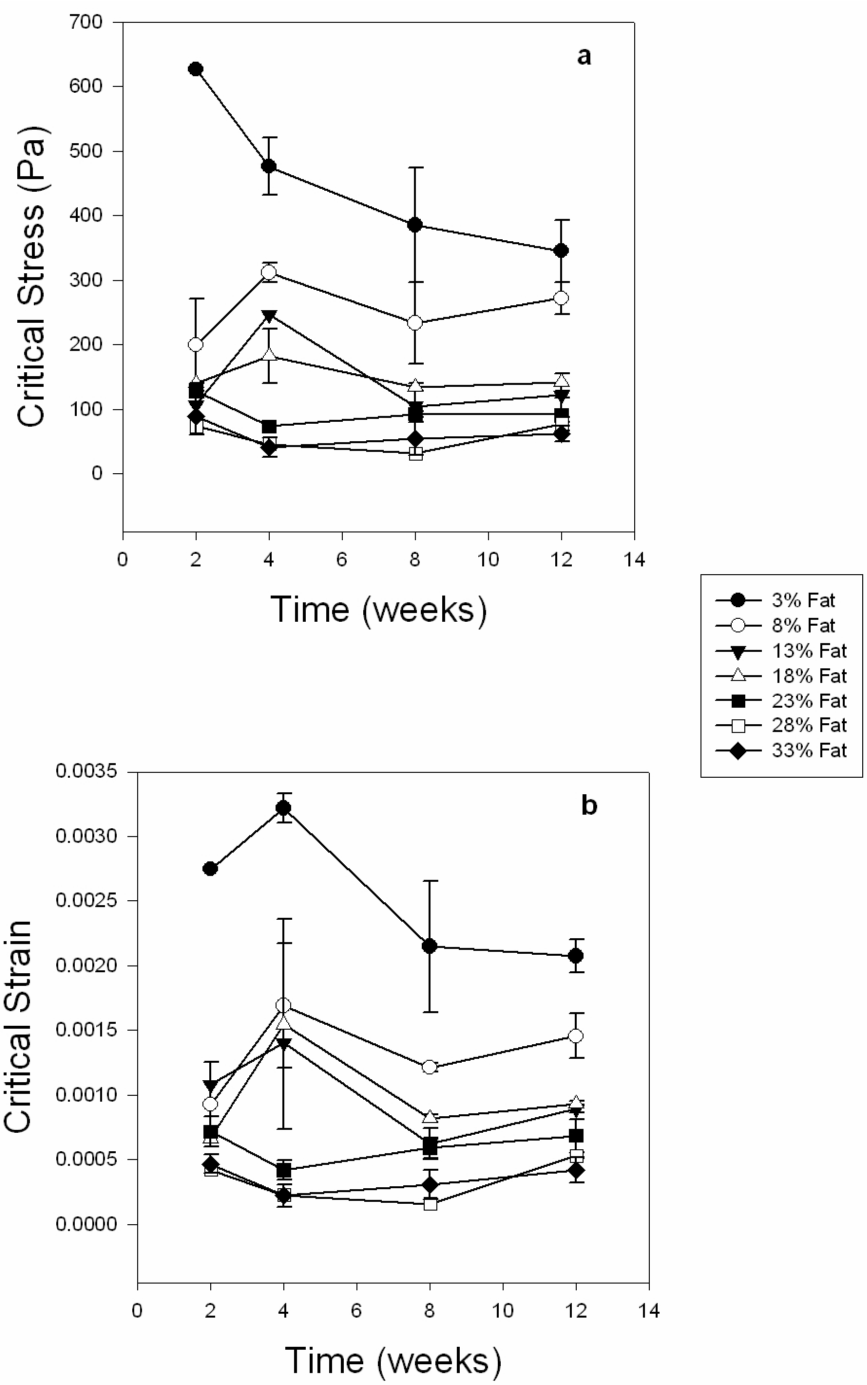

Figure 3-9. Critical stress (a) and strain (b) values for stress sweeps conducted at 10Hz on Cheddar cheese of various fat contents. Error bars represent the standard error of the mean.

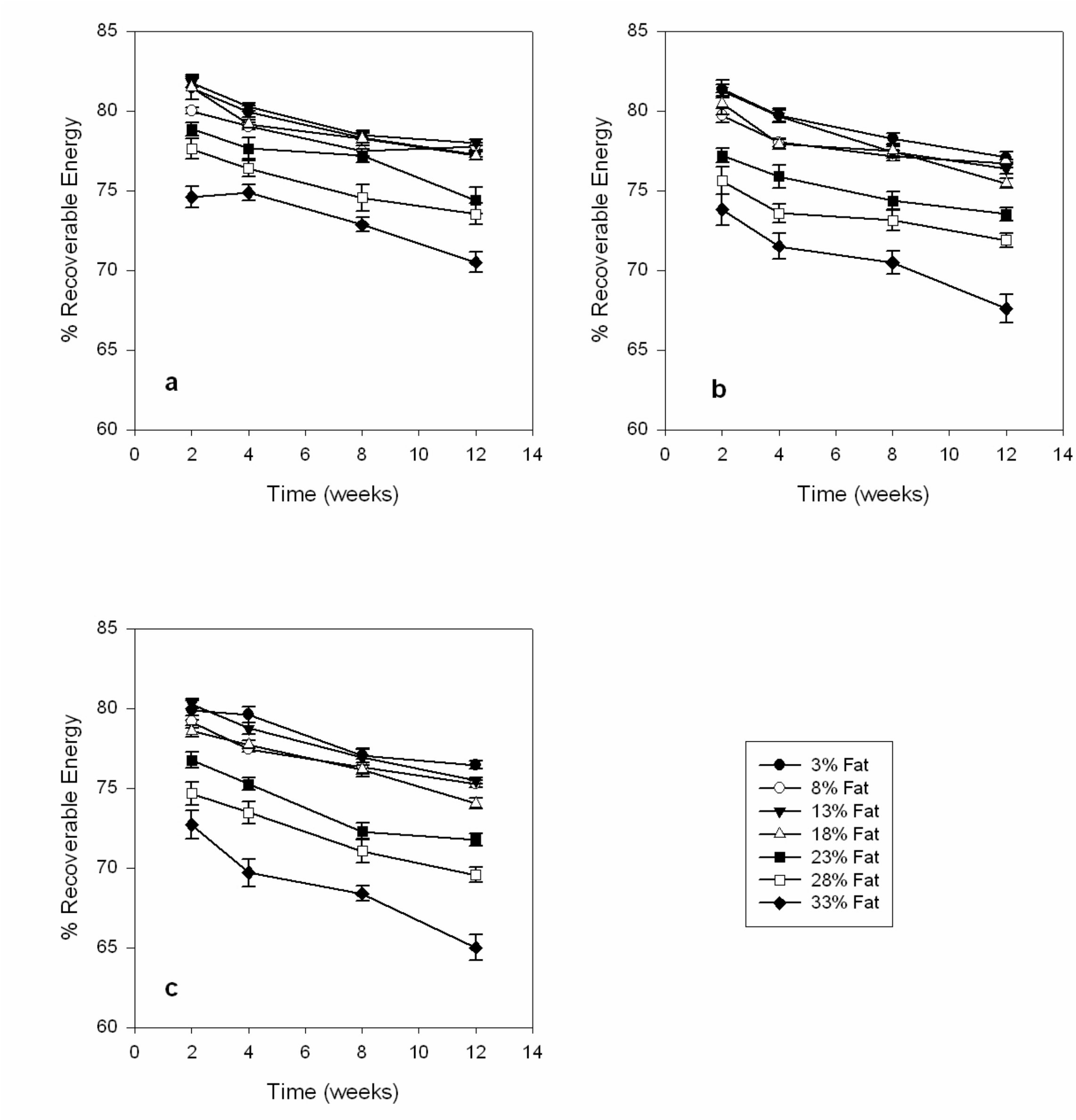

Figure 3-10. Percent recoverable energy of compression curves of Cheddar cheese at strains of 0.18 (a), 0.22 (b), and 0.26 (c). Error bars represent the standard error of the mean.

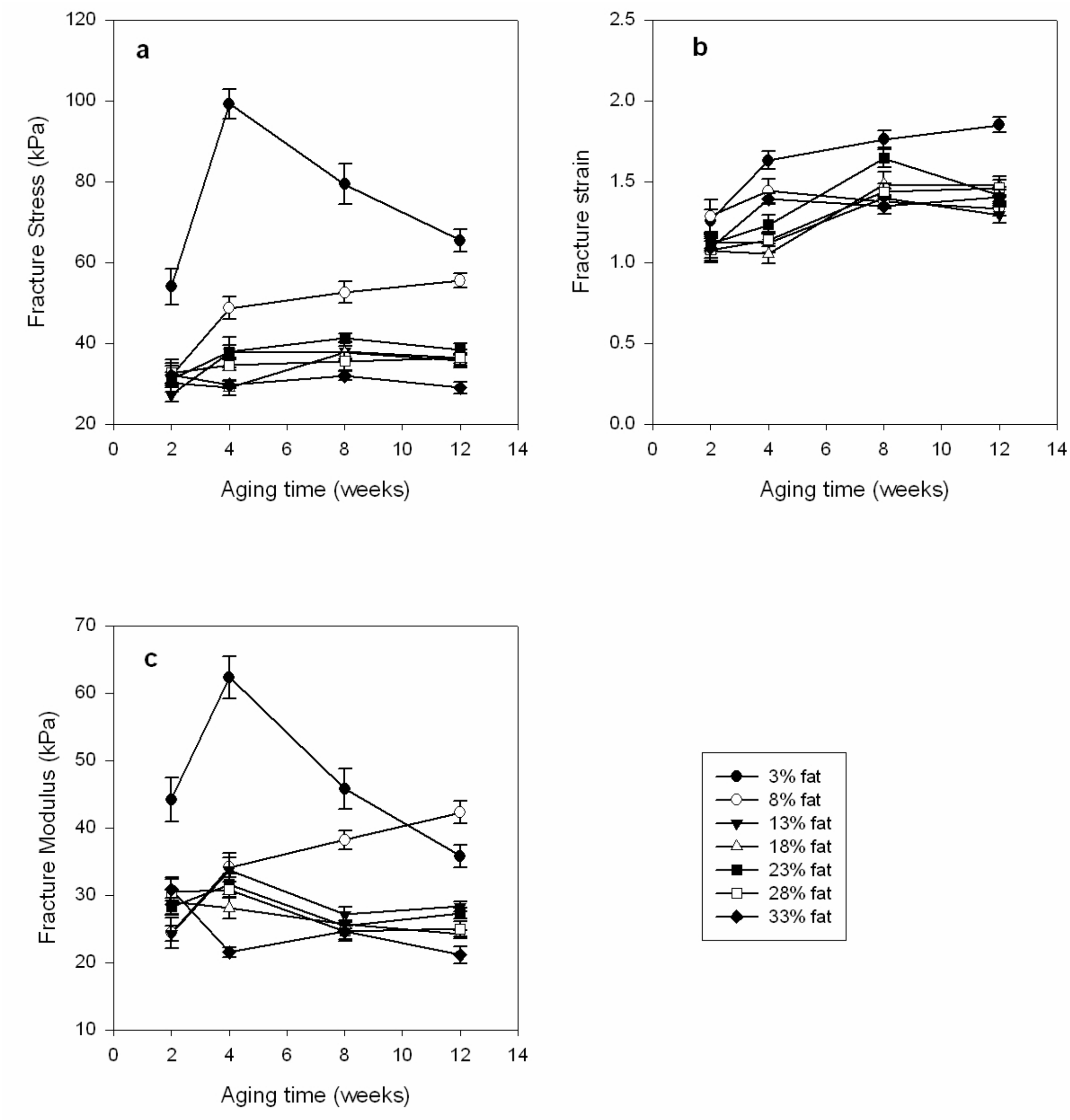

Figure 3-11. Torsional fracture stress (a), strain (b), and modulus (c) determined at 0.41 1/s for Cheddar cheese. Error bars represent the standard error of the mean.

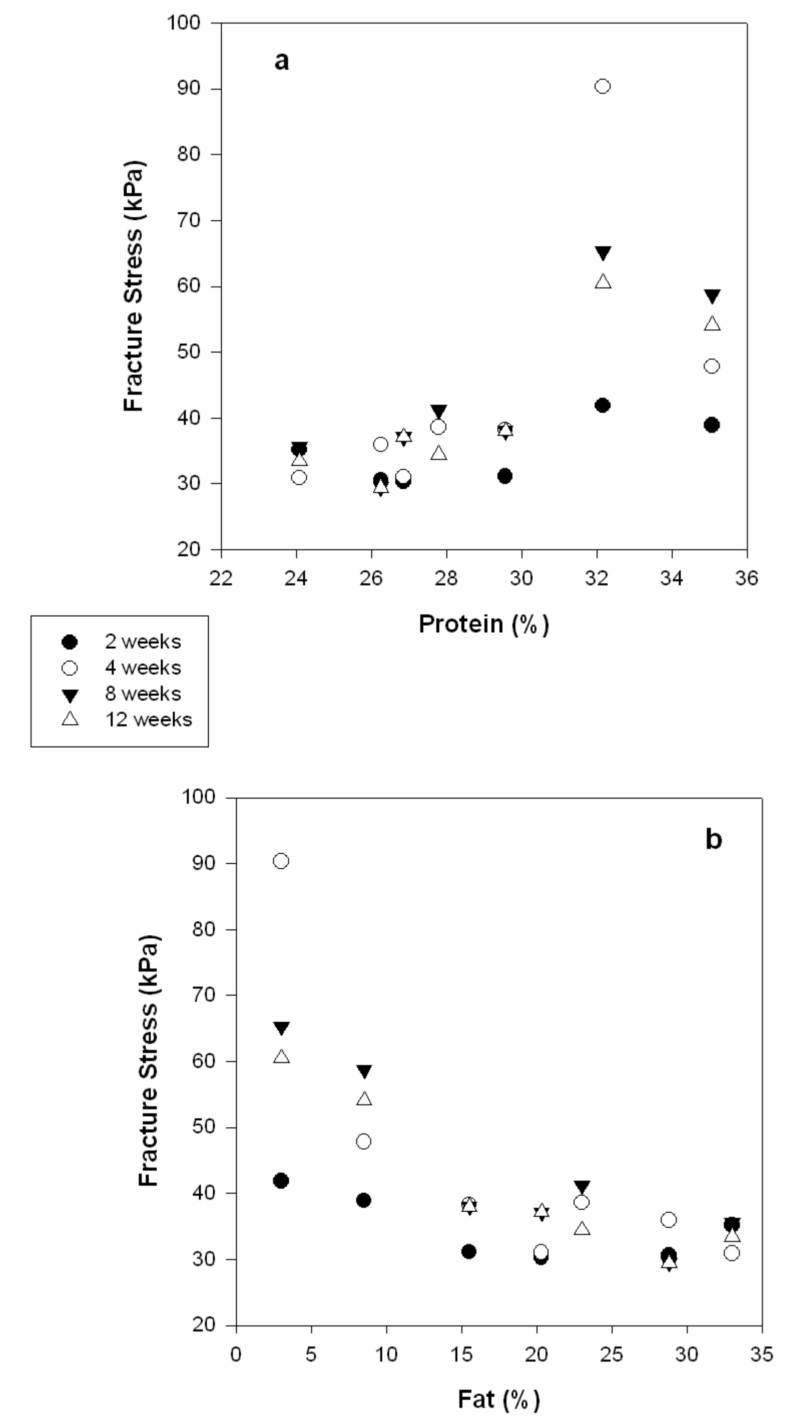

Figure 3-12. Fracture stress of Cheddar cheeses of varying fat contents with respects to protein content (a) and fat content (b).