

ABSTRACT

CHILDS, JESSICA LEIGH. Factors regulating shreddability of cheese. (Under the direction of E. Allen Foegeding)

Shredding cheese is a way to increase the functionality of the cheese by allowing it to melt more evenly and easily. A high quality shred would ideally be one that is uniformly cut with little variation from shred to shred. Some, but not all, factors affecting the shred quality are cheese composition, temperature at which cheese is shred, shredding equipment and properties of the cheese including rheological and adhesive properties. In this experiment, three sets of cheeses were evaluated to determine factors that affect shred quality. The first set of cheeses was made up of three commercial cheeses, Monterey Jack, mozzarella and process. The second set of cheeses, Experimental Cheese Set A, was made up of three mozzarella cheeses with varying levels of protein and fat and constant moisture content. The third set of cheese, Experimental Cheese Set B, was made up of four cheeses formulated to have varying levels of moisture and calcium.

A shred distribution of long shreds, short shreds and fines was obtained by shredding blocks of cheese in a food processor under a constant load of 4 Kg. A probe tack test was used to directly measure adhesion of the cheese to a stainless steel surface. Adhesion is related to surface energy and rheological properties. Surface energy was determined by measuring the contact angle that is formed when liquids are dropped on the cheese surface. Once the contact angles were measured, the surface energy of the cheese was determined based upon equations derived from the Young equation.

Rheological characterization was done by creep and recovery tests. Creep and recovery data allowed for calculating the maximum and initial compliance and retardation time. Tests for commercial cheeses were done at 4°C, 12°C and 20°C. Tests for the second and third experiments were carried out on 2, 7, 14, 21 and 28 days after cheese processing and properties were measured at 7°C.

For the commercial cheeses, two defects in shredding were observed: production of fines and adhesion to the blade. Mozzarella produced the most fines during shredding and had the highest maximum compliance, implying that the softest cheese produced the most fines during shredding. Monterey Jack and process cheeses had the greatest amount of cheese adhere to the blade as well as the highest tack energy. This indicated that a relationship exists between tack energy and amount of cheese adhered to the blade. In addition, the tack energy increased as the maximum compliance increased, implying that the softer cheese had a higher tack energy.

For Experimental Cheese Set A, the defect observed in shredding was production of fines; there was very little adhesion to the blade. The cheese that produced the most fines was the cheese with the highest fat and lowest protein content. This cheese also had the highest compliance of the three cheeses tested. In addition, the softest cheese also had the highest tack energy of the three cheeses. The cheese that had the highest tack energy produced the most fines when shredded. From this experiment, the softer cheeses (higher maximum compliance) had the greatest tack energy and the most fines produced during shredding.

Cheeses in Experimental Cheese Set B also showed production of fines as the main defect during shredding. The cheese with the highest tack energy produced the

most fines during shredding. The maximum compliance also showed to have an effect on the fines produced during shredding. Since the moisture content of these cheeses was controlled, it was possible to see that the moisture content had a significant effect ($p < 0.05$) on the amount of fines produced during shredding. The higher moisture cheeses had more fines produced.

FACTORS REGULATING SHREDDABILITY OF CHEESE

by

JESSICA LEIGH CHILDS

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

DEPARTMENT OF FOOD SCIENCE

Raleigh

2004

APPROVED BY:

E. Allen Foegeding, Ph.D.
Chair of Advisory Committee

Christopher Daubert, Ph.D.

Leonard Stefanski, Ph.D.

BIOGRAPHY

Jessica Childs was born in Winston-Salem, NC on August 8, 1980. She lived with her parents Bill and Cheryl Powell and older sister Jill. She lived in Winston-Salem for ten years then moved to Kernersville, NC. There she attended East Forsyth High School where she was horribly labeled a “band geek”. In addition to playing the saxophone in the band, Jessica also swam and played soccer. After graduation from high school in 1998, she made her way to NC State University. She entered the university as a Food Science major, which was very unusual. As an undergraduate, she interned at GoodMark Foods where she worked as a quality control technician on products such as Slim Jims and beef jerky. She also did a summer internship at Nabisco working with the Planters group. After graduation in May 2002, she continued her education at NC State University to pursue a Master’s degree in Food Science. During her years at NC State University, she was very active in the Food Science Club. She headed up many committees and won the award for “Outstanding Undergraduate Student” as well and “Outstanding Graduate Student”. Her favorite food science activity was being part of the college bowl team. She played on the team for three years and acted as the Captain for the last year. During her years in graduate school she married a wonderful man by the name of Peter Childs of Haddonfield, NJ (yes, a Yankee). Peter and Jessica enjoy spending time with their two “beastly” dogs Victor and Bailey.

ACKNOWLEDGEMENTS

I would first like to thank Dr. E. Allen Foegeding and The Southeast Dairy Foods Research Center for providing the opportunity to do this research. Dr. Foegeding has taught me many things about learning. I always felt that I had everything figured out, but he helped me to see that just because it is written on paper does not mean that you have to believe it. I owe him greatly for teaching me the critical thinking skills that I have gained from this project. I know that those will serve me well in the many years to come. Thank you for pushing me past my comfort zone and making me look at things in a different light.

I would like to acknowledge the other members of my graduate committee as well. Dr. Chris Daubert was always willing to help me with whatever kind of problem that I had, rheology related or not. I enjoyed his teaching and his company. College bowl would not have been nearly as much fun without his as coach! Thank you Dr. Stefanski for helping me support my research with statistics. You helped me to finally understand what the heck a split-plot design is!

I would also like to thank Paige Luck. Without Paige, the lab would be complete chaos, but she knows how to keep all of us in line. She also has some of the best problem solving skills that I have ever experienced. I hope to one day be the scientist that she is now. I appreciate her willingness to listen any time I needed and I am grateful that I have come away from this with her as a good friend.

I cannot imagine this experience without the entertainment of my lab group. I don't think that there is a better group of people to work with out there. It is so nice to

come to work and have a group of people that I consider as close to me as family. Lisa, Dany, Matt, Jack, Jennifer (regular Ireland girl) and especially Mandy I will always remember you and how lucky I was to get to work with you all on a daily basis! I will miss you all dearly! I would also like to thank all the other friends I made in the Food Science department. All the fun times we had here will not be forgotten and I thank each and every one of you for making my experience here so much more enjoyable! I know our paths will cross many more times in the future and I hope we will party even when we are way too old to be partying!

I would also like to thank my family. My mom, my dad and my sister have always been there to support me and cheer me on until the finish. Without your support and love I don't think I would have had the confidence to do what I have done this far. Thank you for always being there to listen and give advice whether I wanted to hear it or not! I am lucky to have such a great family.

Finally, I would like to thank my husband Peter, my rock. You are always willing to listen to me complain and gripe without complaints of your own. You never let me give up and that means the world to me. I am so thankful that you will always be there for me in whatever challenge we take on. I am thankful for our ability to laugh when things get tough and I hope that we will carry that with us forever. Some may think I am crazy, but I would also like to thank my two dogs. If you know me, you know that I am crazy about these guys because they always help keep life interesting and can always find a way to make me smile.

TABLE OF CONTENTS

	Page
LIST OF TABLES.....	vii
LIST OF FIGURES.....	viii
REVIEW OF LITERATURE.....	1
Introduction.....	2
Cheese Manufacture.....	2
Mozzarella Cheese.....	5
Cheddar Cheese.....	6
Colby Cheese.....	6
Monterey Jack.....	7
Cheese Ripening.....	7
Machinability of Cheese.....	11
Adhesion.....	14
Pressure Sensitive Adhesion.....	18
Measurement of Pressure Sensitive Adhesion.....	22
Food Adhesion.....	23
Conclusion.....	25
References.....	27
FACTORS REGULATING SHREDDABILITY OF CHEESE.....	33
Introduction.....	34
Materials and Methods.....	38

Commercial Cheese.....	38
Experimental Cheese Set A.....	38
Experimental Cheese Set B.....	39
Shreddability.....	39
Tack.....	40
Conversion of g^* to mJ/m^2	41
Surface Energy.....	42
Rheological Characterization.....	42
Statistical Analysis.....	43
Results and Discussion.....	45
Commercial Cheeses.....	45
Experimental Cheese Set A.....	53
Experimental Cheese Set B.....	58
Conclusion.....	61
References.....	63
Appendix A.....	108

LIST OF TABLES

	Page
Table 1. Factors influencing the shreddability of cheese.....	66
Table 2. Proximate Composition for all cheeses tested.....	67
Table 3. Percentage of fines and percentage of cheese adhered to the blade during shredding.....	72
Table 4. Correlation analysis for commercial cheeses.....	77
Table 5. Initial compliance (J_0), maximum compliance (J_{max}), storage modulus (G') and retardation time (λ_{ret}) for Monterey Jack, mozzarella and process cheese at 4°C, 12°C and 20°C.....	80
Table 6. Correlation analysis for Experimental Cheese Set A.....	92
Table 7. Initial compliance (J_0), maximum compliance (J_{max}), storage modulus (G') and retardation time (λ_{ret}) for Cheeses 1, 2 and 3 over 28 days of aging.....	93
Table 8. Correlational analysis for Experimental Cheese Set B.....	101
Table 9. Initial compliance (J_0), maximum compliance (J_{max}), storage modulus (G') and retardation time (λ_{ret}) for Low Calcium-Low Moisture (LC-LM), Low Calcium-High Moisture (LC-HM), High Calcium-Low Moisture (HC-LM), High Calcium-High Moisture (HC-HM) Cheeses from Experimental Cheese Set B over 28 days of aging.....	107

LIST OF FIGURES

	Page
Figure 1. Contact angle measurement.....	65
Figure 2. Graph obtained from TAX-T2 for tack.....	68
Figure 3a. Shred Distribution for Monterey Jack cheese at 4°C, 12°C and 20°C.....	69
Figure 3b. Shred Distribution for mozzarella cheese at 4°C, 12°C and 20°C.....	70
Figure 3c. Shred Distribution for process cheese at 4°C, 12°C and 20°C.....	71
Figure 4a. Creep and recovery for Monterey Jack cheese at 4°C, 12°C and 20°C.....	73
Figure 4b. Creep and recovery for mozzarella cheese at 4°C, 12°C and 20°C.....	74
Figure 4c. Creep and recovery for process cheese at 4°C, 12°C and 20°C.....	75
Figure 5. Tack energy for Monterey Jack, mozzarella and process cheeses at 4°C, 12°C and 20°C.....	76
Figure 6. Comparison of cheese adhered to the blade and tack energy for Monterey Jack, mozzarella and process cheeses at 4°C, 12°C and 20°C.....	78
Figure 7. Comparison of tack energy and maximum compliance for Monterey Jack, mozzarella and process cheeses at 4°C, 12°C and 20°C.....	79
Figure 8. Comparison of tack energy and initial compliance for Monterey Jack, mozzarella and process cheeses at 4°C, 12°C and 20°C.....	81
Figure 9. Mechanisms of pressure sensitive adhesion.....	82

Figure 10. Surface energy for Monterey Jack, mozzarella and process cheeses over 4°C, 12°C and 20°C.....	83
Figure 11. Comparison of tack energy and surface energy for Monterey Jack, mozzarella and process cheeses at 4°C, 12°C and 20°C.....	84
Figure 12. Comparison of cheese adhered to the blade and surface energy for Monterey Jack, mozzarella and process cheeses at 4°C, 12°C and 20°C.....	85
Figure 13a. Shred distribution for Cheese 1 over 28 days of aging.....	86
Figure 13b. Shred distribution for Cheese 2 over 28 days of aging.....	87
Figure 13c. Shred distribution for Cheese 3 over 28 days of aging.....	88
Figure 14a. Creep and recovery for Cheese 1 Over 28 days of aging.....	89
Figure 14b. Creep and recovery of Cheese 2 over 28 days of aging.....	90
Figure 14c. Creep and recovery for Cheese 3 over 28 days of aging.....	91
Figure 15. Surface energy of Cheeses 1, 2 and 3 over 28 days of aging.....	94
Figure 16. Tack energy for Cheeses 1, 2 and 3 over 21 days of aging.....	95
Figure 17a. Shred distribution for low calcium-low moisture (LC-LM) cheese over 28 days of aging.....	96
Figure 17b. Shred distribution for low calcium-high moisture (LC-HM) cheese over 28 days of aging.....	97
Figure 17c. Shred distribution for high calcium-low moisture (HC-LM) cheese over 28 days of aging.....	98
Figure 17d. Shred distribution for high calcium-high moisture (HC-HM) cheese over 28 days of aging.....	99

Figure 18. Tack energy for low calcium-low moisture (LC-LM), low calcium-high moisture (LC-HM), high calcium-low moisture (HC-LM), and high calcium-high moisture (HC-HM) cheeses over 28 days of aging.....	100
Figure 19. Surface energy for low calcium-low moisture (LC-LM), low calcium-high moisture (LC-HM), high calcium-low moisture (HC-LM), and high calcium-high moisture (HC-HM) cheeses over 28 days of aging.....	102
Figure 20a. Creep and recovery for low calcium-low moisture (LC-LM) cheese over 28 days of aging.....	103
Figure 20b. Creep and recovery for low calcium-high moisture (LC-HM) cheese over 28 days of aging.....	104
Figure 20c. Creep and recovery for high calcium-low moisture (HC-LM) cheese over 28 days of aging.....	105
Figure 20d. Creep and recovery for high calcium-high moisture (HC-HM) cheese over 28 days of aging.....	106

REVIEW OF LITERATURE

J. L. Childs

Department of Food Science
North Carolina State University

INTRODUCTION

Cheese was once used as a method to preserve milk but has transformed into a highly nutritious food that has epicurean qualities (Fox 1987). The National Dairy Council (2000) defines cheese as the fresh or matured product obtained by draining the whey after coagulation of casein, the major protein in milk. The coagulation of casein can happen by addition of food grade acidulants to the milk, or addition of acid producing microorganisms and/or coagulating enzymes (National Dairy Council 2000).

Cheese is a very popular food and its popularity continues to grow. According to the USDA (2002), 8,599 million pounds of cheese were produced in the year 2002. In the US alone, annual consumption was up to 30.6 pounds per capita in 2002 (USDA/ERS 2002). Of the 8,599 million pounds of cheese produced, 33% was cheddar and 32.7% was Mozzarella. (USDA 2002). With the popularity of cheese on the rise, it is important to understand the science behind it to ensure a high quality product. Thus, it has become a very popular subject for many dairy researchers.

CHEESE MANUFACTURE

Cheese manufacture is essentially a dehydration process where fat and casein in milk are greatly concentrated (Fox 1987). In the manufacture of cheese, the basic steps that are followed are acidification, coagulation, dehydration (cutting the coagulum, cooking, stirring, pressing, salting or anything that promotes gel syneresis), shaping and salting. Coagulation of casein can be done in three different ways. The first method,

used for most cheeses, is to add a coagulating enzyme to the milk. The enzyme splits κ -casein into para κ -casein and a macropeptide. Once para κ -casein is formed, the casein micelle stability is lost and the casein micelles combine to form the gel network that entraps other components in the milk (Scott 1986). Originally, the coagulating enzyme was obtained from the stomach of a calf and was called rennet. The most important enzyme present in rennet is chymosin or rennin, which hydrolyzes κ -casein to initiate the coagulation of milk (Farkye 1995). Now there are many other sources where coagulating enzymes can be obtained. The second method of clotting is done by lowering the pH to destabilize the casein, used for cream cheese and cottage cheese. The reduced pH decreases the number of stabilizing negative charges on the casein micelles, which causes them to clot or aggregate (Johnson and Law 1999). The third method of coagulation, used for cheeses such as queso fresco and ricotta, uses high heat and acid to precipitate casein and whey proteins to form a clot (Fox 1987). No matter how the casein is coagulated, the milk fat is surrounded by a casein network and trapped with the serum or whey portion of the milk (Johnson and Law 1999). Typically, to remove the whey from the coagulated milk, the coagulum is cut into small pieces called curd. Cutting the coagulum causes the curd to shrink and expel whey. The casein molecules undergo a rearrangement or tightening and push out more whey, which is called syneresis (Johnson and Law 1999). The curd and whey mixture is heated and stirred, and then the whey is separated from the curd. Once the whey is drained, the curd may be textured, milled and salted depending on type of cheese. Next, the curd is put into a mold or hoop and pressed. Pressure may be applied to the mold, but the time and pressure depends on the

variety of cheese being made. If the cheese was not salted at an earlier step, it is dry salted by applying salt to the surface or immersed in a salt containing brine.

The protein network of cheese is primarily formed by α_{s1} -casein, which forms chains that trap fat globules (Jack and Paterson 1992). The casein chains form a flexible network that is determined mostly by the dimension of the milk fat globules. Fat globules are trapped by the open network of casein, and water fills open spaces within the network (Jack and Paterson 1992). The ratio of fat and protein determines the structure of cheese. If the fat and water content are high, the protein structure is weakened and the cheese is soft. If the fat and water content are low, then the cheese structure is hardened and the cheese is firm. Jack and Paterson (1992) reported that the firmness is largely related to the casein content of the cheese.

Aroma, flavor and texture of the cheese are regulated by moisture, salt content and microflora present in the cheese during ripening (Fox 1987). The manufacturing steps help differentiate varieties of cheese to some extent, but the ripening phase helps give the characteristic flavor and texture specific to certain varieties of cheese. Once the cheese is made and ripened, it may go on to further processing such as shredding, slicing, or cubing. Shredding is the machining step focused on in this investigation. There are a large number of cheeses sold after shredding or shredded after consumer purchase. The cheeses typically shredded are Mozzarella (extensively for pizza), Colby, Monterey Jack and Cheddar. Each of these cheeses has specific make procedures that will influence the quality of shredded cheese produced.

Mozzarella Cheese

Mozzarella is a semi-soft/semi-hard, plastic-curd cheese. Mozzarella was originally produced from buffalo milk, but is now made from cow's milk as well. It is a pasta filata cheese, which means that it goes through a cooker-stretcher step during processing. This step allows for the protein chains in the cheese to coalesce into larger strands that are oriented in the direction of the stretching (McMahon and others 1999). McMahon and others (1999) explain that the coalescence results in redistribution of water and fat with larger protein strands or fibers separated by channels containing water, water-soluble cheese components, bacteria and fat. During the first few weeks after manufacture, low moisture varieties of Mozzarella cheese undergo many textural changes that affect the melt properties (Kindstedt and others 1992). McMahon and others (1999) concluded that water, formerly in the fat-serum channels, becomes entrapped in the cheese protein matrix during the first three weeks of storage. This occurs due to rearrangement of protein molecules in the matrix because of salting and refrigeration of the cheese (McMahon and others 1999).

Mozzarella is a cheese where much importance is placed on functional properties. The pizza restaurant industry accounts for the greatest percentage of Mozzarella cheese users (Fife and others 1996). In 2002, pizza retailers bought \$2.5 billion worth of shredded cheese according to the National Association of Pizzeria Operators. The largest pizza chain and the largest buyer of cheese uses more than 300 million pounds of cheese for its pizzas every year (Gersema 2003). Kindstedt and others (1992) reported that compositional factors such as calcium and phosphorus concentration in the curd, moisture content, intact casein, fat content, physical state of the fat and the interaction of fat with

casein affect the functional behavior of Mozzarella cheese. In some cases, low moisture Mozzarella develops a soft, pasty and sometimes wet surface during aging. This soft surface of the cheese is difficult to shred and the shredded cheese has a poor appearance and is prone to matting and clumping (Kindstedt and others 1996).

Cheddar Cheese

Cheddar cheese was first made in the village of Cheddar in Somersetshire, England, and is the most widely made cheese in the world (Ridgway 1999). Cheddar cheese is a hard cheese that can range from white to various shades of yellow. “Cheddaring” is the name of a processing step that is characteristic of this cheese. When the curds are drained from the whey, they are packed about 7 or 8 inches deep on either side of the vat. Once the curds are firm enough to be turned without breaking it is turned frequently and then piled or cheddared (USDA 1969). Once the cheddaring process is complete, the cheese is milled and salted. Once salted, the cheese is put into hoops and pressed. Once the cheese is pressed, it is allowed to cure at 4 to 10°C for at least sixty days and sometimes up to a year. Cheddar cheese is free from cracks and holes due to the oriented fibrous protein resulting from the cheddaring process (Jack and Paterson 1992).

Colby Cheese

Colby cheese is a granular or stirred curd cheese, and is made similarly to cheddar cheese without the matting and milling step. After cutting, stirring and heating of the curd, the whey is drained to the level of the curd. Cool water is added to the curd and

stirred until the temperature is lowered to the desired level. Adding water to the curd is atypical in making stirred cured cheeses (USDA 1969). After the whey is drained completely, the curd is salted and pressed. Colby has a softer body, a more open texture, and higher moisture content than cheddar (USDA 1969).

Monterey Jack

Monterey Jack is a semi-soft cheese originating from Monterey County, California made similarly to Colby. Cool water is run through the curd or into the vat jacket, but unlike Colby the Monterey Jack curd is salted and placed directly into muslin and pressed between boards or a hoop (USDA 1969). The cheese is cured for at least six months. Monterey Jack has a softer texture than Colby.

CHEESE RIPENING

During ripening of cheese, many chemical and biochemical changes take place causing the main components of the cheese to be degraded to primary and secondary products (Fox 1989). Maturation of cheese is influenced by the size and shape of the cheese, conditions of maturation (temperature and humidity), nature and amount of rennet added in the coagulation, and bacteria and enzymes present in milk (Creamer and Olson 1982). Of the many changes that take place during maturation, proteolysis appears to be the most significant, because it results in the breakdown of the casein network which allows a rubbery “green” cheese to transform to a soft and smooth mature cheeses

(Faryke 1995). Proteolysis of cheese is the main cause of textural changes and flavor development in cheese during ripening.

During the first two weeks of aging, the α_{s1} -casein is hydrolyzed by proteinases present in the cheese, which causes a weakening in the protein network (Jack and Paterson 1992). The weakening of the casein network is caused originally by four, and possibly five, agents. These are rennet or rennet substitute, indigenous milk proteins, starter bacteria and their enzymes, enzymes from secondary starters and nonstarter bacteria (Fox 1989). Other factors influencing the proteolytic activity in cheese are levels of residual rennet and native milk proteinases, salt to moisture ratio, temperature of ripening, type of coagulant used and changes in pH during ripening. In proteolysis, casein is converted into large peptides. Once the large peptides are formed, lactic acid bacteria, and secondary starter proteinases convert the large peptides into smaller peptides. These smaller peptides are then further converted into free amino acids by starter and non-starter lactic acid bacteria (Sousa and others 2001). The amino acids are broken down to amines, aldehydes, alcohols and sulfur compounds (Law 1987). Rate and pattern of proteolysis may be influenced by location within the cheese such as surface ripened, smear ripened or brined-salted cheeses (Sousa and others 2001).

Ledford and others (1966) initially reported that rennet cleaved α_{s1} -casein during the initial stages of ripening of cheddar cheese. Mulvihill and Fox (1979) reported that six different peptides were generated by rennet action on pure α_{s1} -casein. The first degradation product of α_{s1} -casein is α_{s1} -I casein. α_{s1} -I casein is then further broken down into the other five peptides at different conditions. The coagulant is typically drained off with the whey, but conditions such as pH at draining and whey remaining in the curd

determine how much coagulant is left in the cheese curd. Creamer and others (1985) reported that when the pH of the curd at draining is relatively low, more rennet was retained in the curd. This process allowed for more of the α_{s1} -casein to be hydrolyzed by the chymosin in the rennet.

In addition to rennet, the α_{s1} -casein can also be broken down by milk proteinases. It appears that most proteinases present in cheese have the ability to degrade α_{s1} -casein (Grappin and others 1985). The milk proteinase of interest in cheese ripening is plasmin. Noomen (1978) found that α_{s1} -casein was degraded by native milk proteinases in a rennet-free simulated soft cheese and produced a similar product to the α_{s1} -I casein. The native milk proteinases may play an important role in cheeses when heated to high temperatures, such as Swiss and Mozzarella, where rennet is inactivated. Plasmin has relatively high heat stability, and Somers and Kelly (2002) reported that cheese manufactured from milk that was heated to 63°C for 30 minutes had the highest plasmin activity throughout ripening. Proteolytic activity of plasmin in milk is thought to increase after heating due to inactivation of plasmin activity inhibitors (Richardson 1983). The pH at draining determines the amount of plasmin remaining in the cheese. In milk, plasmin is associated with the casein micelle, but when the pH is decreased plasmin dissociates from the casein micelle (Lawrence and others 1987). Cheeses that are drained at high pH have more plasmin present in the curd.

Proteolysis can also occur in milk prior to the cheese making process. The major causes for proteolysis in milk prior to manufacture are due to microbial and indigenous milk proteinases (Fox 1989). In cooled milk, psychotropic bacteria dominate the microflora, but according to Fox (1989) proteolysis is not affected by psychotropic

bacteria unless the population exceeds about 10^6 cfu/ml. Plasmin preferentially hydrolyzes β -casein to γ -casein and proteose peptones and has little effect on κ -casein (Fox 1989). Similar to the study of Somers and Kelly (2002), Sousa and others (2001), found that heat-treating milk to 63°C for 30 minutes increased plasmin activity as compared to raw milk. But they also found that a more severe heat treatment significantly reduced the plasmin activity in the milk.

Lawrence and others (1987) hypothesized that there are two distinct phases in texture development during ripening. During the first phase of ripening, occurring during the first 7 to 14 days after manufacture, the rubbery texture is converted to a smoother and less rubbery texture. This concept suggests that proteolysis of the continuous casein phase is taking place. Lawrence and others (1987) explained that only a small amount of proteolysis is necessary for a large change in texture. During the second phase, a more gradual change in texture occurs due to a lower rate of proteolysis and rise in pH. A small decrease in water activity will greatly decrease the proteolytic activity in cheese. Also, low moisture cheeses contain a lower rennet to casein ratio so the rate of change in the texture of the cheese during aging is slower.

Temperature has an affect on the proteolysis of cheese during storage. Fedrick and Dulley (1984) reported that ripening of Cheddar cheese at 15°C for 8 weeks developed a similar texture to Cheddar cheese that was ripened at 8°C for 16 weeks. In addition, they found that the cheese became more brittle and less springy when storage temperatures went up to 20°C . But Cheddar cheeses stored between 2 and 10°C are not extremely different because hydrolysis of α_{s1} -casein is similar between these temperatures and α_{s1} -casein is the most important component to the structural framework

of cheese (Lawrence and others 1987). The degree of proteolysis affects the texture of the cheese. A greater amount of proteolysis is correlated with a less firm and less springy cheese (Fedrick and Dulley 1984). As the protein matrix breaks down, the body of the cheese becomes softer. The pH of the cheese is also a factor in the degree of proteolysis in cheese. The extent of proteolysis in cheese was reported to increase in simulated cheese with a pH greater than 5.8 (Noomen 1978).

Lawrence and others (1987) comment that there are three factors of manufacture that influence the change in texture during ripening. The first is the pH at which the curd is drained since this determines the amount of chymosin and plasmin left in the cheese. The second is the salt to moisture ratio of the cheese that, along with temperature, controls the activity of the residual rennet and plasmin in the cheese. The third factor is the pH of the cheese after salting which is the most important factor that influences texture.

MACHINABILITY OF CHEESE

Cheese can be machined in a variety of ways. Slicing, shredding and cubing are the most common types of machining that is done. Shredding is done to increase the surface area of the food and helps to get the maximum result in mixing or covering with the minimum amount of product (Apostolopoulos and Marshall 1994). Cheese is one the most important foods where shredding is used extensively by both the consumer and the manufacturer (Apostolopoulos and Marshall 1994). Shredding allows for faster melting

of cheese as compared to other methods of size reduction such as slicing and cubing (Ni and Guansekaran 2004).

The term “shreddability” is a broad term that encompasses many characteristics of shredded cheese. It can take into account the ease at which the block of cheese is processed through the shredding machine, the geometry and integrity of the cheese shreds (length and thickness of cut, ragged or clean edges), the propensity of shreds to remain free flowing or mat together after shredding, the propensity of shredded particles to shatter into fines either during or after shredding (Kindstedt 1995). If cheese is soft, pasty or wet, the shredder can become clogged with cheese and the shredded cheese may produce shreds with ragged edges, many fines, “gummy balls” of cheese and excessive matting of the cheese shreds. In contrast, if the cheese is too firm and dry, the resulting shreds are typically shattered into smaller particles and fines (Kindstedt 1995).

Ideally, cheese shreds should be uniformly and precisely cut, which allows the cheese to melt evenly and easily when used in hot dishes or as a topping (Dubuy 1980). A high quality shred would be one that has little variation in shred size and shape distribution. There is a lot of importance placed on the integrity of cheese shreds with regard to uniform size and shape, so it is crucial that the shreds retain these characteristics during handling, distribution and storage (Ni and Guansekaran 2004). In addition to uniformity of shred size and shape, it is important that the shreds do not stick to each other or the shredding equipment, mat together, or crumble. But oftentimes, cheese shreds do crumble, stick, or mat. Special processes are introduced during shredding to maintain the length of each shred so that breakage or crumbling is held to a minimum. To keep cheese shreds from matting and sticking, microcrystalline cellulose is added to

the cheese (Ni and Guansekarán 2004). The size and shape of the cheese shreds are routinely evaluated by manufacturers to ensure a high quality cheese is being produced. Assessing the size and shape of the cheese shreds can give a good indication of how well the cheese making process, handling, distribution and storage operations are running (Ni and Guansekarán 2004). There is also a lot of emphasis put on the amount of “fines” produced during shredding. Production of fines causes waste that the cheese processors would like to avoid (Dubuy 1980).

Age of the cheese at time of shred regulates the quality of shreds produced as well. Very young or newly manufactured Mozzarella cheese does not shred very well. This is due mostly to excessive free moisture at the surface and within the body of the cheese (Kindstedt 1995). When cheese is wet when shred, the particles tend to clump and mat into wet aggregates (Kindstedt 1995). The excess moisture of Mozzarella is typically absorbed back into the block of cheese after aging for a few days. In order to allow for moisture to absorb back into the cheese block, Mozzarella cheese is typically aged for four to five days prior to shredding. On the other hand, Mozzarella cheese cannot be aged too long before shredding because as it ages and as ripening occurs, the texture becomes too soft and gummy to produce high quality shreds. Since Mozzarella cheese undergoes substantial changes during short-term aging, there is a window from 4-5 days post manufacture to 20 days post manufacture that satisfactory shreds can be produced (Kindstedt 1995).

Composition of the cheese is also an important factor that regulates the shreddability of cheese. Kindstedt (1995) states that problems with surface wetness, soft body and matting are common in Mozzarella cheeses containing high moisture. In

addition, fat content affects the matting behavior of shredded Mozzarella cheese. Kindstedt (1995) reports that cheese containing 45% FBD (fat on a dry basis) showed a relatively high degree of matting whereas cheeses containing 30%, 20% and 10% showed much less matting. Masi and Addeo (1986) stated that increases in fat and moisture contents of Mozzarella cheese are accompanied by a decrease in modulus of elasticity, resulting in a softer bodied cheese and difficulty in shredding.

Another factor that is problematic in the machining of cheese is adhesion of the cheese to the processing equipment. Factors that influence this adhesion are cheese composition, texture and surface properties including surface energy. Adhesion to the blade during shredding results in a great deal of lost product. Lost product results in a loss of money for the cheese manufacturer. In order to minimize cheese adhesion to the blade and lost product, it is necessary to know what exactly promotes adhesion. If these factors can be determined, then suggestions can be made to alter cheese composition or materials used in shredding equipment to produce a cheese shredding operation that will result in less cheese adhered to the blade and therefore less lost product.

ADHESION

Adhesion is the phenomenon by which two materials stick together. In many cases adhesion is a desired property of materials such as glue and tape. In the food industry, adhesion typically presents many problems. Adhesion of food to equipment surfaces causes an increase in equipment cleaning and sanitation costs as well a reduction in efficiency due to problems such as fouling.

Many theories as to why adhesion occurs have been developed including mechanical interlocking, wetting and thermodynamic adsorption, diffusion, chemical adhesion and weak boundary layers (Michalski and others 1997). In the food industry, the theories of adhesion that are of concern are mechanical interlocking, wetting and thermodynamical adsorption. Mechanical interlocking is considered to be the simplest and oldest adhesion theory. Adhesion by means of mechanical interlocking takes place through locking between pores and flaws of the material (Michalski and others 1997).

Wetting and thermodynamic adsorption requires a more thorough explanation. Thermodynamic wetting is the extent to which a liquid will spread on the surface of a solid. An important measurement in assessing the extent of wetting is the contact angle. The contact angle is the angle formed at the junction of three phases, in this case solid-liquid-air (Dickenson 1992) (Figure 1). Complete wetting occurs when the liquid spreads on the surface of a solid and forms a contact angle of zero. Partial wetting occurs when a drop does not spread out completely on the surface and makes a contact angle of 0° to 180° at equilibrium (Binks 2001). Thermodynamic wetting is a function of four parameters included in the Young Equation:

$$\cos\theta * \gamma_{lv} = \gamma_{sv} - \gamma_{sl} - \pi_e \quad (\text{Equation 1})$$

where θ is the contact angle of the liquid on the solid, γ_{lv} is the free energy of the liquid against saturated vapor, γ_{sv} is the free energy of the solid against the saturated vapor, γ_{sl} is the free energy of the solid-liquid interface and π_e is the equilibrium pressure of adsorbed vapor of the liquid on the solid (Owens and Wendt 1969). Wetting is favored by low interfacial free energy, high solid surface energy and low liquid surface energy (Owens

and Wendt 1969). If a liquid wets the surface well, the liquid and solid have a strong affinity for each other and indicates that the liquid and the solid will adhere well (Michalski and others 1997).

Zisman introduced a concept of critical surface tension of wetting (γ_c) as a method to obtain a value for surface energy. A liquid with γ_{lv} less than γ_c would spread on the surface of the solid. Many researchers use the critical surface tension of wetting as a measurement for the free energy of the solid (γ_{sv}) also called surface energy of a solid. According to Zisman, γ_c is not necessarily equal to the solid surface free energy because it is not likely that γ_{sl} and $\pi_e = 0$ when $\theta = 0$ (Owens and Wendt 1969).

The value of the solid surface energy is valuable because the strength of attraction of an adhesive is determined by the surface energy of the material. The limiting factor in measuring surface energy is that it cannot be measured directly. The contact angle (θ) and the free energy of the liquid (γ_{lv}) can be measured directly. A method for calculating the value of surface energy has been proposed by Fowkes (1964). Fowkes suggested that the total free energy at the surface is the sum of all contributing forces at the surface. For example the surface free energy of water would be:

$$\gamma_{lv} = \gamma_l^d + \gamma_l^h \quad \text{(Equation 2)}$$

where the superscript d represents the dispersion forces and the superscript h stands for hydrogen bonding (Fowkes 1964). By assuming $\pi_e = 0$ and:

$$\gamma_{sl} = \gamma_{sv} + \gamma_{lv} - 2 \sqrt{(\gamma_s^d * \gamma_l^d)} \quad \text{(Equation 3)}$$

Fowkes derived an equation from the Young Equation to represent the contact angle of a liquid on a solid with respect to the dispersion force contributions of the solid and the liquid:

$$1 + \cos\theta = 2\sqrt{\gamma_s^d} \left(\frac{\sqrt{\gamma_l^d}}{\gamma_{lv}} \right) \quad \text{(Equation 4)}$$

Since values of γ_{lv} can be measured directly and γ_l^d has been published for many liquids, γ_s^d (component of surface energy due to dispersion forces) can be approximated from a single contact angle measurement (θ) where only dispersion forces operate (non-polar liquid or solid) (Fowkes 1964).

Extending Equation 3 to:

$$\gamma_{sl} = \gamma_{sv} + \gamma_{lv} - 2\sqrt{\gamma_s^d * \gamma_l^d} - 2\sqrt{\gamma_s^h * \gamma_l^h} \quad \text{(Equation 5)}$$

creates an assumption where dispersion forces and hydrogen interactions operate. Again, from the Young Equation, Fowkes derived an expression for the contact angle of a liquid on a solid in terms of dispersion, hydrogen and dipole-dipole interactions:

$$1 + \cos\theta = 2\sqrt{\gamma_s^d} \left(\frac{\sqrt{\gamma_l^d}}{\gamma_{lv}} \right) + 2\sqrt{\gamma_s^h} \left(\frac{\sqrt{\gamma_l^h}}{\gamma_{lv}} \right) \quad \text{(Equation 6)}$$

In this equation, the γ_{lv} can be obtained from direct measurement, and γ_l^h from available values of γ_{lv} and γ_l^d , through Equation 2 (Fowkes 1964). The remaining unknowns are γ_s^d and γ_s^h . Owens and others (1969) explains that by measuring θ of two different liquids against the same solid, simultaneous equations are obtained which can be solved to get γ_s^d and γ_s^h . Once the components of the solid

surface energy are calculated, the total solid surface energy can be calculated by adding the components that contribute to solid surface energy together:

$$\gamma_{sv} = \gamma_s^d + \gamma_s^h.$$

Knowing the surface energy of a solid can give an indication as to how well an adherend will adhere to the solid.

PRESSURE SENSITIVE ADHESION

Pressure sensitive adhesives are materials that adhere when brought in contact with a surface under light pressure but have sufficient cohesiveness that they can be peeled away from the surface without leaving a residue (Dahlquist 1989). Pressure sensitive tack is the underlying property of pressure sensitive adhesion (Saunders and others 1992). The energy required to separate two materials that are not bound permanently is a measure of tack (Russell and Kim 1999). The thumb test for tack is a very crude test for tack, but is still a measure of tack. The thumb test for tack is when an adhesive is touched with the thumb to assess the degree of stickiness. The dwell time and force applied when assessing the degree of tack with the thumb are important factors in this test (Dahlquist 1959). These factors also are important in other less crude tests that measure tack. Tack is generally regarded as a property that is associated and measured with low contact pressures as well as short contact times (Hammond 1989).

The concept of critical surface tension is important to pressure sensitive adhesion as well as to liquid adhesives. An adhesive with a surface tension less than the adherend's critical surface tension will be expected to spread on the surface of the solid (Hammond

1989). Surface chemistries and molecular interaction energetics are the driving potential for adhesive bonds; the adhesive's physical properties establish the rate and extent of contact for the bond strength (Hammond 1989). Toyama and others (1970) have reported that a maximum probe tack can be achieved when the surface energy of the adhesive is slightly greater than that of the adherend.

Pressure-sensitive adhesives (PSAs) are viscoelastic under conditions of use. Pressure sensitive adhesives must contain a viscous portion to flow and dissipate energy during the bonding process. They must also be elastic and store bond rupture energy to allow for good peel and tack performance (Benedek and Heymans 1997). The viscoelastic properties of PSAs are controlled by an elastomer-resin system. The elastomer portion contributes to the elastic component and the viscous portion is composed of a low molecular weight tackifying resin (Saunders and others 1992). Broad molecular weight distribution provided by the elastomer and resin portions contributes to good tack and good cohesive strength (Casey 1989).

The performance of PSAs depends on the viscoelastic response of the material as well as the surface energies of the adhesive and the adherend (Heddelson and others 1993). When the adherend surface energy is less than the surface energy of the adhesive, bond formation becomes a complicated function of surface energies and viscoelasticity of the adhesive (Saunders and others 1992). Although, Zosel (1985) reported that when the surface energy of the adherend (e.g. metal) is much higher than the adhesive (e.g. organic polymer) it is assumed that the performance of the PSA is independent of the surface energy of the adherend. When the surface energy of the adherend is greater than the surface energy of the adhesive, adhesion is dictated by the viscoelastic properties of the

adhesive material. Rheological factors are the key factors driving the phenomenon of pressure-sensitive tack when surface energy no longer contributes to the adhesive forces (Hammond 1989).

PSAs must have sufficient compliance to conform to the surface topography and they must relax so that stored energy due to elastic forces will be dispersed before forces of adhesion are overcome (Dahlquist 1989). In addition, the PSAs must resist flow under stress and maintain elastic cohesiveness (Dahlquist 1989). A rheological criterion for tack was discovered by Dahlquist. The Dahlquist criterion states that tack will not occur when the storage modulus (G') of the adhesive is greater than 10^5 Pa (Dahlquist 1989). But according to Dahlquist (1989), having high compliance only is not enough to ensure pressure sensitive tack.

PSAs must contain a high degree of tack and the ability to rapidly wet the surface where it is applied for instant bonding with little pressure due to the viscous properties. It must also have sufficient cohesion and elasticity to be lifted off without residue left on the surface (Benedek and Heymans 1997). The viscosity of PSAs is dependent upon the rate of shear. At low strain rates, resistance to debonding is low because the viscous components dissipate energy. When shear rates are high, flow is reduced and the elastic modulus is increased which results in additional stored energy and an increase in resistance to debonding. In addition to being strain-rate dependent, PSAs are also temperature dependent. When the temperature decreases, the flow of the molecules is restricted and the elastic modulus is increased (Benedek and Heymans 1997).

A condition that is important to note is whether bond failure in pressure sensitive adhesion is adhesive or cohesive. Cohesive failure occurs when residue is left on the

adherend and adhesive failure occurs when the adhesive cleanly separates from the adherend. Saunders and others (1992) state that adhesion of food materials may not be as big of a problem if they exhibit adhesive failure. Meaning that they have sufficient cohesive strength to hold the food material together. The mode of failure is a function of rate of separation and temperature and is also determined by polymer viscoelastic properties (Saunders and others 1992).

The glass transition temperature (T_g , amorphous polymers become soft and flexible above this temperature) and the storage modulus have been found to be important factors in determining a good pressure sensitive adhesive (Foley and Chu 1986). Foley and Chu (1986) found that maximum tack values of pressure sensitive adhesives were obtained at a storage modulus range of 5×10^4 to 1×10^5 Pa with a T_g between -10°C and 10°C .

With the knowledge of pressure sensitive adhesives, it may be possible to relate these characteristics to food products that are viscoelastic in nature. Pressure sensitive adhesion may be able to explain how some food products adhere to processing surfaces. For example, wheat flour dough mixtures stick to processing equipment through adhesive bonding. Their behavior is synonymous with that of pressure sensitive adhesives due to their viscoelasticity during use (Heddleson 1993). Cheese is also a viscoelastic material. Perhaps the behavior of cheese will be similar to that of wheat flour dough and will act as a pressure sensitive adhesive. The adhesiveness of cheese may be a factor in determining the shreddability of the cheese.

MEASUREMENT OF PRESSURE SENSITIVE ADHESION

One of the oldest and most widely used tack tests is the rolling ball tack test. According to the Pressure Sensitive Tape Council, this method is done by rolling a 11-mm diameter stainless steel ball down an inclined track. At the bottom of the track, the ball comes in contact with the horizontal, upward facing adhesive (Hammond 1989). The distance the ball travels is a measure of the tack. The greater the distance the ball rolls, the less tacky the adhesive.

Another test used for measurement of pressure sensitive adhesion is the peel test. Typically in this test, a loop of adhesive is formed with the adhesive side out. The loop is brought into contact with a solid surface under light pressure. Then the force required to remove the adhesive is measured as an assessment of tack. Another type of peel test is one that is called the “Quick Stick” test developed by the Pressure Sensitive Tape Council (Hammond 1989). In this test the adhesive is placed on a flat stainless steel plate with no contact pressure other than the weight of the adhesive. The tape is peeled from the surface at 90 degrees at 300 mm/min and the force required to peel is used as the tack value.

The probe tack test is yet another method for measuring the tack of a pressure sensitive adhesive. The probe tack test is a simulation of the thumb or finger tack test. In this test, the probe is brought into contact with a supported adhesive under low contact pressures for a short time and then pulled away at a fixed rate (Hammond 1989). During this test the peak force needed to remove the probe from the surface of the adhesive surface is measured. In addition, the amount of energy needed to separate the probe from

the surface of the adhesive is also measured. This measurement is known as tack energy or work of adhesion. The measured probe tack is dependent upon the probe material, the temperature at which the test is run, force applied, contact time and rate of probe removal (Hammond 1989).

FOOD ADHESION

Food adhesion can be very problematic for food manufacturers. Adhesion of food materials to processing equipment can cause an increase in surface cleaning costs, a reduction in efficiency due to sanitation problems and fouling (Michalski and others 1997). Adhesion of food can be attributed to wetting, thermodynamic adsorption, mechanical interlocking and pressure sensitive adhesive properties. In most food systems, the adhesion force is a combination of adhesive force and cohesive force or the force required to hold the food material together (Hosney and Smewing 1999). They found that foods could be described as sticky when they had a high adhesive force and a low cohesive force. There are many issues involved with food adhesion that remain unresolved. This is due to the fact that the manifestation of adhesiveness and its sensory perception vary according to the type of food. Because of this, there is no universally accepted method for measuring stickiness in the food industry (Dobraszyk 1997). Many studies have been done to evaluate adhesion of food products to specific surfaces or food packaging. Of these, the most common food products are fish, dough and rice (Michalski and others 1997). Other studies look into components of food and how they adhere to the surface of processing equipment.

Dough is often studied in relationship to adhesion to various surfaces. This is because dough is typically very adhesive. Dough that has very high adhesiveness can cause serious problems during processing such as production stoppages, product loss and contamination (Dobraszczyk 1997). Heddleson and others (1993) showed how tack increased with an increase in temperature up to 45-50°C. Once passed 50°C, the tack decreased dramatically because the shear storage modulus of the dough surpassed that of the Dahlquist Critereon of 10^5 Pa. Dobraszczyk (1997) used a modified peel test to measure adhesion as a function of moisture content, peel rate and initial peeling layer thickness. From this investigation, it was found that peel force was highly dependent upon the peel rate and adhesion of the dough was mostly dependent upon dough rheology.

In the case of fish meat adhesion, problems can occur with fish meat adhering to the inside of the can (Michalski and others 1997). It was also reported that this adhesion was greater when freshness decreased. Fish meat adhesion can also be of concern with plastic packaging. Surface energy has been determined to be important when researching the adhesion of fish meats to films and casings. For example, Nishino and others (1991) found that plastic films and casings with very good wettability showed better adhesion than films of lower wettability.

Michalski and others (1999) reported in a study of emulsions of mayonnaise-like composition that the amount of an emulsion adhered increased as the solid surface energy (solid-air interface) increased. In this study they found relationships between surface energy and rheology of the emulsion. They were able to determine which of these properties drives adhesion most in different situations. For a low surface energy solid,

surface energy is what governs the adhesion of emulsions to the solid. For a medium surface energy solid, such as stainless steel, both rheological and surface properties affect adhesion of emulsions. For a high surface energy solid, once spreading of the emulsion occurs, adhesion is governed by rheology (Michalski and others 1999). They also reported that the adhesion decreased with an increase in fat droplet size (Michalski and others 1999).

Cheesemaking can be a problematic process due to adhesion to processing equipment. Berridge and Scurlock (1976) found in continuous cheese making machines, adsorption of coagulated milk proteins on surfaces resulted in the adhesion of curdled milk, particularly on stainless steel. It was found that casein adheres more to hydrophobic surfaces (steel, PTFE, paraffin) and practically none adheres to hydrophilic surfaces such as cellulose or starch.

CONCLUSION

The adhesion of cheese to processing equipment may occur through similar mechanisms of pressure sensitive adhesion. Measuring the surface energy of the cheese and stainless steel that is typically found in processing equipment (Grade 304, also known as 1810) will help to determine if the adhesion will be dictated mostly by rheology or by a combination of rheology and surface energy properties. If cheese follows the model for pressure sensitive adhesion, then if the surface energy of the stainless steel is greater than the surface energy of the cheese being shred, then any adhesion occurring can be further characterized by rheology since adhesion will be

mostly dependent on the viscoelasticity of the cheese. If the surface energy of the stainless steel is less than the surface energy of the cheese, adhesion of the cheese will be determined by a combination of both surface energetics as well as rheological properties. Since adhesion of cheese to stainless steel may have an impact on the quality of shreds produced, it is important to understand what drives the adhesion. Table 1 outlines factors that affect shred quality including adhesion due to pressure sensitive adhesion. When it is understood what makes low quality cheese shreds, the cheese may then be formulated to have rheological properties or surface properties that can be conducive to producing high quality shreds.

REFERENCES

- Apostolopoulos C, Marshall RJ. 1994. A quantitative method for the determination of shreddability of cheese. *Journal of Food Quality* 17: 115-128.
- Benedek, I, and Heymans, LC. 1997. Pressure-sensitive adhesives technology. New York: Marcel Dekker Inc.k
- Berridge NJ, Scurlock PG. 1976. Adhesion of coagulating protein (casein) to various surfaces. *Journal of Dairy Science*. 59(8):1401-1408.
- Binks, BP. 2001. Wetting: theory and experiment. *Current opinion in colloid and interface science*. 6:17-21.
- Casey, AZ. 1989. Resin Dispersions. In: Satas, D, editor. *Handbook of Pressure Sensitive adhesive Technology*. 2nd ed. New York: Van Nostrand Reinhold. 545-566.
- Creamer LK, Olson NF. 1982. Rheological evaluation of maturing Cheddar cheese. *Journal of Food Science*. 47: 631-636
- Creamer, LK, Lawrence, RC, Gilles, J. 1985. Effect of acidification of cheese milk on the resultant Cheddar cheese. *NZ J Dairy Sci. Technol*. 20:185.
- Dahlquist, CA. 1959. An investigation into the nature of tack. *Adhesive Age*. October: 25-29.
- Dahlquist, CA. 1989. Creep. In: Satas, D, editor. *Handbook of Pressure Sensitive adhesive Technology*. 2nd ed. New York: Van Nostrand Reinhold. p97-114.
- Dickenson, E. 1992. Surface Activity. Chapter 2 in *An Introduction to food colloids*. Oxford University Press: New York. 32-50.

- Dobraszczyk, BJ. 1997. The rheological basis of dough stickiness. *Journal of Texture Studies*. 28:139-162.
- Dubuy, MM. 1980. The French art of shredding cheese. *Food Processing Industry*. 49: 52-53.
- Farkye, N. 1995. Contribution of milk-clotting enzymes and plasmin to cheese ripening. In: Malin, EL, Tunick, MH, editors. *Chemistry of structure-function relationships in cheese*. New York: Plenum Press. p 195-208.
- Fedrick, IA and Dulley, JR. 1984. The effect of elevated storage temperatures on the rheology of Cheddar cheese. *New Zealand Journal of Dairy Science and Technology*. 19:141.
- Fife RL, McMahon DJ, Oberg CJ. 1996. Functionality of low fat Mozzarella cheese. *Journal of Dairy Science* 79: 1903-1910.
- Foley, KF, Chu, S. 1986. Rheological characterization of elastomer latexes for pressure sensitive adhesives. *Adhesives Age*. 29: 24-28.
- Fowkes, F.M. 1964. Attractive forces at interfaces. *Ind. Engr. Chem*. 56(40): 40-52.
- Fox, PF. 1987. Cheese: An overview. In: Fox, PF, editor. *Cheese: Chemistry, Physics and Microbiology*. Vol 1. New York: Elsevier Applied Science. 1-32.
- Fox, PF. 1989. Proteolysis during cheese manufacture and ripening. *Journal of Dairy Science*. 72: 1379-1400.
- Fox, PF and Guinee, TP. 1987. Italian Cheeses. In: Fox, PF, editor. *Cheese: Chemistry, Physics and Microbiology*. Vol 2. New York: Elsevier Applied Science. P 221-255.

- Gersema, E. August 24, 2003. Pizza spurs rise in cheese consumption. *The Journal Gazette*. Associated Press.
- Grappin, R, Rank, TC, Olson, NF. 1985. Primary Proteolysis of cheese proteins during ripening: A review. *Journal of Dairy Science*. 68:531-540.
- Hammond, FH. 1989. Tack. In: Satas, D, editor. *Handbook of pressure sensitive adhesive technology*. 2nd ed. New York: Van Nostrand Reinhold. p 38-60.
- Heddleson, SS, Hamann, DD, Lineback, DR. 1993. The Dahlquist Critereon: Applicability of a rheological criterion to the loss of pressure-sensitive tack in flour-water dough. *Cereal Chemistry* 70(6): 744-748.
- Hosney, RC and Smewing, J. 1999. Instrumental measurement of stickiness of dough and other foods. *Journal of Texture Studies* 30: 123-136.
- Jack FR, Paterson A. 1992. Texture of hard cheeses. *Trends in Food Science and Technology* 3: 160-164.
- Johnson, M, Law, BA. 1999. The origins, development and basic operations of cheesemaking technology. In: Law, BA, editor. *Technology of cheesemaking*. USA: CRC Press. 1-32.
- Kindsteadt, PS. 1995. Factors affecting the functional characteristics of unmelted and melted Mozzarella cheese. In: Malin, EL, Tunick, MH, editors. *Chemistry of structure-function relationships in cheese*. New York: Plenum Press. 27-41.
- Kindstedt, PS, Kiely, LJ, Gilmore, JA. 1992. Variation in composition and functional properties within brine-salted Mozzarella cheese. *Journal or Dairy Science* 75: 2913-2921.

- Kindstedt, PS, Larose, KL, Gilmore, JA and Daivs, L. 1996. Distribution of salt and moisture in Mozzarella cheese with soft surface defect. *Journal of Dairy Science* 79:2278-2283.
- Law, BA. 1987. Proteolysis in relation to normal and accelerated cheese ripening. In: Fox, PF, editor. *Cheese: Chemistry, Physics and Microbiology*. Vol 1. New York: Elsevier Applied Science. 365-388.
- Lawrence, RC, Creamer, LK, Gilles, J. 1987. Texture development during cheese ripening. *Journal of Dairy Science*. 70: 1748-1760.
- Ledford, RA, O'Sullivan, AC and Nath, KR. 1966. Residual casein fractions in ripened cheese determined by polyacrylamide gel electrophoresis. *Journal of Dairy Science*. 49:1098.
- Masi P, Addeo F. 1986. An examination of some mechanical properties of a group of Italian cheeses and their relationship to structure and conditions of manufacture. *Journal of Food Engineering* 5(3): 217-229.
- McMahon, DJ, Fife, RL, Oberg, CJ. 1999. Water partitioning in Mozzarella cheese and its relationship to cheese meltability. *Journal of Dairy Science*. 82: 1361-1369.
- Michalski MC, Desobry S, Babak V, Hardy J. 1999. Adhesion of food emulsions to packaging and equipment surfaces. *Colloids and Surface A: Physicochemical and Engineering Aspects* 149:107-121.
- Michalski MC, Desobry S, Hardy, J. 1997. Food Materials Adhesion: A Review. *Critical Reviews in Food Science and Nutrition* 37(7): 591-619.
- Mulvihill, DM, Fox, PF. 1979. Proteolytic specificity of chymosin on bovine α_{s1} -casein. *Journal of Dairy Research*. 46:641.

- National Dairy Council. 2000. Newer knowledge of dairy foods: Cheese.
- Ni, H, and Guansekar, S. 2004. Image processing algorithm for cheese shred evaluation. *Journal of Food Engineering*. 61(1): 37-45.
- Nishino, H, Tanaka, M and Yokoyama, M. 1991. Studies on adhesion of fish meat products to casing in retort sterilized sausage. IV. Effect of surface properties of plastic casings on meat adhesion of retort sterilized fish sausage. *Nippon Suisan Gakkaishi*. 57(4): 667-671.
- Noomen, A. 1978. Activity of proteolytic enzymes in simulated soft cheeses (Meschanger type). 1. Activity of milk protease. *Netherlands Milk and Dairy Journal*. 32:26.
- Owens DK, Wendt RC. 1969. Estimation of the Surface Free Energy of Polymers. *Journal of Applied Polymer Science* 13:1741-1747.
- Richardson, BC. 1983. The proteinases of bovine milk and the effect of pasteurization on their activity. *New Zealand Journal of Dairy Science and Technology*. 18:233-245.
- Ridgway, J. 1999. *The cheese companion*. Philadelphia: Running Press.
- Russell, TP, Kim, HC. 1999. Tack-A sticky subject. *Science*. 285(5431):1219-1221.
- Saunders, SR, Hamann DD and Lineback, DR. 1992. A systems approach to food material adhesion. *Lebensmittel-Wissenschaft und Technologie*. 25: 309-315.
- Scott, R. 1986. *Cheesemaking practice*. Elsevier: New York. P 186-212.
- Somers, JM and Kelly, AL. 2002. Contribution of plasmin to primary proteolysis during ripening of cheese: effect of milk heat treatment and cheese cooking temperature. *Lait*. 82: 181-191.

- Sousa, MJ, Ardo, Y, McSweeney, PLH. 2001. Advances in the study of proteolysis during cheese ripening. *International Dairy Journal*. 11:327-345.
- Toyama, M, Ito, T and Moriguchi, H. 1970. Studies on tack of pressure-sensitive adhesive tapes. *Journal of applied polymer science*. 14:2039-2048.
- USDA. 2002. Dairy products annual summary.
- USDA/ERS. 2002. Livestock, dairy and poultry, situation and outlook.
- USDA. 1969. Cheese varieties and descriptions. *Agriculture handbook 54*.
Washington, DC.
- Zosel, A. 1985. Adhesion and tack of polymers: Influence of mechanical properties and surface tensions. *Colloid and Polymer Science* 263:541-553.

Factors Regulating Shreddability Of Cheese

J. L. Childs*, E. A. Foegeding*, C. R. Daubert*, L. Stefanski[†]

*Department of Food Science

[†]Department of Statistics

North Carolina State University

INTRODUCTION

Cheese is one the most important foods where shredding is used extensively by both the consumer and the manufacturer (Apostolopoulos and Marshall 1994). Shredding allows for faster melting of cheese as compared to other methods of size reduction such as slicing and cubing (Ni and Guansekaran 2004).

The term “shreddability” is a broad term that encompasses many characteristics of shredded cheese. It can take into account the ease at which the block of cheese is processed through the shredding machine, the geometry and integrity of the cheese shreds (length and thickness of cut, ragged or clean edges), the propensity of shreds to remain free flowing or mat together after shredding, the propensity of shredded particles to shatter into fines either during or after shredding (Kindstedt 1995). If cheese is soft, pasty or wet the shredder can become clogged with gummy cheese and the shredded cheese may produce shreds with ragged edges, many fines, “gummy balls” of cheese and excessive matting of the cheese shreds. In contrast, if the cheese is too firm and dry, the resulting shreds are typically shattered into smaller particles and fines (Kindstedt 1995).

Ideally, cheese shreds should be uniformly and precisely cut, which allows the cheese to melt evenly and easily when used in hot dishes or as a topping (Dubuy 1980). A high quality shred would be one that has little variation in shred size and shape distribution. There is a lot of importance placed on the integrity of cheese shreds with regard to uniform size and shape, so it is crucial that the shreds retain these characteristics during handling, distribution and storage (Ni and Guansekaran 2004). In addition to uniformity of shred size and shape, it is important that the shreds do not stick to each other or the shredding equipment, mat together or crumble. But often, cheese shreds do

crumble, stick or mat. Special processes are introduced during shredding to maintain the length of each shred so that breakage or crumbling is held to a minimum. To keep cheese shreds from matting and sticking, microcrystalline cellulose is added to the cheese (Ni and Guansekaran 2004). There is also a lot of emphasis put on the amount of “fines” produced during shredding. Production of fines causes waste that the cheese processors would like to avoid (Dubuy 1980).

There are many factors that regulate the production of a high quality shred (Table 1). Composition of the cheese is one important factor that regulates the shreddability of cheese. Kindstedt (1995) states that problems with surface wetness, soft body and matting are common in Mozzarella cheeses containing high moisture. In addition, fat content affects the matting behavior of shredded Mozzarella cheese. Kindstedt (1995) reports that cheese containing 45% FBD (fat on a dry basis) showed a relatively high degree of matting whereas cheeses containing 30%, 20% and 10% showed much less matting. Masi and Addeo (1986) stated that increases in fat and moisture contents of Mozzarella cheese are accompanied by a decrease in modulus of elasticity, resulting in a softer bodied cheese and difficulty in shredding.

Age of the cheese at time of shred regulates the quality of shreds produced as well. Very young or newly manufactured Mozzarella cheese does not shred very well. This is due mostly to excessive free moisture at the surface and within the body of the cheese (Kindstedt 1995). When cheese is wet when shred, the shredded particles tend to clump and mat into wet aggregates (Kindstedt 1995). The excess moisture of Mozzarella is typically absorbed back into the block of cheese after aging for a few days. In order to allow for moisture to absorb back into the cheese block, Mozzarella cheese is typically

aged for four to five days prior to shredding. On the other hand, Mozzarella cheese cannot be aged too long before shredding because as it ages, the texture becomes too soft and gummy to produce high quality shreds. Since Mozzarella cheese undergoes substantial changes during short-term aging, there is a window from 4-5 to 20 days post manufacture to produce satisfactory shreds (Kindstedt 1995).

Another problematic factor in the machining of cheese is adhesion to the processing equipment. Factors that influence adhesion are cheese composition, texture and surface properties including surface energy. Texture and surface properties combine to cause adhesion due to pressure sensitive properties. Pressure sensitive adhesives are materials that adhere when brought in contact with a surface under light pressure but have sufficient cohesiveness that they can be peeled away from the surface without leaving a residue (Dahlquist 1989). The performance of pressure sensitive adhesives depends on the viscoelastic response of the material as well as the surface energies of the adhesive and the adherend (Hedderson and others 1993). When the adherend surface energy is less than the surface energy of the adhesive, bond formation becomes a complicated function of surface energies and viscoelasticity of the adhesive (Saunders and others 1992). Although, Zosel (1985) reported that when the surface energy of the adherend is much higher than the adhesive, it is assumed that the performance of the pressure sensitive adhesive is independent of the surface energy of the adherend.

In addition to surface energies of the adherend and adhesive, Dahlquist discovered a rheological criterion for tack. The Dahlquist criterion states that tack will not occur when the storage modulus (G') of the adhesive is greater than 10^5 Pa (Dahlquist 1989). Foley and Chu (1986) found that maximum tack values of pressure sensitive adhesives

were obtained at a storage modulus range of 5×10^4 to 1×10^5 Pa with a T_g between -10°C and 10°C.

Adhesion to the blade during shredding results in a great deal of lost product, resulting in a loss of money for the cheese manufacturer. In order to minimize cheese adhesion and lost product, it is necessary to know what promotes adhesion. The objective of this experiment was to evaluate how texture and the combination of texture and surface energy come together to cause adhesion of cheese to shredding equipment as well as a decrease in overall shreddability.

MATERIALS AND METHODS

Commercial Cheese

Three types of cheeses were purchased from the store and will be referred to as commercial cheeses. These three cheeses were Thumann's Mozzarella (Carlstadt, NJ), Land O' Lakes Process American (Arden Hills, MN) and Kraft Monterey Jack (Glenview, IL.). All cheeses were deli style cheeses purchased as approximately five-pound blocks. Proximate composition of the three cheeses can be found in Table 2. Cheese is typically shredded at refrigeration temperature so testing temperature was 4°C. In order to observe effects of temperature increase on shreddability of cheese, the cheeses were also tested at 12°C and 20°C. All tests were replicated on three different lots of cheese.

Experimental Cheese Set A

The cheeses used in Experimental Cheese Set A were made at the University of Wisconsin (Madison, WI) Dairy Plant. There were three different Mozzarella cheeses made with varying levels of fat and protein with moisture content remaining the same for all three cheeses (Table 2). Creep and recovery were done at 25°C, and all remaining tests were performed at 7°C. The day the cheeses were manufactured was labeled as Day 0, and tests were done on Day 2, Day 7, Day 14, Day 21 and Day 28 to observe aging effects. All tests were replicated three times on three different batches of cheese.

Experimental Cheeses Set B

For Experimental Cheese Set B, four cheeses were made in the University of Wisconsin, Madison Dairy Plant. These cheeses were formulated around the lowest fat cheese from Experimental Cheese Set A. The four cheeses were formulated to have differing levels of moisture and calcium. A low calcium-low moisture (LC-LM), low calcium-high moisture (LC-HM), high calcium-low moisture (HC-LM) and high calcium-high moisture (HC-HM). Composition of the four cheeses can be found in Table 2. The cheeses were tested on day 2, 7, 14, 21 and 28, all at 7°C. Tests were replicated three times with three different batches of cheese.

Shreddability

The shreddability of cheese was assessed by shredding the cheese in a food processor (Cuisinart, East Windsor, NJ) equipped with a Grade 304 or 1810 (18% Chromium, 10% Nickel) stainless steel shredding blade. The cheese was cut into blocks of 4 cm width, 4 cm height and 9 cm length. Since Mozzarella cheese has a definite fiber orientation, the cheeses were cut so that the fibers were parallel to the shredding blade along the length of the rectangle of cheese. This was done to eliminate any effects that fiber orientation may have on shreddability. Before shredding the block of cheese, food processor cup, blade and food processor top were weighed. The block of cheese was placed in the chute of the food processor and shred under a constant load of 4 Kg. The food processor blade and top were weighed after shredding to determine the weight of adhered cheese. The food processor cup was then weighed to determine how much cheese remained for the shred analysis. The shredded cheese was shaken for five seconds

through two sieves with openings of 12.7 mm² (½ in²) and 6.35 mm² (¼ in²). The shreds that did not fall through the 12.7 mm² sieve were classified as long shreds, the shreds that did not fall through the 6.35 mm² sieve were classified as short shreds and the ones that fell through the 6.35 mm² sieve were classified as fines. Since the shreds were long and thin it was possible for the shreds to fall through the holes lengthwise, if this occurred it was necessary to pick through the shreds by hand and separate the long shreds and short shreds that fell to the lower levels. The percentage of cheese that adhered to the blade, cheese that adhered to the top of the food processor, long shreds, short shreds and fines were calculated and used to evaluate the shreddability of the cheese.

Tack

The adhesiveness of the cheese was measured using a TAX-T2 Texture Analyzer (Texture Technologies, Scarsdale, NY) with a flat, 13 mm diameter, stainless steel probe. The cheeses were cut into squares with a length and width of 4 cm and sliced to 6.35 cm thick. The cheese was placed on a platform below the probe arm. The probe was brought to the surface of the cheese at a speed of 1 mm/s. Once the probe reached the surface of the cheese, a force of 2.0 N was applied and held on the surface for five seconds. After five seconds, the probe was removed at a speed of 0.1 mm/s. As the probe was removed, a graph was produced that showed the maximum force needed to separate the probe from the surface as well as the energy required to separate the probe from the cheese. The maximum force, or tack force, was represented by the peak of the graph. The tack energy was represented by the area under the curve (Figure 2). This test was performed three times on each cheese and the values of the peak of the curve and the

area under the curve were averaged. Tack energy values were initially in g·s and had to be converted to mJ/m². Conversion of g·s to mJ/m² can be found below.

Conversion of g·s to mJ/m² for Tack Energy

$$F \cdot d = N \cdot m$$

$$N \cdot m \equiv \left(\frac{\text{kg} \cdot \text{m}}{\text{s}^2} \right) \cdot \text{m}$$

$$\equiv \frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} \cdot \frac{\text{s}}{\text{s}}$$

$$\equiv (\text{kg} \cdot \text{s}) \cdot \frac{\text{m}^2}{\text{s}^3}$$

$$\equiv (\text{kg} \cdot \text{s}) \cdot \left(\frac{\text{m}}{\text{s}^2} \right) \cdot \left(\frac{\text{m}}{\text{s}} \right) = \frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} = 1 \text{ J}$$

$$\text{kg} \cdot \text{s} = \text{"Work" of Adhesion} = 1000 \text{ g} \cdot \text{s}$$

$$\frac{\text{m}}{\text{s}^2} = \text{Acceleration due to gravity} = \frac{9.8 \text{ m}}{\text{s}^2}$$

$$\frac{\text{m}}{\text{s}} = \text{Withdrawal rate of probe}$$

$$\frac{\text{J}}{1000} = \text{mJ}$$

$$\frac{\text{mJ}}{\text{m}^2}$$

$$\text{m}^2 = \text{area of probe}$$

Surface Energy

The surface energy measurements were made with a Ramè-Hart goniometer (Model 100-00 115, Ramè-Hart Inc., Mountain Lakes, NJ) (Development of this method can be found in Appendix 1). Surface energy measurements were made by using two solutions with different polarity, formamide and dimethyl sulfoxide. A 12 μ L solution drop was suspended from the tip of a 16-gauge stainless steel non-sterile needle (Popper and Sons, Inc., New Hyde Park, NY). The solution drop was lowered to the surface of the cheese. Once in contact with the surface, the drop detached from the needle and the measurement started within one second of the drop being placed on the surface of the cheese. The contact angles of both sides of the drop were measured at one-second intervals for five seconds (Figure 1). This process was repeated ten times over a total of, at least, three slices of cheese. The Drop Image software package was used for all data calculations.

Rheological Characterization

Rheological analysis of the cheese was done by a creep and recovery test. A smooth parallel plate configuration was used on a Stresstech Rheometer (ATS RheoSystems, Bordentown, NJ). The diameter of the parallel plate was 20 mm, and the sample gap was 2 mm. Cheese was sliced to a thickness of 2mm (on a deli slicer) and glued to the top and bottom parallel plates with superglue (Loctite 401, Loctite Corp., Rock Hill, CT) to avoid slip while running the creep and recovery tests. Once the cheese was glued to the plates, a synthetic lubricant (Synco Chemical Corp, Bohemia, NY) was spread around the edge of the cheese to prevent drying. A stress sweep was run from 0 to

500 Pa to determine the linear viscoelastic region of the cheeses. When this test was complete G^* remained constant for all the stresses applied to the cheese. Therefore a constant stress of 100 Pa was used for additional dynamic tests. The constant stress was applied to the cheese for 10 min and then the cheese was allowed to recover for 20 min. Maximum compliance was the highest value for compliance during the creep portion of the test, which was typically found at the last time point during creep. G' was calculated at the reciprocal of maximum compliance. Retardation time was calculated as the time where the strain reached 63.2% ($1 - \frac{1}{e}$) of its maximum. Commercial cheeses were tested at 4°C, 12°C and 20°C. In an industrial setting, most cheese is shred at refrigeration temperatures. That is why 4°C was chosen for the commercial cheeses. The remaining two temperatures 12°C and 20°C were chosen to observe how temperature increases affected cheese properties and, in turn, shreddability. Cheeses in Experimental Cheese Set A were tested at 25°C. Cheeses in Experimental Cheese Set B were tested at 7°C.

Statistical Analysis

The experimental design used for testing the commercial cheeses, Experimental Cheese Set A and B was a randomized complete split plot design. For the commercial cheeses, the five-pound samples of cheese were the whole plot units and the three different cheeses were the whole plot treatments. Each five-pound sample of cheese was split into three sub plot units and the sub plot treatments applied were the three different temperatures of 4°C, 12°C and 20°C. The three replications acted as blocks of the experiment. For Experimental Cheese Set A and B, the same design was used. The

different formulations were the whole plot treatments and day of testing was the sub plot treatment. The three replications acted as blocks of the experiment.

The general linear model (PROC GLM) using SAS statistical software package (Version 8, SAS Institute, Inc. Cary, NC) allowed for distinguishing statistically significant differences between whole plot treatments and sub plot treatments.

Correlational analysis (PROC CORR) using SAS statistical software package allowed for determination of relationships among parameters of cheese functionality.

RESULTS AND DISCUSSION

Commercial Cheeses

Commercial cheeses were evaluated to observe how properties of cheese such as rheology, tack and surface energy affect shreddability. The shred distribution graphs (Figures 3a-c) show the differences produced during shredding for the Monterey Jack, Mozzarella and process cheeses. In shredding there were two different defects that were observed to diminish the shreddability of the cheese. These defects were production of fines and adhesion of cheese to the blade. In this case, fines were any shred that was less than 6.35 mm ($\frac{1}{4}$ ") long. Mozzarella produced the greatest amount of fines of the three cheeses. At all three temperatures, fines produced were greater than twenty percent. Monterey Jack and process cheese both produced about the same amount of fines during shredding, which was much less than the Mozzarella cheese. The fines produced when shredding Mozzarella cheese were significantly greater ($p < 0.05$) than those from Monterey Jack and process cheese (Table 3). Although the Monterey Jack and the process cheese produced less fines, they both had more cheese adhere to the blade during shredding. The amount of fines produced for Mozzarella increased with increasing temperature and the amount of cheese adhered to the blade increased with increasing temperature (Figure 3a-c). The increase in temperature caused a statistically significant increase in adhesion of cheese to the blade for both Monterey Jack and process cheese (Table 3). Both of these defects caused the percentage of long shreds, the most desirable of the shreds, to decrease as the temperature increased.

Proximate composition for all three commercial cheeses can be found in Table 2. In reference to Table 1, cheeses with high moisture and fat content will have a decrease in shreddability. Mozzarella had the highest moisture and the lowest fat of the three cheeses. Monterey Jack and process cheese had a high fat content ($\geq 45\%$ on a dry basis). Mozzarella, the higher moisture cheese, had more fines produced during shredding and Monterey Jack and process cheeses, the higher fat cheeses, had more cheese adhere to the blade. The composition may be important when evaluating shreddability, but there are other factors that must be taken into consideration such as processing methods and age when comparing shreddability.

Rheological properties contribute to two factors affecting shreddability. First, overall firmness has been associated with shreddability (Table 1). Second, rheology plays an instrumental part in tack energy and pressure sensitive adhesion. Creep and recovery of all three cheeses over all three temperatures can be seen in Figures 4a-c. Mozzarella was the most compliant of the three cheeses at 12°C and 20°C, meaning that it has a softest texture of the three cheeses at these two temperatures. The Mozzarella cheese also had the most fines produced during shredding at all three temperatures. The softer texture may have caused the increase in fines produced during shredding. In addition to the soft texture, a possible cause for production of fines is the fibrous nature of Mozzarella cheese. After shredding, the fibers may separate allowing the cheese to shatter into fines once the cheese is shred. Since the other two cheeses do not have this fibrous structure, it may explain why Mozzarella had so many more fines produced during shredding. In addition, the maximum compliance increases as the temperature increases. Therefore, as the temperature increased, the cheese became softer and more

finer particles were produced. Kindsteadt (1995) commented that soft cheese can cause the shredder to become clogged with gummy cheese and also produce many fines during.

Rheological properties as well as adhesion of the cheese to shredding equipment will influence shreddability of cheese. In order to evaluate adhesion of the cheese to surfaces such as shredding equipment, the principle of tack was used. The energy required to separate two materials that are not bound permanently is a measure of tack (Russell and Kim 1999). Probe tack and tack energy were both measured (Figure 2) and were significantly correlated ($p < 0.05$) with each other. Since they showed similar trends, tack energy was used to represent the measurement of tack. The tack energy increased for all three cheeses as the temperature increased (Figure 5). Dough tack showed a similar trend. Heddleson and others (1993) reported that tack energy of dough increased with increasing temperature up until about 50°C. The tack energy for Monterey Jack and process cheese was greater than the tack energy for Mozzarella cheese, meaning that Monterey Jack and process cheese had greater adhesion to the tack probe than the Mozzarella cheese. It is important to note that the removal of the probe resulted from adhesive failure (no cheese remained on the probe) rather than cohesive failure (cheese remained on the probe). Failing adhesively rather than cohesively is an important property of pressure sensitive adhesives. Benedek and Heymans (1997) note that pressure sensitive adhesives must have sufficient cohesion and elasticity to be removed from a surface without leaving a residue on the surface. As mentioned before, Monterey Jack and process cheese had more cheese adhere to the blade. Conversely, Mozzarella had the least amount of cheese adhere to the blade as well as the lowest tack energy. Taking all cheeses into account, a statistically significant correlation between amount of

cheese adhered to the blade and tack energy was found (Table 4). The general relationship between cheese adhered to the blade and tack energy can be seen in Figure 6. An increase in tack energy appears to have an effect on the amount of cheese adhered to the blade since the amount of cheese adhered to the blade was greater as the tack energy increased and this correlation proved to be statistically significant. However, no simple relationship exists because the amount of cheese adhered to the blade at a given tack energy was different for each cheese (Figure 6).

Maximum compliance of the cheese was not correlated with amount of cheese adhered to the blade, but was correlated with tack energy (Table 4). In Figure 7, the general relationship between tack energy and maximum compliance can be seen. As the maximum compliance increased, the tack energy increased slightly. Therefore, softer cheese allowed for greater tack energy. Zosel (1985) reported that tack increases with temperature until the maximum tack is reached. This is primarily due to the increasing ability of the material to deform and flow. The initial compliance (J_0), the response of the cheese when the stress was initially applied, was also calculated (Table 5). Initial compliance for all three cheeses increased as temperature increased. The general relationship between tack energy and initial compliance can be found in Figure 8. Similar to the relationship between tack energy and maximum compliance, as the initial compliance increased the tack energy increased. Therefore, the more initial deformation allowed for a greater tack energy. Initial compliance was significantly ($p < 0.05$) correlated with tack energy. In addition to maximum compliance and initial compliance, retardation time was also calculated (Table 5). Retardation time is the amount of time under a constant load for a material to reach 63.2% ($1 - \frac{1}{e}$) of the maximum strain. A

higher retardation time would indicate that the material would take longer to reach maximum strain and is flowing more slowly. The retardation time for Monterey Jack, Mozzarella and process cheese decreased with an increase in temperature. This indicates that the material flowed more rapidly at 20°C than at 4°C for the three cheeses. The increase in tack energy with temperature may be due to the ability of the material to flow and deform more rapidly at higher temperatures. Since the material can flow more rapidly, it may wet the surface of the tack probe more completely requiring greater energy to separate the probe from the surface of the cheese. Retardation time was not correlated with tack but was negatively correlated with amount of cheese adhered to the blade (Table 4). This would indicate that a faster flowing cheese will most likely have more cheese adhere to the blade during shredding.

One requirement that must be taken into consideration when discussing tack is the Dahlquist criterion. The Dahlquist criterion states that the storage modulus of a pressure sensitive adhesive must be below 10^5 Pa for adhesion to occur (Dahlquist 1989). Table 5 shows the G' (calculated as the reciprocal of the maximum compliance) for all three cheeses at all three temperatures. Two cheeses, Mozzarella at 4°C and process at 4°C, did not fall within the Dahlquist criterion for tack. They both had G' values slightly above the 10^5 Pa limit for tack based on rheological properties. However, they do have low levels of tack (Figure 5). Since the tack of these two cheeses is most likely not attributed to viscoelastic properties, any adhesion that occurs would most likely be due to mechanical interlocking or surface energy differences. Heddleson and others (1993) reported that the tack energy of dough decreased dramatically, but did not go to zero, once the G' reached the limit of 10^5 Pa of the Dahlquist Criterion.

The performance of a pressure sensitive adhesive, cheese in this case, depends not only on the viscoelastic properties, but also on the surface energies of the adhesive and the adherend (Hedderson and others 1993). Figure 9 shows a pictorial representation of how pressure sensitive adhesion is affected through the relationship of the surface energy of the adhered and the adhesive. Zosel (1985) reported that when the surface energy of the adherend is much higher than the adhesive, it is assumed that the performance of the pressure sensitive adhesive is independent of the surface energy as reported in the bottom half of Figure 9. Michalski and others (1999) tested emulsions of mayonnaise-like consistency against five solids of increasing surface energy. The greatest amount of adhesion occurs where the surface energy of the solid materials is greater than the surface energy of the emulsions. Maximum adhesion is most likely caused by viscoelastic properties since the most adhesion occurs where the surface energy of the adherend is greater than the surface energy of the adhesive. Michalski and others (1999) also showed that at a given solid surface energy that is above the surface energy of the emulsions, there was no relationship between amount of emulsion adhered and surface energy of the emulsion, which is consistent with the model of Figure 9.

When the adherend surface energy is less than the surface energy of the adhesive, bond formation becomes a complicated function of surface energies and viscoelasticity of the adhesive (Saunders and others 1992) as represented by the top half of Figure 9. Zosel (1985) reported in an experiment of adhering a polymer adhesive to several different polymer adherends, in the region where the surface energy of the adherend is less than the adhesive, the adhesion decreases as surface energy decreases. The surface energy for the stainless steel was experimentally determined to be 35.6 mN/m. The surface energy

for all three cheeses at all temperatures was higher than the stainless steel, meaning that the surface energy of the adherend is less than the surface energy of the adhesive (Figure 10). Therefore, the adhesion of all cheeses at all temperatures was a function of surface energy and viscoelasticity as represented by the top half of Figure 9. Surface energy for all three cheeses over all three temperatures did not show any definite trends (Figure 10). There were no significant differences ($p > 0.05$) among the three different cheeses over all three temperatures. Also, surface energy was not correlated with any other property (Table 4). In the literature, there are very few and often contradictory results concerning the relationship of tack and surface energy. Toyama (1970) found maximum tack values where the surface energy of the adherend is almost equal to the surface energy of the adhesive. Sherriff (1973) found that tack increased with increasing surface energy of the adherend.

The relationship between tack and surface energy was not consistent among the three cheeses. There are two different patterns that are present among the three cheeses that can be seen in Figure 11. For Mozzarella and process cheese, the surface energy starting at 4°C was higher than that at 12°C but then at 20°C the surface energy went higher than the surface energy at 4°C and 12°C. The second pattern that can be seen was that Monterey Jack had a direct increasing relationship; tack energy increased as the surface energy increased. Similar trends can be seen between the relationship of surface energy and amount of cheese adhered to the blade (Figure 12). It is not clear as to why these two patterns are present. From this experiment, it appears that the tack energy does increase slightly as the surface energy increases from 4°C to 20°C for all three cheeses.

Something interesting to note is the surface energy of the Mozzarella and process cheese at 4°C, the two cheeses that had a G' above the maximum level for the Dahlquist criterion. These two cheeses had surface energies higher than the Monterey Jack at 4°C. Since there is some indication that tack energy may increase with increasing surface energy, this may explain why there was adhesion to the tack probe even though their G' was not within the limit for adhesion due to viscoelastic properties.

Adhesion of cheese to the blade during shredding is a complicated matter of pressure sensitive adhesion involving surface energy and rheology. All these factors are intermingled to cause a decrease in the amount of long shreds produced. Since Mozzarella had the greatest amount of fines produced during shredding, it is important to understand the mechanism by which this happens. From all outstanding data, it looks as if the maximum compliance and low tack energy were what set Mozzarella apart from the Monterey Jack and process cheese. It appears that tack energy can reveal a lot about how much cheese will adhere to the blade during shredding. Both Monterey Jack and process cheese had higher tack energy and a greater amount of cheese adhere to the blade. Since the commercial cheeses gave some indication as to what causes defects in shredding, further experimentation was necessary to characterize shredding behavior. The next experiment was designed to observe how compositional changes affect shredding. The three cheeses used in the next experiment were formulated to have similar moisture content and altered levels of fat and protein. By keeping the moisture content the same, the properties that are affected by different levels of fat and protein can be extracted.

Experimental Cheese Set A

For Experimental Cheese Set A, the cheeses were formulated to have varying fat and protein content with constant moisture content. The proximate compositions of the three experimental cheeses are found in Table 2. Cheese 1 had the lowest fat content and the highest protein content, Cheese 3 had the highest fat content and the lowest protein content. Cheese 2 fell in between cheese 1 and 3 for both fat and protein content. The moisture content remained around 46.5% for all the cheeses. The shred distribution for all three cheeses is found in Figures 13a-c.

The most prominent shredding defect observed in this set of experimental cheese was production of fines. There was very little cheese that adhered to the blade. This is consistent with the shredding behavior of the commercial Mozzarella cheese. There was not a significant difference in the amount of cheese adhered to the blade among the three cheeses and age did not have a significant effect on the amount of cheese that adhered to the blade. Cheeses 1 and 2 had very similar shred distributions with long shreds around 75%. Fines around for Cheese 1 and Cheese 2 fell slightly under 20%. The shred distribution for Cheese 3 had long shreds around 60% and fines were much higher than Cheese 1 and 2 at around 30%. The amount of fines produced during shredding of Cheese 3 was significantly higher ($p < 0.05$) than Cheeses 1 and 2 and the amount of fines produced from shredding Cheese 2 was significantly higher ($p < 0.05$) than Cheese 1. As the cheese aged over 28 days, there was very little variation in the shred distribution among each cheese and statistically there was no effect on fines produced due to age. This is contrary to Kindsteadt's (1995) report that age regulates the quality of shred. Kindsteadt (1995) states that very young or newly manufactured Mozzarella

cheese does not shred very well due mostly to excessive free moisture at the surface and within the body of the cheese. On the other hand, Mozzarella cheese cannot be aged too long before shredding because as it ages and as ripening occurs, the texture becomes too soft and gummy to produce high quality shreds.

Creep and recovery of the three cheeses can be found in Figures 14a-c. Creep and recovery was done at 25°C rather than at room temperature because the previous experiments with the commercial cheeses showed more differentiation at a higher temperature. The maximum compliance (J_{\max}) of Cheese 3 was found to be significantly higher ($p < 0.05$) than Cheeses 1 and 2, but there was no difference between Cheeses 1 and 2. Cheese 1 and 2 had a much lower compliance than Cheese 3, meaning that cheese three is the softest of the three cheeses. Cheese 3 is softest due to its low protein, high fat content. Masi and Addeo (1986) reported that increases in fat and moisture contents of Mozzarella cheese are accompanied by a decrease in modulus of elasticity and resulting in softening of the cheese, which can cause difficulty in shredding. Jack and Paterson (1992) comment that the ratio of fat to protein largely determines the structure of cheese. High moisture and fat content produce a weaker protein structure and lower moisture and fat produce a hard protein structure causing a firmer textured cheese. Aging had a significant effect on maximum compliance of all three cheeses; as the cheeses aged they showed a higher compliance. The cheese with the highest compliance, Cheese 3, was also the cheese that produced the most fines during shredding. Maximum compliance was significantly correlated with fines produced during shredding (Table 6). It can be assumed that the fines produced during shredding were related to the soft texture of the cheese. In addition, maximum compliance was significantly correlated with the amount

of cheese adhered to the blade (Table 6). There was very little cheese that adhered to the blade, but perhaps there would have been more if the cheese were softer. If cheese is soft, pasty or wet the shredder can become clogged with gummy cheese and the shredded cheese may produce shreds with ragged edges, many fines, “gummy balls” of cheese and excessive matting of the cheese shreds. (Kindsteadt 1995).

In addition to maximum compliance, initial compliance (J_0) was calculated (Table 7). Similarly to maximum compliance, initial compliance was highest for Cheese 3 and lowest for Cheese 1. Cheese 3 also had the most fines produced during shredding. Therefore, the cheese that deformed more as the initial stress was applied to the cheese produced more fines. The initial compliance for these three cheeses was significantly correlated ($p < 0.05$) with the amount of fines produced. Retardation time was also calculated for all three cheeses. For all three cheeses, the retardation time decreased as the cheeses aged (Table 7). This indicates that the cheeses flowed more rapidly under the constant load after aging. The retardation time for Cheese 3 was higher than the other two cheeses.

Surface energy for all three cheeses can be found in Figure 15. There was no significant difference in surface energy among the three cheeses. Age did have a significant effect on the surface energy of the three cheeses. At Day 2 the surface energy starts high for all three cheeses. On Day 7 it dropped dramatically and for the remainder of the aging period, the surface energy for all three cheeses remained close to 40 mN/m. Since the moisture content is very similar for all three of the cheeses, it appears in this case that surface energy may be a function of the moisture content of the cheese. The first day, when surface energy started higher than the later days, the cheese was still

expelling water and the surface of the cheese was moist. A wet surface would have a surface energy with a higher polar component causing an increase in the total surface energy. At and after Day 7, the water was taken back up into the network and the surfaces of the cheeses were dry. The dotted line on Figure 15 represents the surface energy of the stainless steel. From day 7 on, the three cheeses had surface energies close to the surface energy of stainless steel. Rheology appeared to be the cause of a difference in shred since the three cheeses had very similar surface energies over 28 days but differences were present in the shred distributions.

The tack energy for all three cheeses can be found in Figure 16. Cheese 1 had little to no tack at all. Cheese 2 had more tack than Cheese 1 and Cheese 3 had the most tack energy of all the cheeses. The tack energy for Cheese 3 was found to be significantly higher ($p < 0.05$) than both Cheeses 1 and 2, whereas Cheeses 1 and 2 were not found to be significantly different. In comparison to the commercial Mozzarella cheese tested, the tack values for Cheeses 1 and 2 are much lower. The tack values for the commercial Mozzarella near 7°C were similar to the tack values for Cheese 3, which was tested at 7°C. As mentioned earlier, Cheese 3 had the highest maximum compliance. The more compliant cheese, Cheese 3, also had the highest tack energy. There was a significant correlation ($p < 0.05$) between maximum compliance and tack energy for these three cheeses (Table 6). In addition to maximum compliance, initial compliance for Cheese 3 was higher than both Cheeses 1 and 2. There was a significant correlation ($P < 0.05$) between initial compliance and tack energy (Table 6). Cheese 3, with the highest tack values also had the most amount of fines produced during shredding. There was a significant correlation found between tack and fines produced during shredding

(Table 6). This may help to explain shredding behavior. If a cheese is more compliant, it may have a higher tack energy, which might allow for greater production of fines when shred.

In this experiment, the properties of the cheese could be evaluated in relation to keeping the moisture constant. From this experiment, further experimentation was developed. In the next experiment, four new cheeses were formulated around the cheese with the lowest fat. The moisture and calcium levels were altered to see if changes in shred could be detected.

Experimental Cheese Set B

In Experimental Cheese Set B four cheeses were formulated around the lowest fat cheese of Experimental Cheese Set A, all having a fat content around 15% (on a wet basis). The moisture and the calcium content were altered to determine if changes in these levels affect the shredding behavior. There were four combinations of moisture and calcium used to formulate the cheeses. The combinations were: low calcium-low moisture (LC-LM), low calcium-high moisture (LC-HM), high calcium-low moisture (HC-LM) and high calcium-high moisture (HC-HM). Proximate composition for all four cheeses can be found in Table 2.

Shred distributions of the four cheeses can be found in Figure 17a-c. The most prominent shredding defect in these four cheeses is production of fines, which is similar to the cheeses in Experimental Cheese Set A as well as the commercial Mozzarella. The shred distributions for the four cheeses are very similar, but the fines for the LC-HM cheese were found to be significantly higher ($p < 0.05$) than the other three cheeses. The two cheeses with the lower moisture content were not found to be significantly different. The moisture content of the cheeses had a significant effect on the amount of fines produced among the cheeses.

Tack energy for the four cheeses can be found in Figure 18. The tack energy for the LC-HM cheese was found to be significantly higher ($p < 0.05$) than the other three cheeses. The other three cheeses were not found to be significantly different. The LC-HM cheese had the highest tack energy and greatest amount of fines produced during

shredding. The tack energy was significantly correlated with the amount of fines produced during shredding (Table 8).

The surface energy for the four cheeses over aging does not show any definite trends (Figure 19). Surface energy does not appear to be influencing the shredding behavior of these four cheeses. The surface energy, at almost all time points, of all four cheeses is above the surface energy of the stainless steel. The LC-HM and HC-HM cheeses showed a similar pattern of surface energy of the cheeses in Experimental Cheese Set A. These cheeses started out with a higher surface energy on Day 2 then decreased dramatically on Day 7 and remained at a rather constant surface energy through the remainder of the aging period. Surface energy was affected significantly ($p < 0.05$) by the moisture content of the cheeses.

Creep and recovery of the four cheeses can be found in Figure 20a-d. The maximum compliance of the four cheeses was not found to be significantly different. Although the four cheeses were not found to be different, the amount of fines produced during shredding was significantly correlated with maximum compliance. From previous experiments, it seems that the amount of fines produced during shredding would increase for a softer cheese. Therefore, the rheological properties may be an integral part of explaining the shredding behavior of cheeses.

This experiment, where the cheeses were formulated to have differing levels of moisture and calcium, illustrated the importance of how moisture in cheese is related to shredding behavior. Moisture had a significant effect of the amount of fines produced during shredding. In addition to the moisture content, the amount of fines produced was also significantly correlated with tack energy and the maximum compliance. From

previous experiments, a higher maximum compliance will result in greater tack energy if the G' of the solid is less than the Dahlquist criterion of 10^5 Pa. All four of these cheeses had a G' less than the Dahlquist criterion at 7°C (Table 9) allowing adhesion due to pressure sensitive adhesion. From this experiment, the cheese with the highest tack energy also had the highest amount of fines produced. Although the rheological parameters did not show significant difference in this experiment, it is most likely the determining factor for shredding behavior since it also affects tack and surface energy did not show any trends in production of fines or adhesion of cheese to the blade for these cheeses.

CONCLUSION

For the commercial cheeses, two defects in shredding were observed: production of fines and adhesion to the blade. Mozzarella produced the most fines during shredding and had the highest maximum compliance, implying that the softest cheese produced the most fines during shredding. Monterey Jack and process cheeses had the greatest amount of cheese adhere to the blade as well as the highest tack energy. This indicated that a relationship between tack energy and amount of cheese adhered to the blade exists. A significant correlation ($p < 0.05$) was found between tack energy and amount of cheese adhered to the blade. In addition, the tack energy increased as the maximum compliance increased, implying that, as the three cheeses became softer with an increase in temperature, higher tack energy was observed. Maximum and initial compliance were significantly correlated ($p < 0.05$) with tack energy.

For Experimental Cheese Set A, the defect observed in shredding was production of fines; there was very little adhesion to the blade. The cheese that produced the most fines was the cheese with the highest fat and lowest protein content. This cheese also had the highest compliance of the three cheeses tested. There was a significant correlation ($p < 0.05$) between maximum compliance and fines. In addition, the softest cheese also had the highest tack energy of the three cheeses. There was a significant correlation ($p < 0.05$) between tack energy and maximum compliance. The cheese that had the highest tack energy produced the most fines when shredded. A significant correlation ($p < 0.05$) was found between tack energy and fines produced. From this experiment, the

softer the cheese (higher maximum compliance), had the greatest tack energy and the most fines produced during shredding.

Cheeses in Experimental Cheese Set B also showed production of fines as the main defect during shredding. The cheese with the highest tack energy produced the most fines during shredding. There was a significant correlation ($p < 0.05$) between tack energy and fines produced during shredding. The maximum compliance also showed to have an effect on the fines produced during shredding. Although not extremely noticeable in this experiment, cheeses with higher maximum compliance produced more fines during shredding. A significant correlation ($p < 0.05$) was found between maximum compliance and fines produced during shredding. Since the moisture content of these cheeses was one of the measured factors, it was possible to observe that the moisture content had a significant effect ($p < 0.05$) on the amount of fines produced during shredding. The higher moisture cheeses had more fines produced.

REFERENCES

- Apostolopoulos C, Marshall RJ. 1994. A quantitative method for the determination of shreddability of cheese. *Journal of Food Quality* 17: 115-128.
- Benedek, I, Heymans, LC. 1997. Pressure-sensitive adhesives technology. New York: Marcel Dekker Inc.
- Dubuy, MM. 1980. The French art of shredding cheese. *Food Processing Industry*. 49:52-53.
- Hammond, FH. 1989. Tack. In: Satas, D, editor. *Handbook of pressure sensitive adhesive technology*. 2nd ed. New York: Van Nostrand Reinhold. p 38-60.
- Jack FR, Paterson A. 1992. Texture of hard cheeses. *Trends in Food Science and Technology* 3: 160-164.
- Kindsteadt, PS. 1995. Factors affecting the functional characteristics of unmelted and melted Mozzarella cheese. In: Malin, EL, Tunick, MH, editors. *Chemistry of structure-function relationships in cheese*. New York: Plenum Press. p 27-41.
- Masi P, Addeo F. 1986. An examination of some mechanical properties of a group of Italian cheeses and their relationship to structure and conditions of manufacture. *Journal of Food Engineering* 5: 217.
- Michalski MC, Desobry S, Babak V, Hardy J. 1999. Adhesion of food emulsions to packaging and equipment surfaces. *Colloids and Surface A: Physicochemical and Engineering Aspects* 149:107-121.
- Ni, H, and Guansekaran, S. 2004. Image processing algorithm for cheese shred evaluation. *Journal of Food Engineering*. 61(1):37-45.

- Saunders, SR, Hamann DD and Lineback, DR. 1992. A systems approach to food material adhesion. *Lebensm. Wiss. u. Technol.* 25: 309-315.
- Sherriff, M, Knibbs, RW, Langley, PG. Mechanism for the action of tackifying resins in pressure-sensitive adhesives. *Journal of applied polymer science* 17:3423-3438.
- Toyama, M, Ito, T and Moriguchi, H. 1970. Studies on tack of pressure-sensitive adhesive tapes. *Journal of applied polymer science* 14:2039-2048.
- Zosel, A. 1985. Adhesion and tack of polymers: Influence of mechanical properties and surface tensions. *Colloid and Polymer Science* 263:541-553.

TABLES AND FIGURES

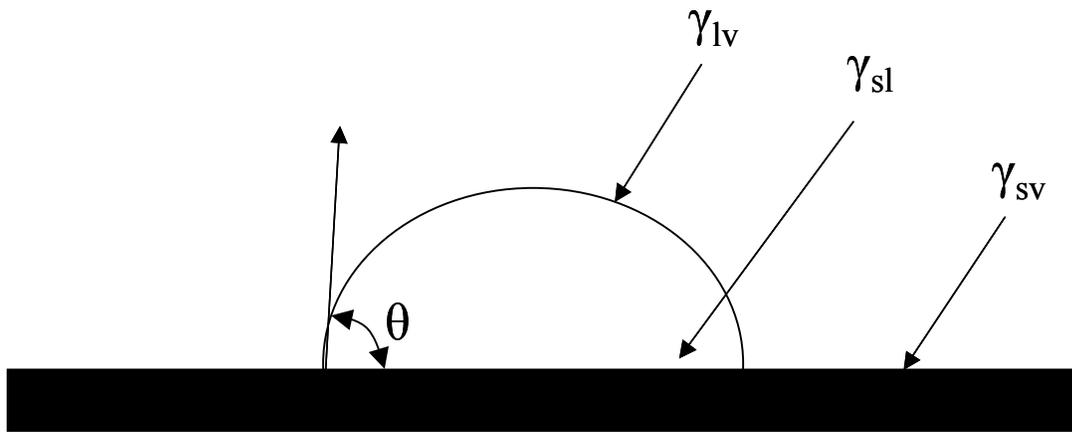


Figure 1. Contact angle measurement. θ represents the contact angle. γ_{lv} represents the liquid-vapor interface, γ_{sl} represents the solid-liquid interface and γ_{sv} represents the solid-vapor interface.

Table 1. Factors influencing the shreddability of cheese

Factor	Effect	Shreddability	Source
Composition			
High Moisture	Matting of shreds	Decreases	Kindsteadt 1995, Masi and Addeo 1986
High Fat ($\geq 45\%$ dry basis)	Matting of shreds	Decreases	Kindstedt 1995, Masi and Addeo 1986
Age			
Too young (within the first days of manufacture)	Excessive free moisture at the surface causes matting	Decreases	Kindstedt 1995
Too old (i.e. Mozzarella 20 days post-manufacture)	Soft and gummy body	Decreases	Kindstedt 1995
Texture			
Soft Bodied, Pasty or Wet Surface	Ragged edges, fines, matting, produces “gummy balls”	Decreases	Kindstedt 1995
Too firm, too dry	Shatter into fines, and small particles	Decreases	Kindstedt 1995
Dahlquist Criterion			
$G' > 10^5$ Pa	No pressure sensitive adhesion	Increase	Dahlquist 1989
$G' < 10^5$ Pa	Adhesion due to pressure sensitive adhesion	Decrease	Dahlquist 1989
Surface Energy			
Surface energy of cheese GREATER than stainless steel shredding blade	Adhesion of cheese due to surface energy as well as viscoelastic properties	Decreases	Saunders and others 1992
Surface energy of cheese LESS than stainless steel shredding blade	Adhesion of cheese due only to viscoelastic properties	DECREASES if below Dahlquist criterion, INCREASES if above Dahlquist Criterion	Zosel 1985
Glass Transition Temperature			
$-10 < T_g < 10$	Optimum for pressure sensitive adhesion	Decreases if within optimum range for pressure sensitive adhesion	Foley and Chu 1986

Table 2. Proximate Composition for all cheeses tested

	Moisture (%)	Fat (% on a wet basis)	Fat (% on a dry basis)	Protein (%)	Calcium (mg/g protein)
Commercial Cheeses					
Monterey Jack	41.6	28.7	49.1	23.0	-
Mozzarella	46.9	22.2	41.8	25.0	-
Process	39.1	30.1	49.4	19.3	-
Experimental Cheese Set A					
Cheese 1	46.7	15.8	29.6	31.6	-
Cheese 2	45.9	21.5	39.7	27.4	-
Cheese 3	46.9	26.1	49.2	22.9	-
Experimental Cheese Set B					
Low Calcium-Low moisture (LC-LM)	45.8	15.7	29.0	33.0	26.0
Low Calcium-High Moisture (LC-HM)	49.8	15.2	30.3	30.1	27.2
High Calcium-Low Moisture (HC-LM)	46.5	16.3	30.5	29.4	33.8
High Calcium-High Moisture (HC-HM)	49.5	13.9	27.5	28.3	33.1

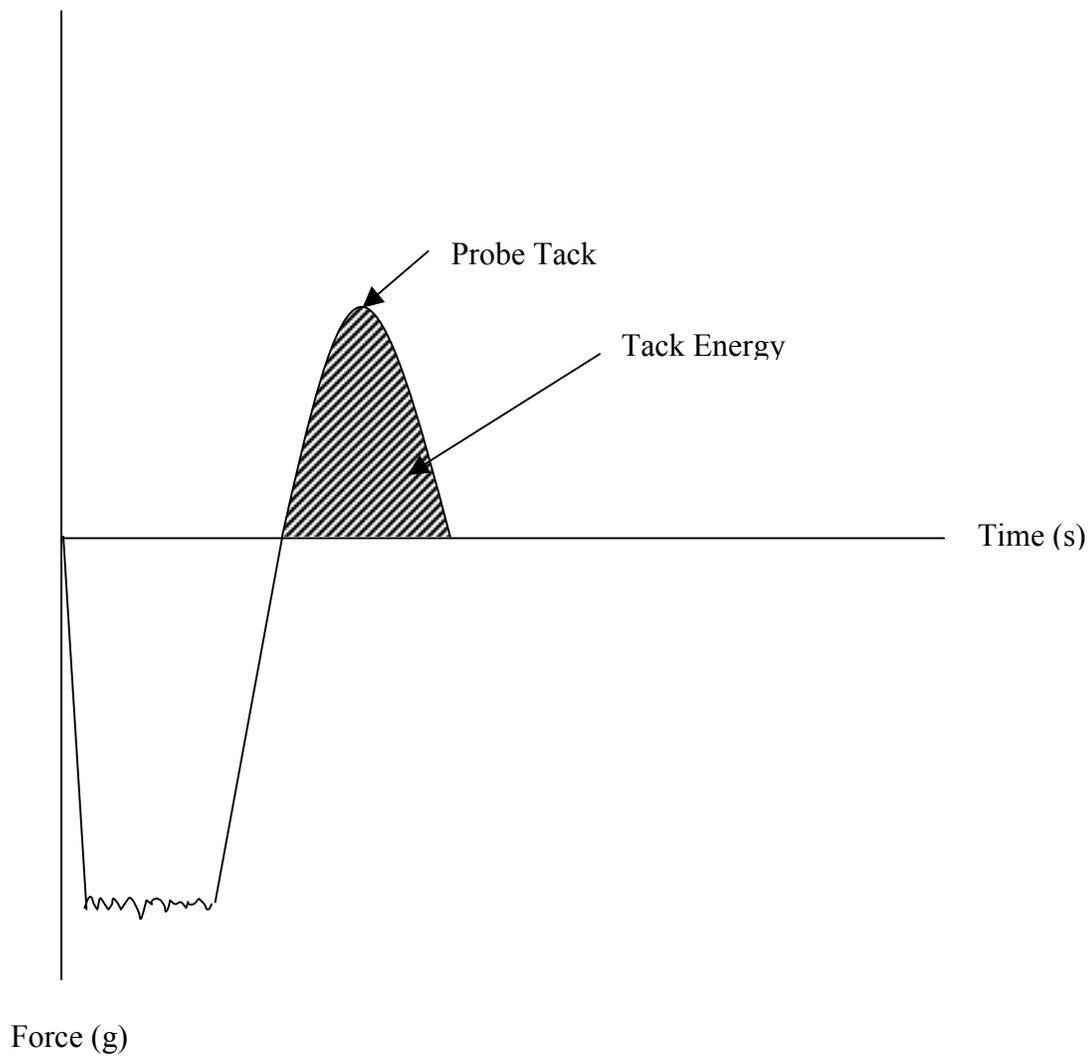


Figure 2. Graph obtained from TAX-T2 for tack. Probe tack is represented by the peak force of the curve and tack energy is represented by the area under the curve.

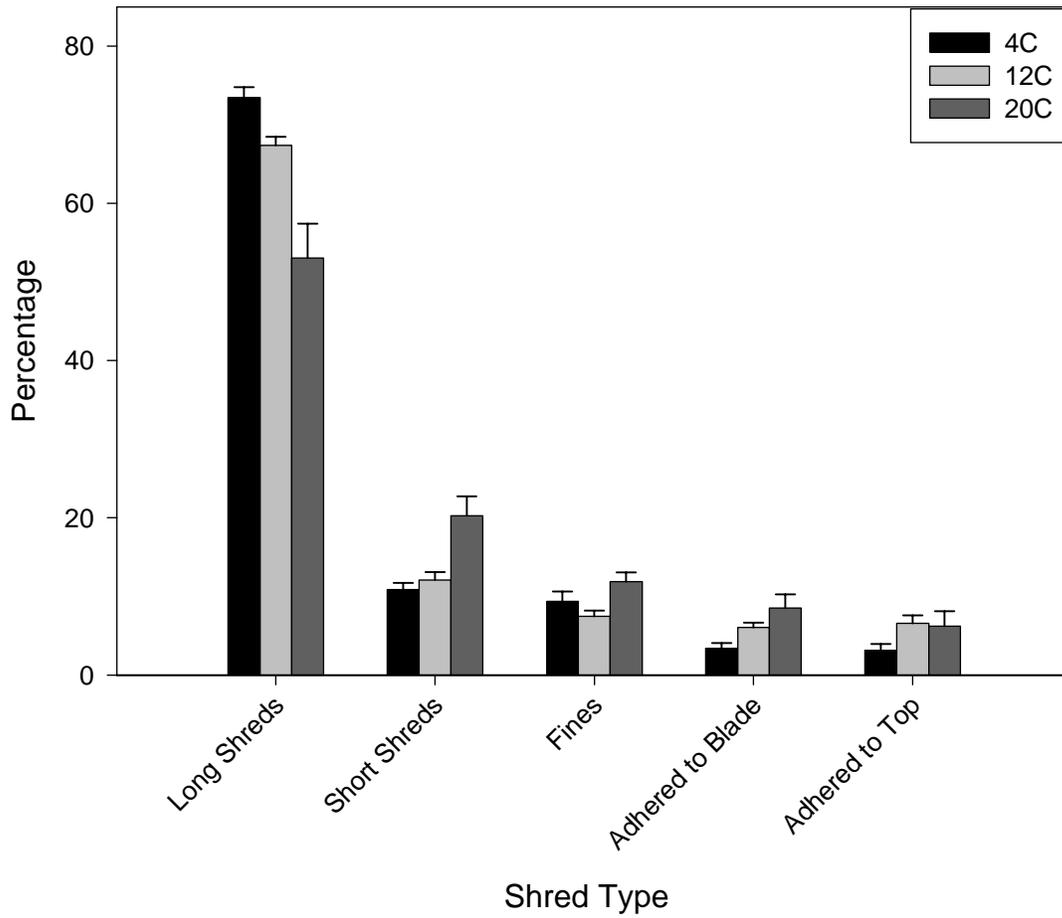


Figure 3a. Shred Distribution for Monterey Jack cheese at 4°C, 12°C and 20°C. Error bars represent standard error of the mean.

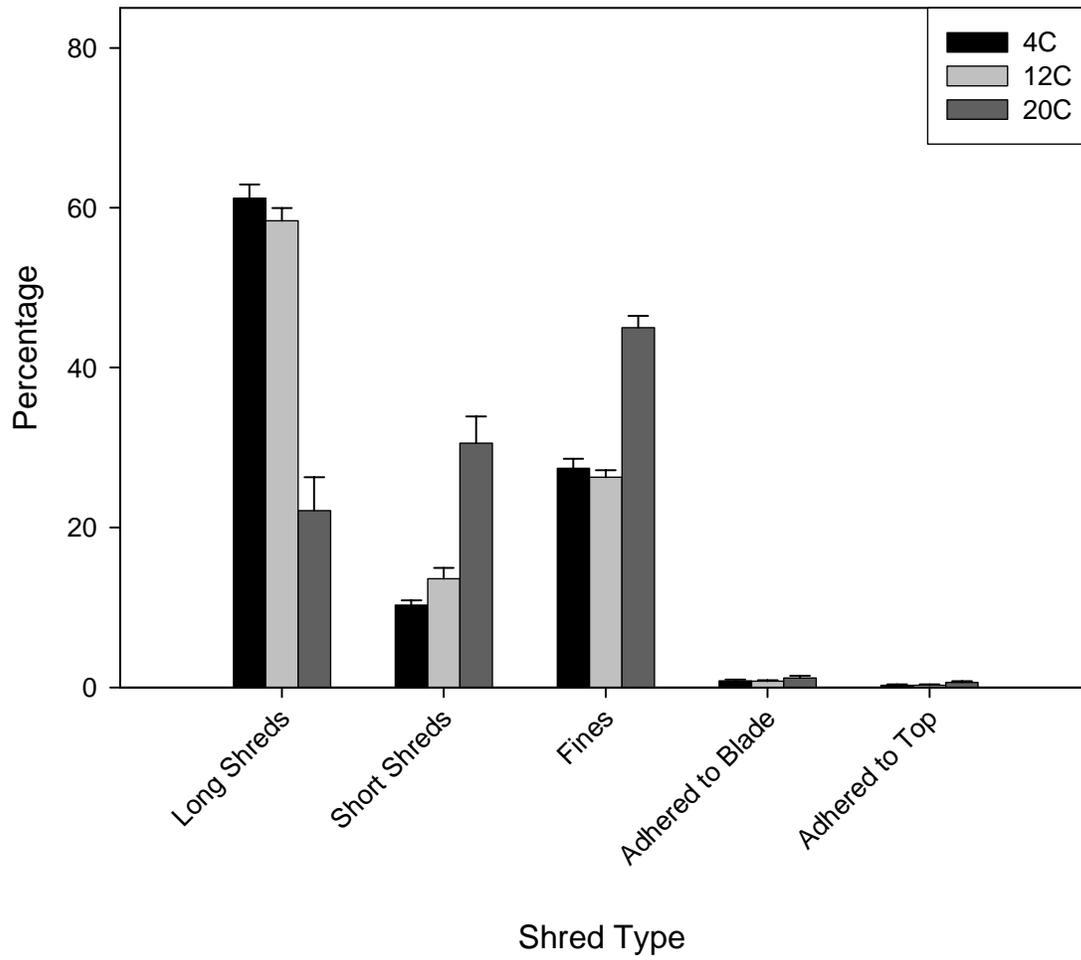


Figure 3b. Shred Distribution for Mozzarella cheese at 4°C, 12°C and 20°C.

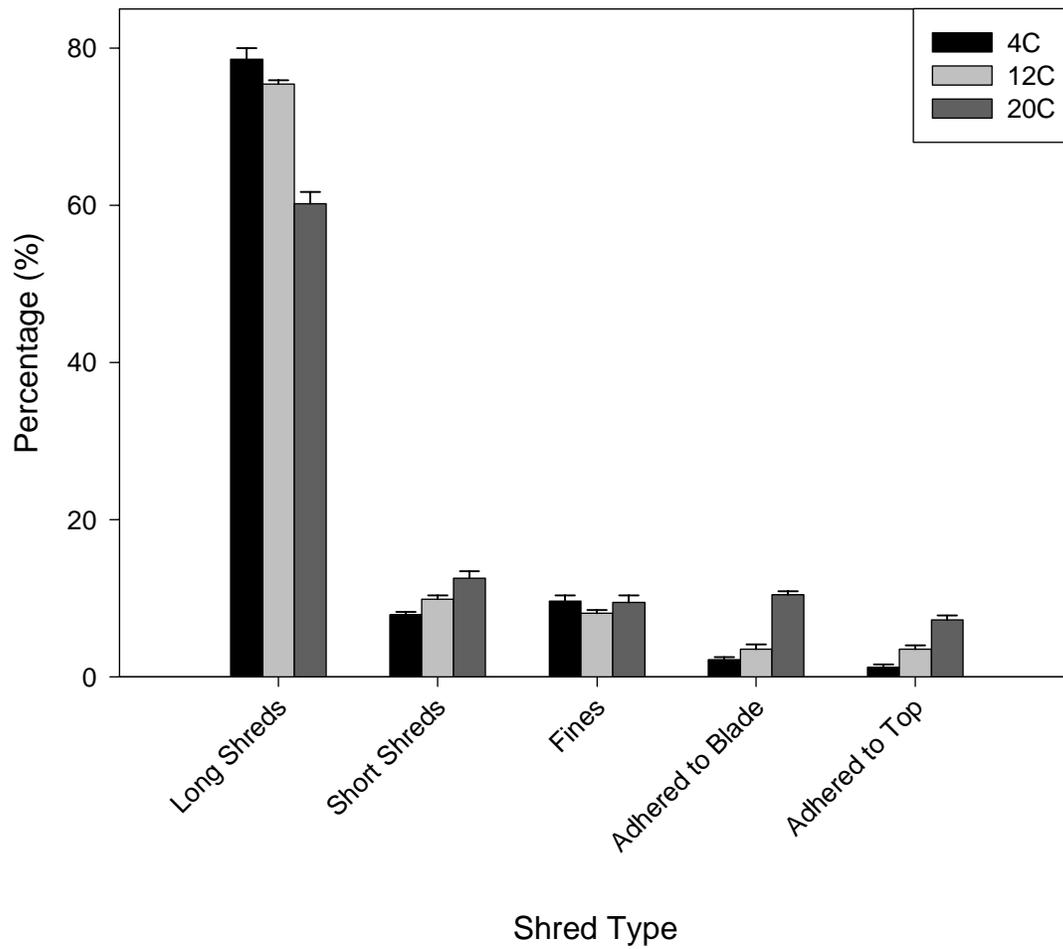


Figure 3c. Shred Distribution for process cheese at 4°C, 12°C and 20°C.

Table 3. Percentage of fines and percentage of cheese adhered to the blade during shredding. Significant differences are represented by different letters ($p < 0.05$).

Cheese and Temperature	Fines (%)	Adhered to Blade (%)
Monterey Jack 4°C	9.6 ^{ab}	3.4 ^c
Monterey Jack 12°C	7.5 ^b	6.1 ^b
Monterey Jack 20°C	11.9 ^a	8.5 ^a
Mozzarella 4°C	27.4 ^c	0.8 ^d
Mozzarella 12°C	26.3 ^c	0.8 ^d
Mozzarella 20°C	45.0 ^d	1.2 ^d
Process 4°C	9.7 ^b	2.2 ^{cd}
Process 12°C	8.1 ^b	3.5 ^d
Process 20°C	9.5 ^{ab}	10.5 ^e

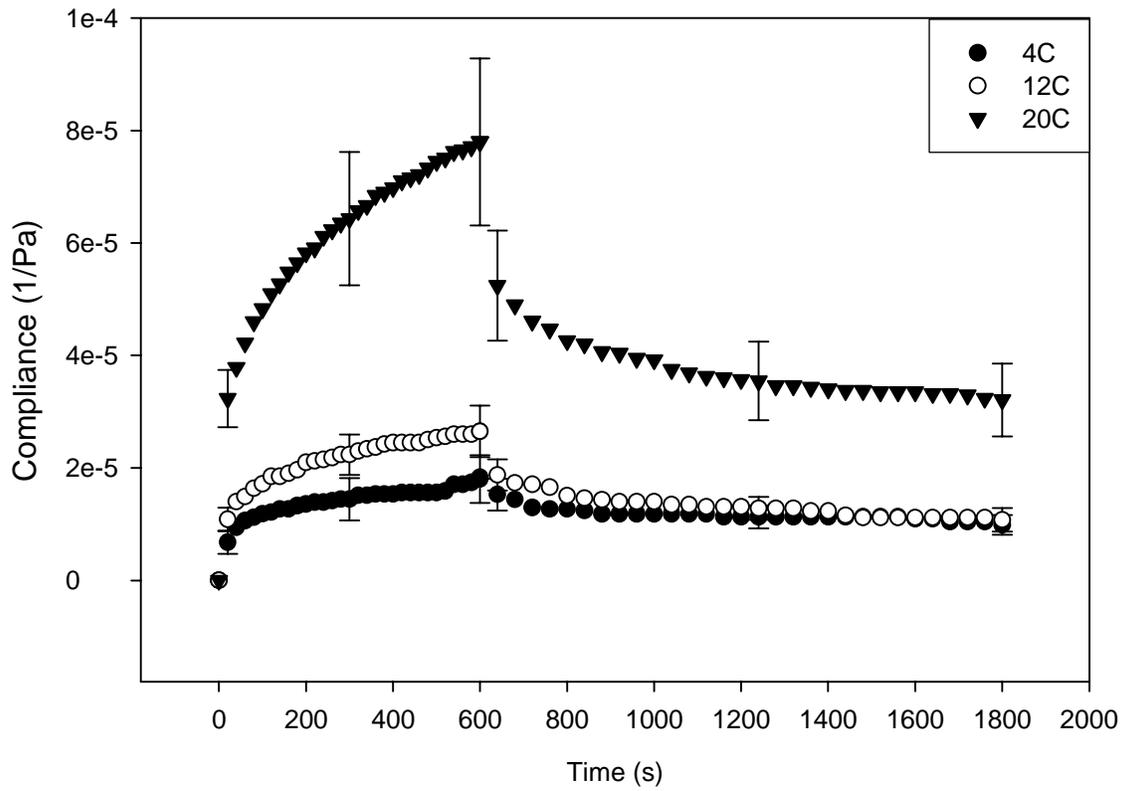


Figure 4a. Creep and recovery for Monterey Jack cheese at 4°C, 12°C and 20°C. Error bars represent standard error of the mean.

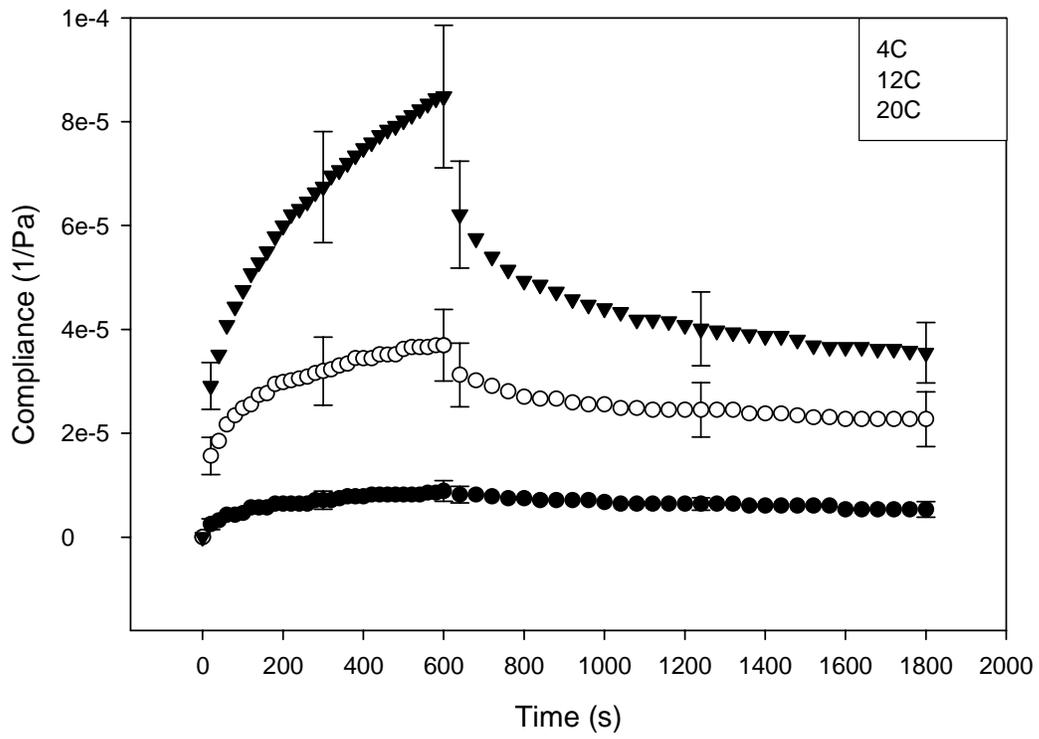


Figure 4b. Creep and recovery for Mozzarella cheese at 4°C, 12°C and 20°C.

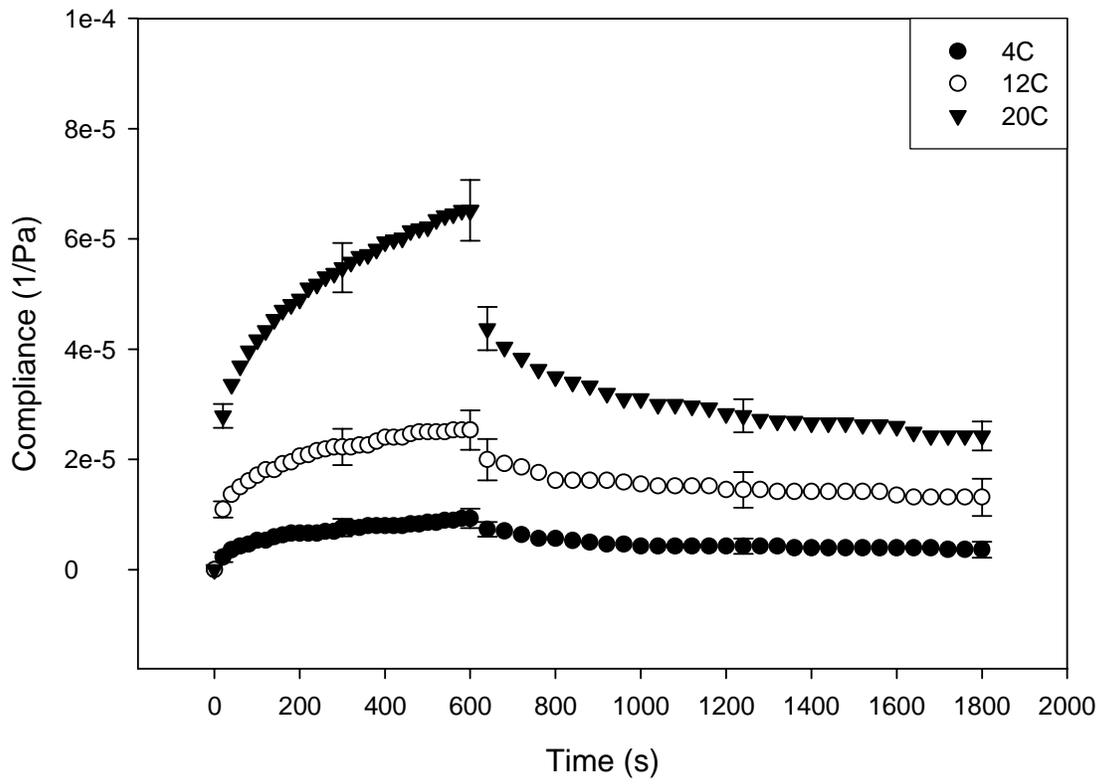


Figure 4c. Creep and recovery for process cheese at 4°C, 12°C and 20°C.

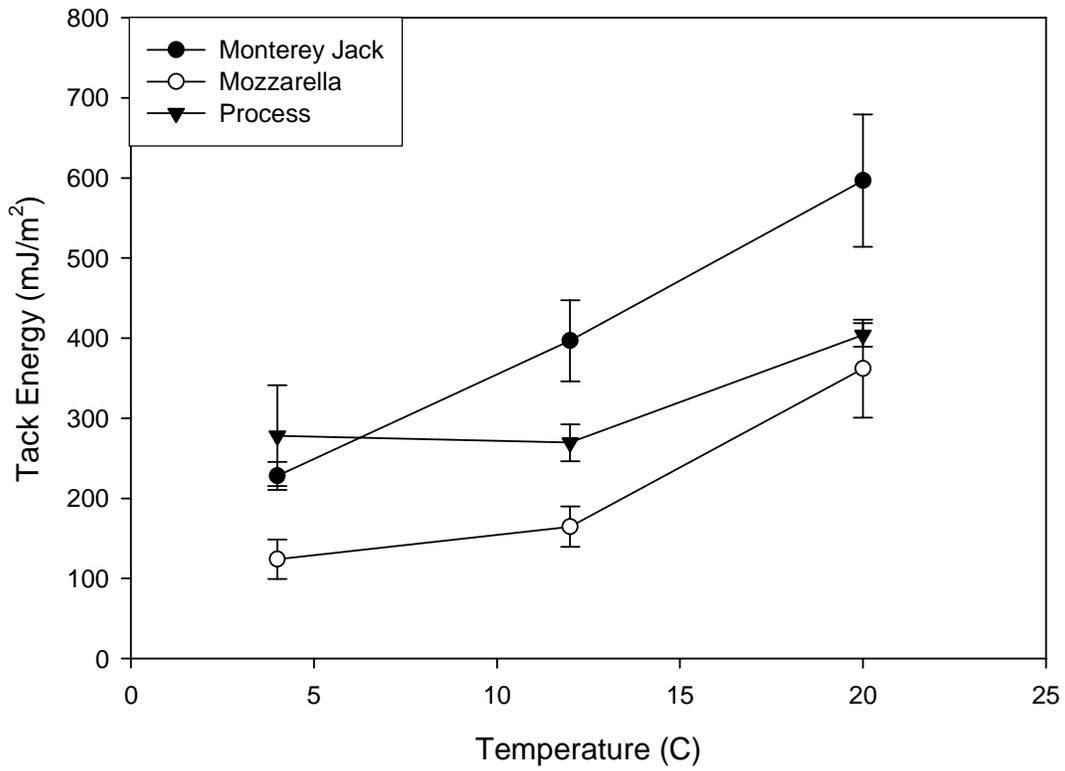


Figure 5. Tack energy for Monterey Jack, Mozzarella and process cheeses at 4°C, 12°C and 20°C. Error bars represent standard error of the mean.

Table 4. Correlation analysis between tack energy, fines, cheese adhered to blade, surface energy, maximum compliance (J_{\max}), initial compliance (J_0) and retardation time (λ_{ret}) for commercial cheeses.

	Fines	Adhered to Blade	Surface Energy	Tack Energy	J_{\max}	J_0	λ_{ret}
Fines	1.000	-0.579	-0.207	-0.239	0.386	0.262	0.360
Adhered to blade		1.000	0.595	0.753*	0.400	0.554	-0.723*
Surface Energy			1.000	0.504	0.324	0.326	-0.159
Tack Energy				1.000	0.682*	0.738*	-0.597
J_{\max}					1.000	0.985*	-0.547
J_0						1.000	-0.636
λ_{ret}							1.000

* significant correlation at $p \leq 0.05$

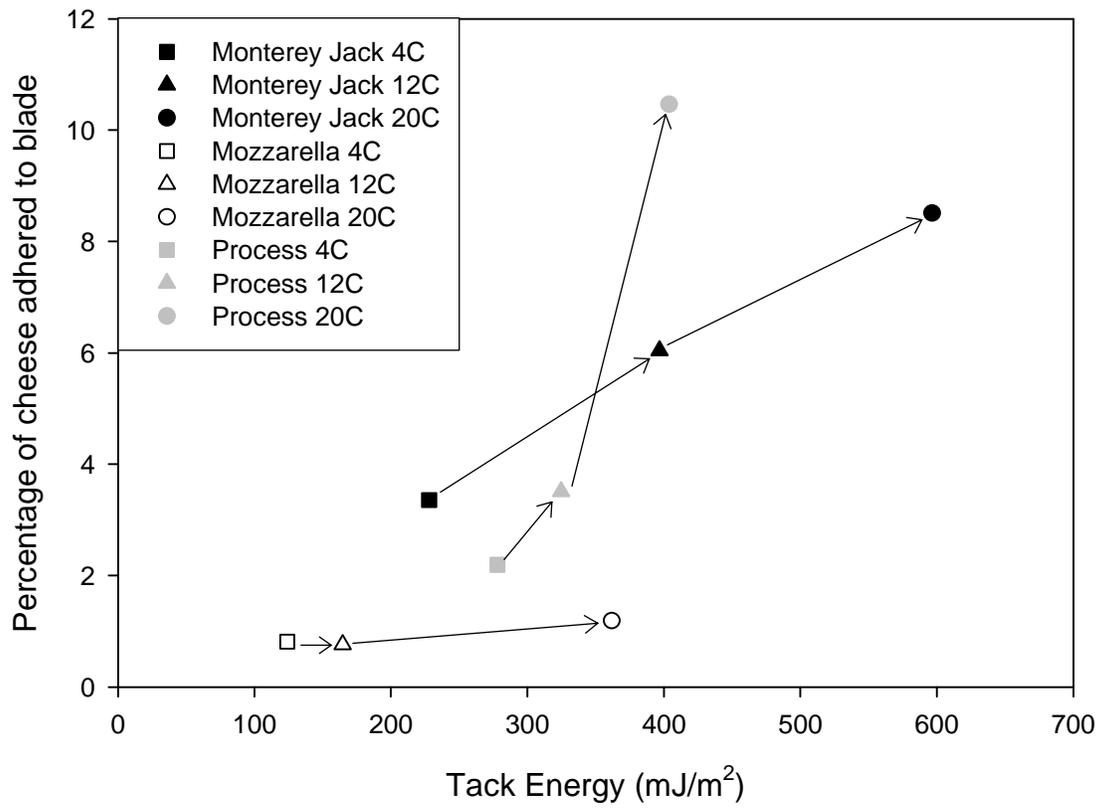


Figure 6. Comparison of cheese adhered to the blade and tack energy for Monterey Jack, Mozzarella and process cheeses at 4°C, 12°C and 20°C.

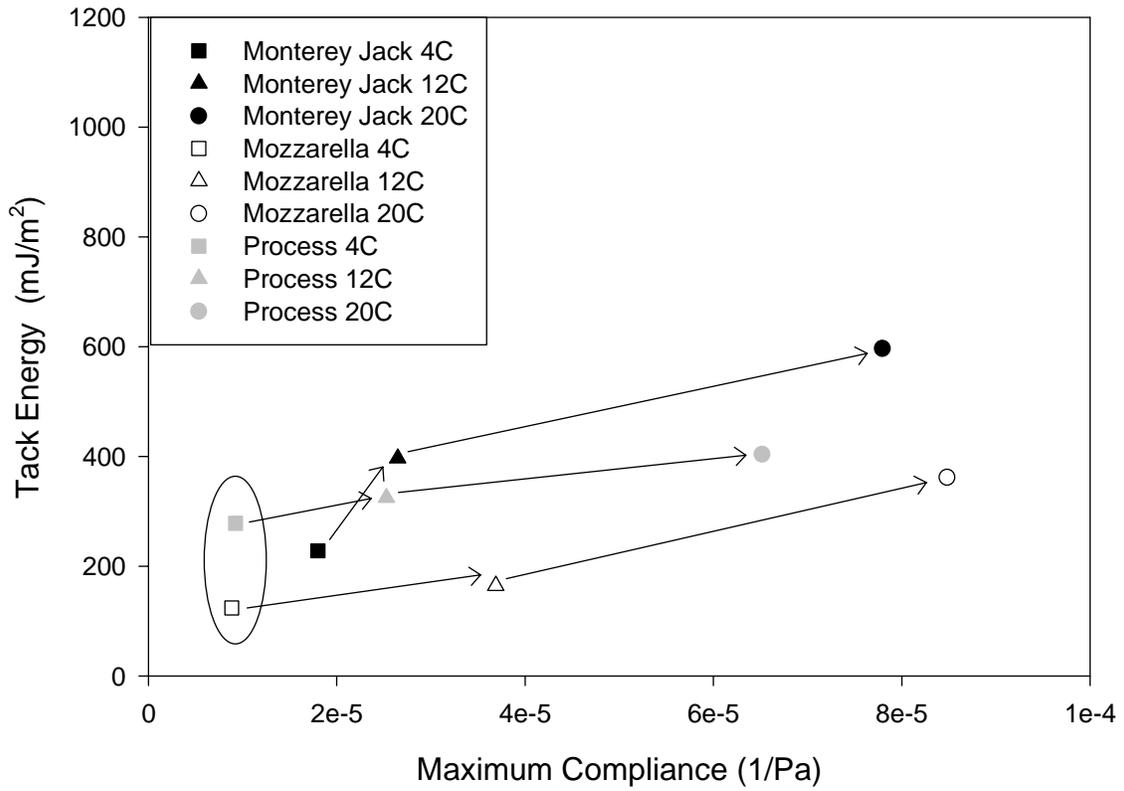


Figure 7. Comparison of tack energy and maximum compliance for Monterey Jack, Mozzarella and process cheeses at 4°C, 12°C and 20°C. Circled points have G' above Dahlquist Criterion.

Table 5. Initial compliance (J_0), maximum compliance (J_{\max}), storage modulus (G') and retardation time (λ_{ret}) for Monterey Jack, Mozzarella and process cheese at 4°C, 12°C and 20°C

Cheese	J_0 (1/Pa)	J_{\max} (1/Pa)	G' (Pa)	λ_{ret} (s)
Monterey Jack 4°C	6.75E-06	1.8E-05	5.55E+04	113
Monterey Jack 12°C	1.08E-05	2.65E-05	3.77E+04	108
Monterey Jack 20°C	3.23E-05	7.80E-05	1.28E+04	96
Mozzarella 4°C	2.48E-06	8.87E-06	1.13E+05	186
Mozzarella 12°C	1.56E-05	3.69E-05	2.71E+04	135
Mozzarella 20°C	2.91E-05	8.48E-05	1.18E+04	131
Process 4°C	2.25E-06	9.26E-06	1.08E+05	183
Process 12°C	1.09E-05	2.53E-05	3.95E+04	104
Process 20°C	2.79E-05	6.52E-05	1.53E+04	90

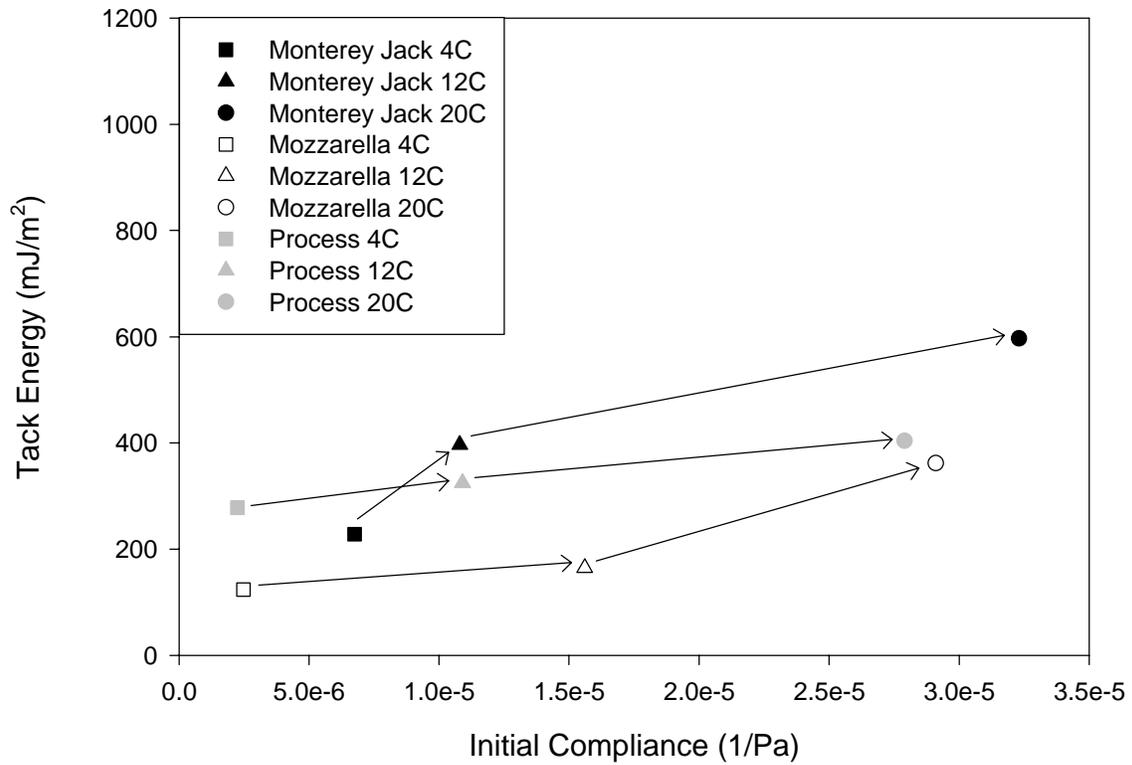


Figure 8. Comparison of tack energy and initial compliance for Monterey Jack, Mozzarella and process cheeses at 4°C, 12°C and 20°C.

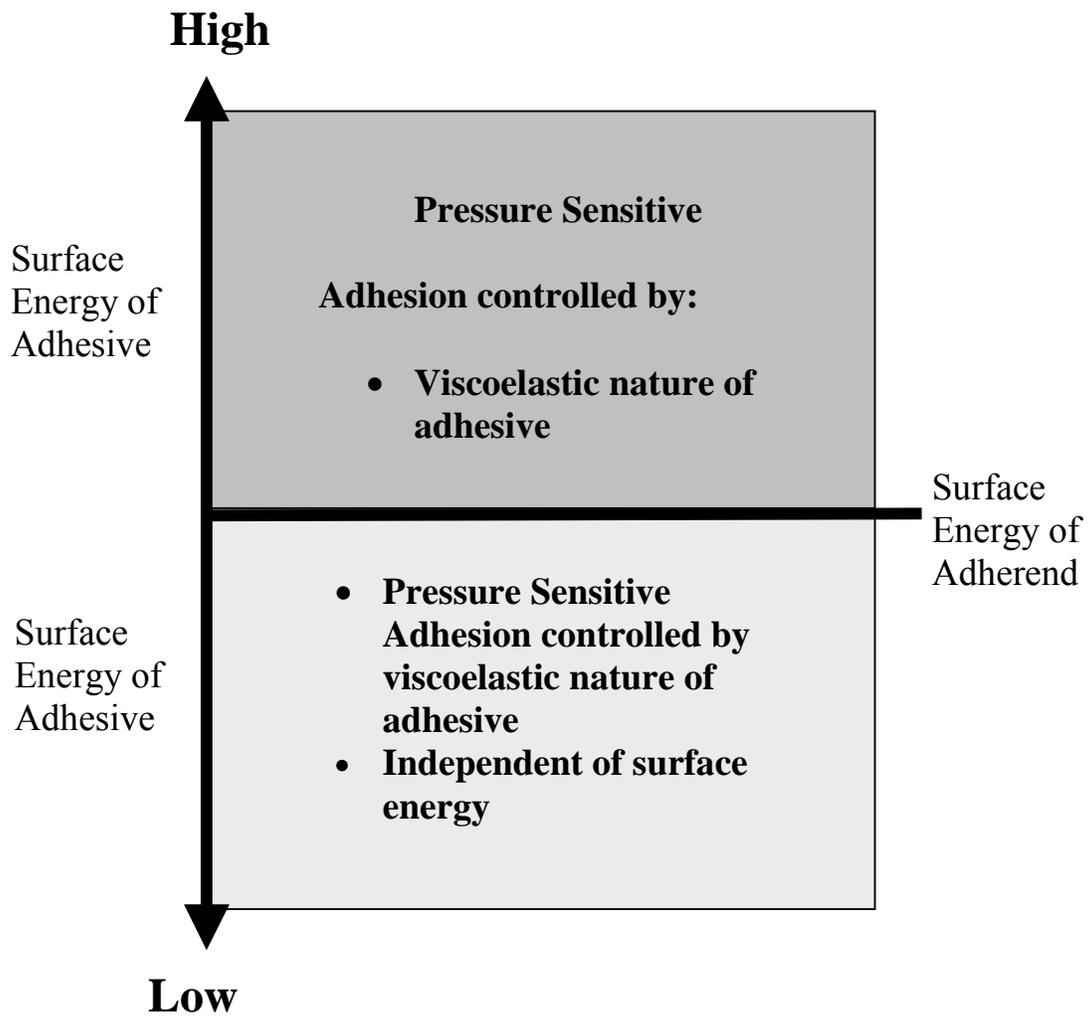


Figure 9. Mechanisms of pressure sensitive adhesion

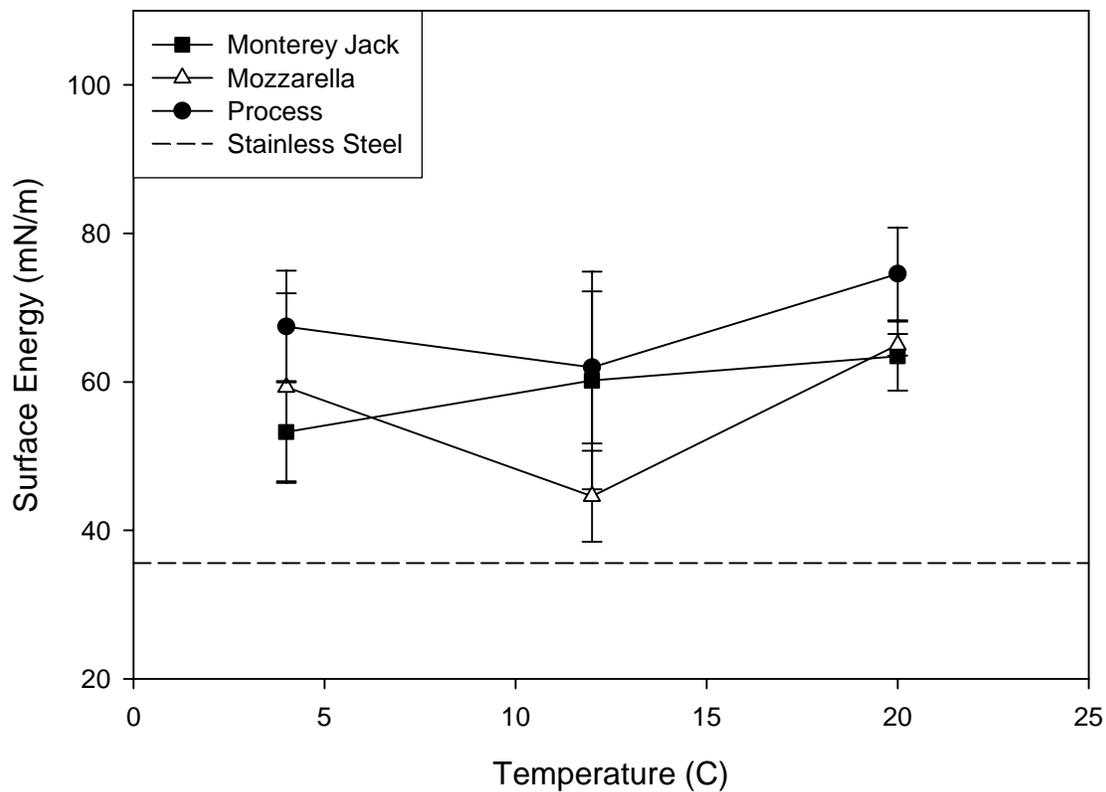


Figure 10. Surface energy for Monterey Jack, Mozzarella and process cheeses over 4°C, 12°C and 20°C. Dotted line represents surface energy of stainless steel (35.6 mN/m). Error bars represent standard error of the mean.

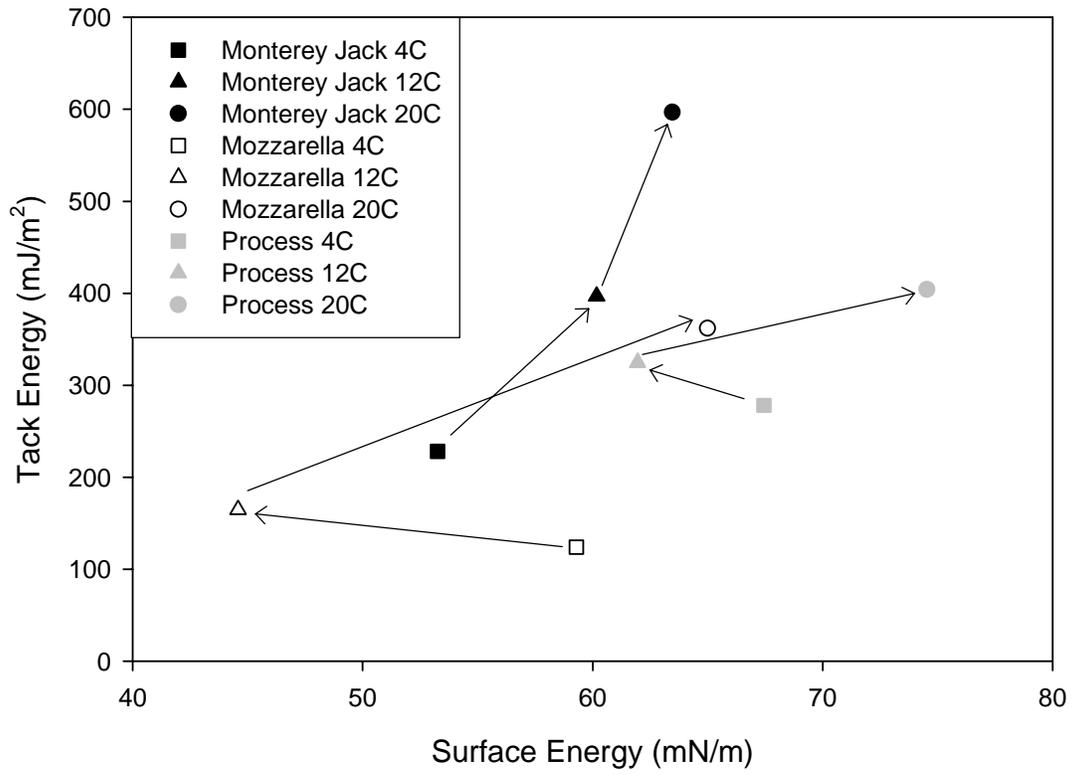


Figure 11. Comparison of tack energy and surface energy for Monterey Jack, Mozzarella and process cheeses at 4°C, 12°C and 20°C

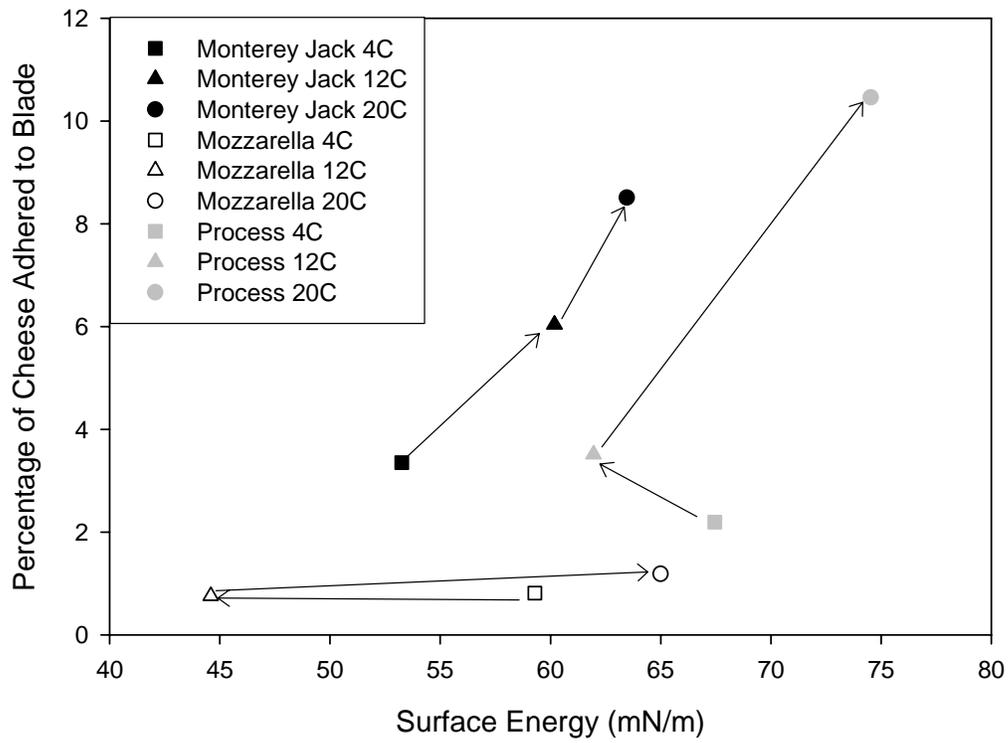


Figure 12. Comparison of cheese adhered to the blade and surface energy for Monterey Jack, Mozzarella and process cheeses at 4°C, 12°C and 20°C.

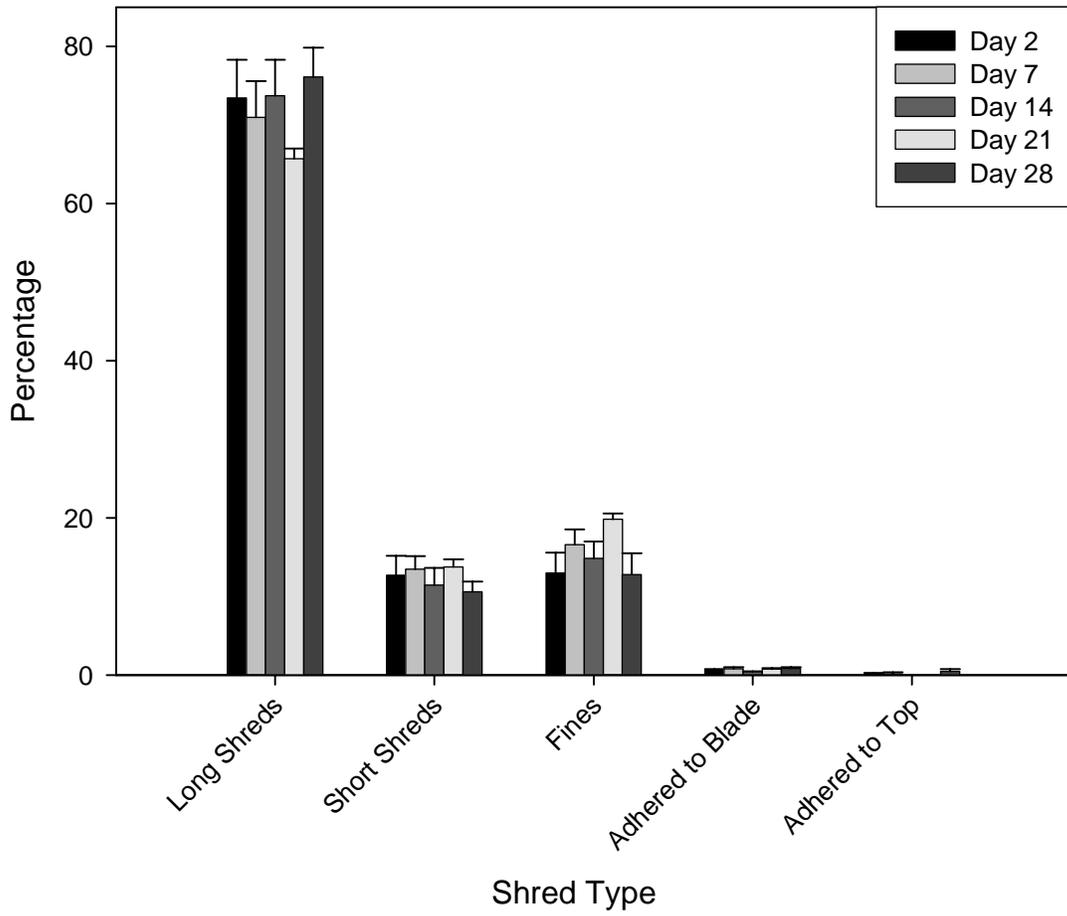


Figure 13a. Shred distribution for Cheese 1 over 28 days of aging. Error bars represent standard error of the mean.

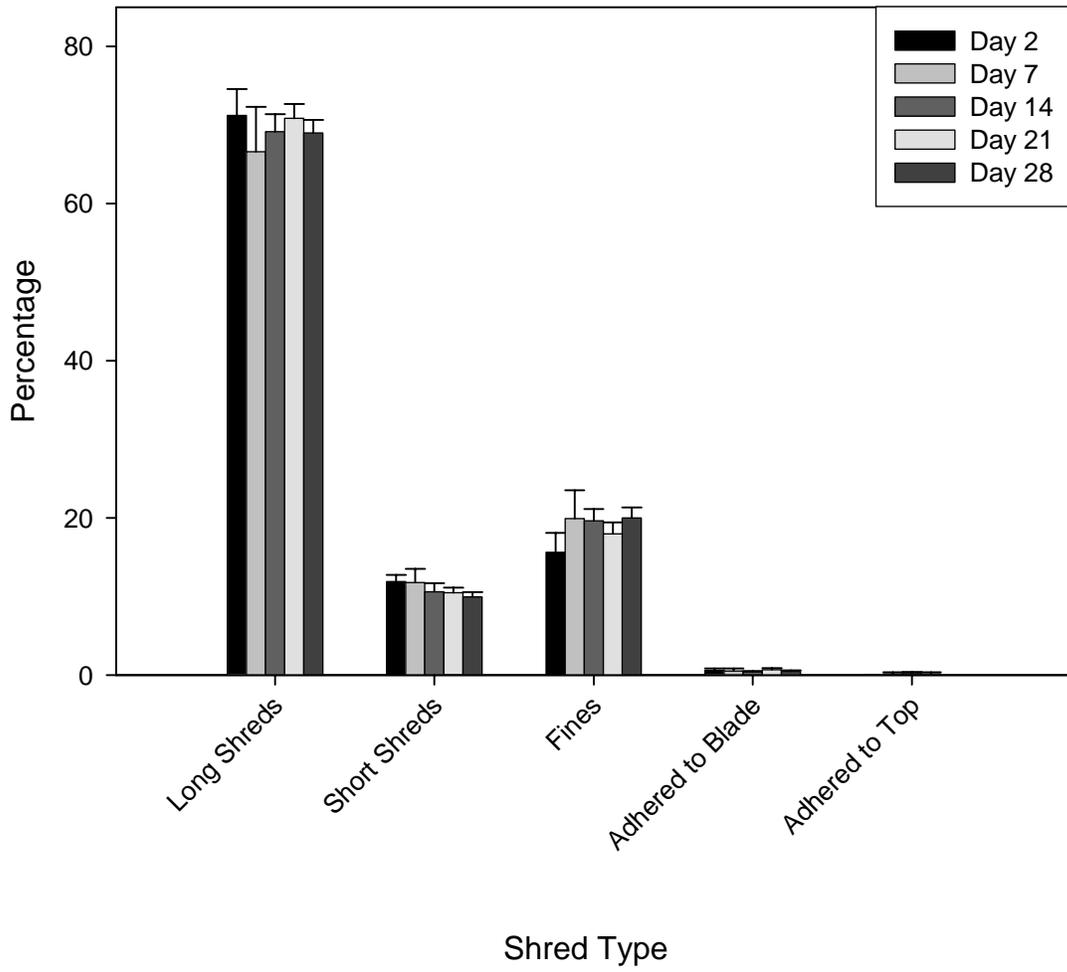


Figure 13b. Shred distribution for Cheese 2 over 28 days of aging.

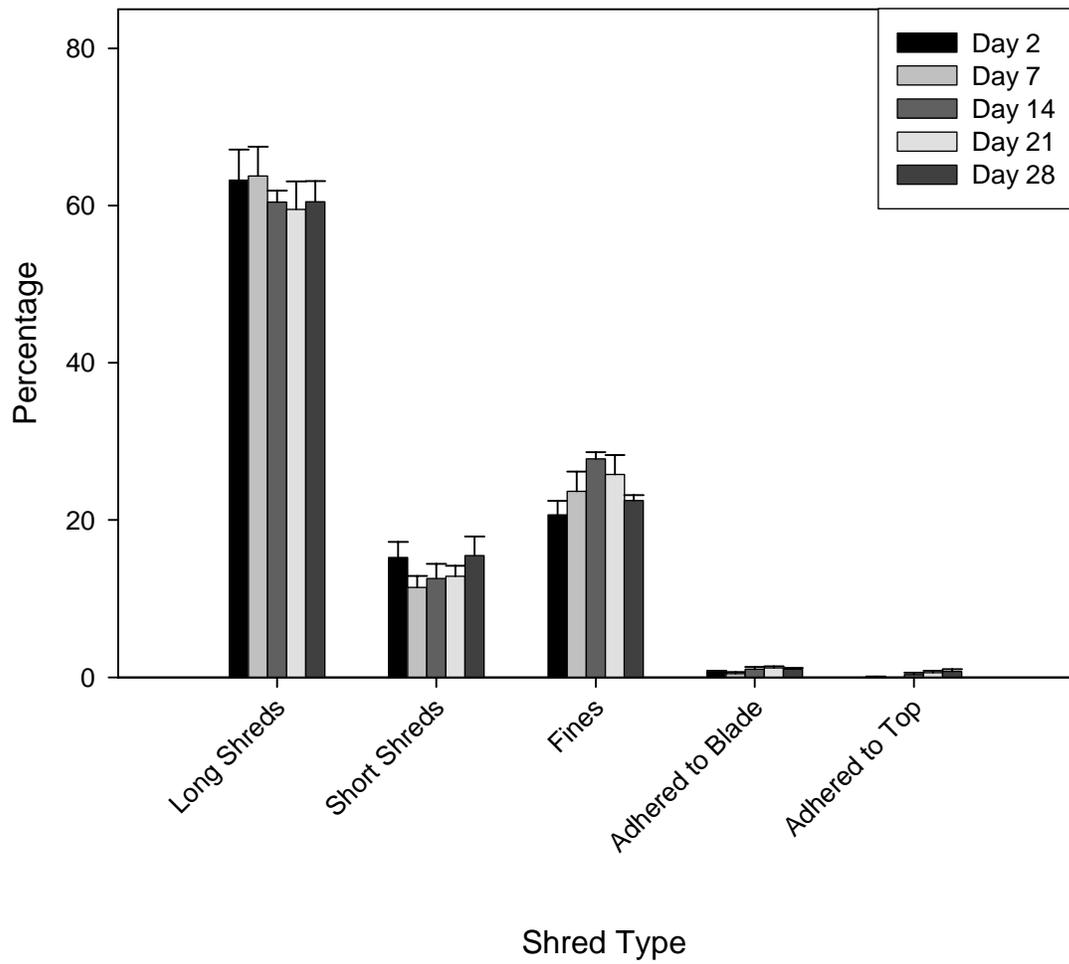


Figure 13c. Shred distribution for Cheese 3 over 28 days of aging.

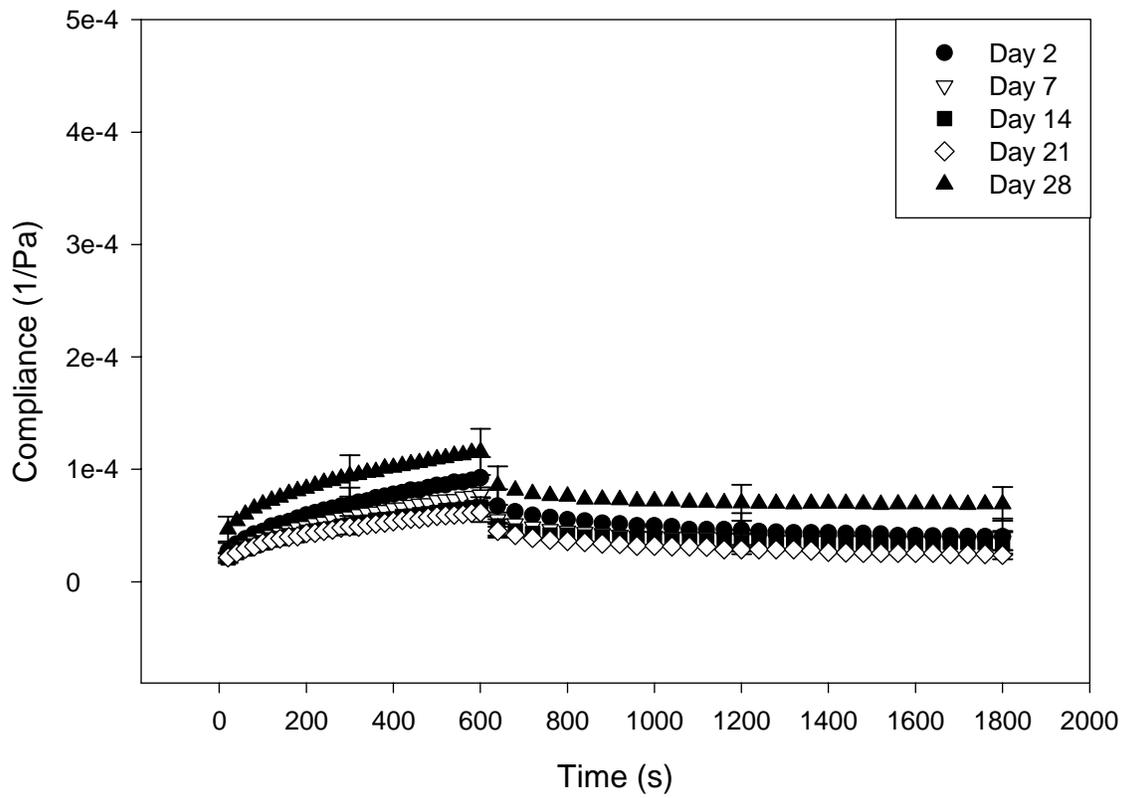


Figure 14a. Creep and recovery for Cheese 1 Over 28 days of aging. Error bars represent standard error of the mean.

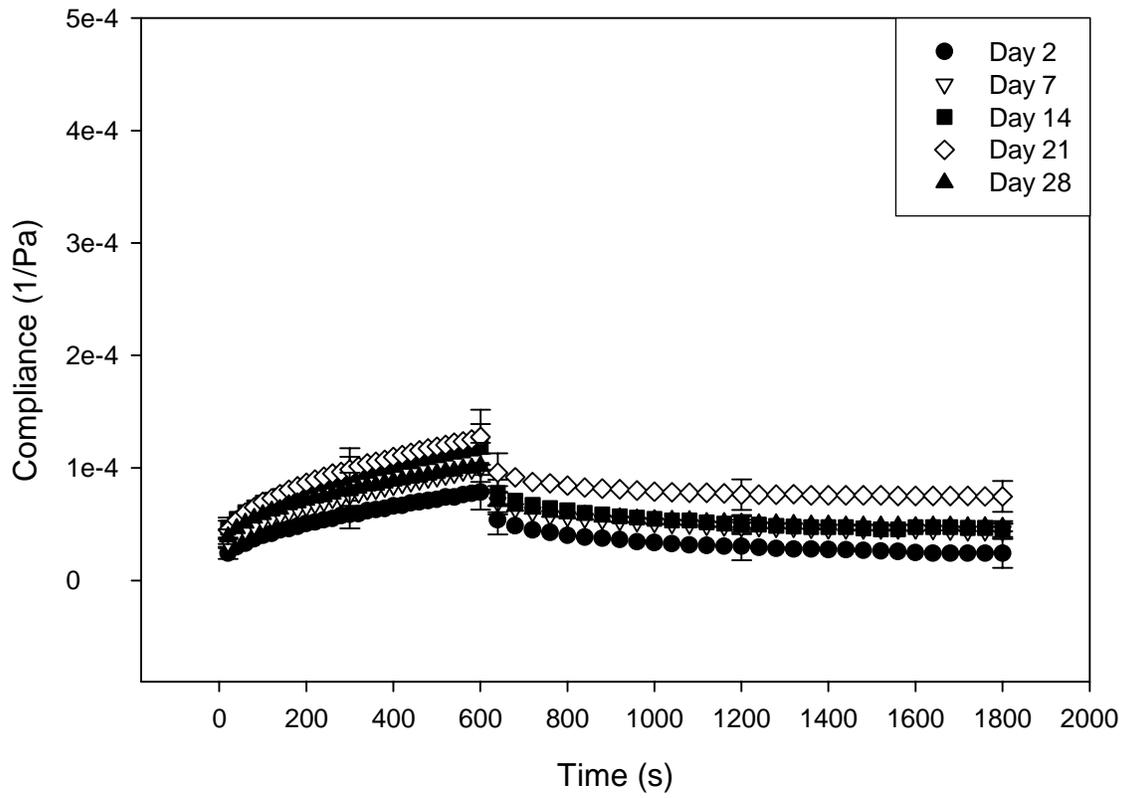


Figure 14b. Creep and recovery of Cheese 2 over 28 days of aging.

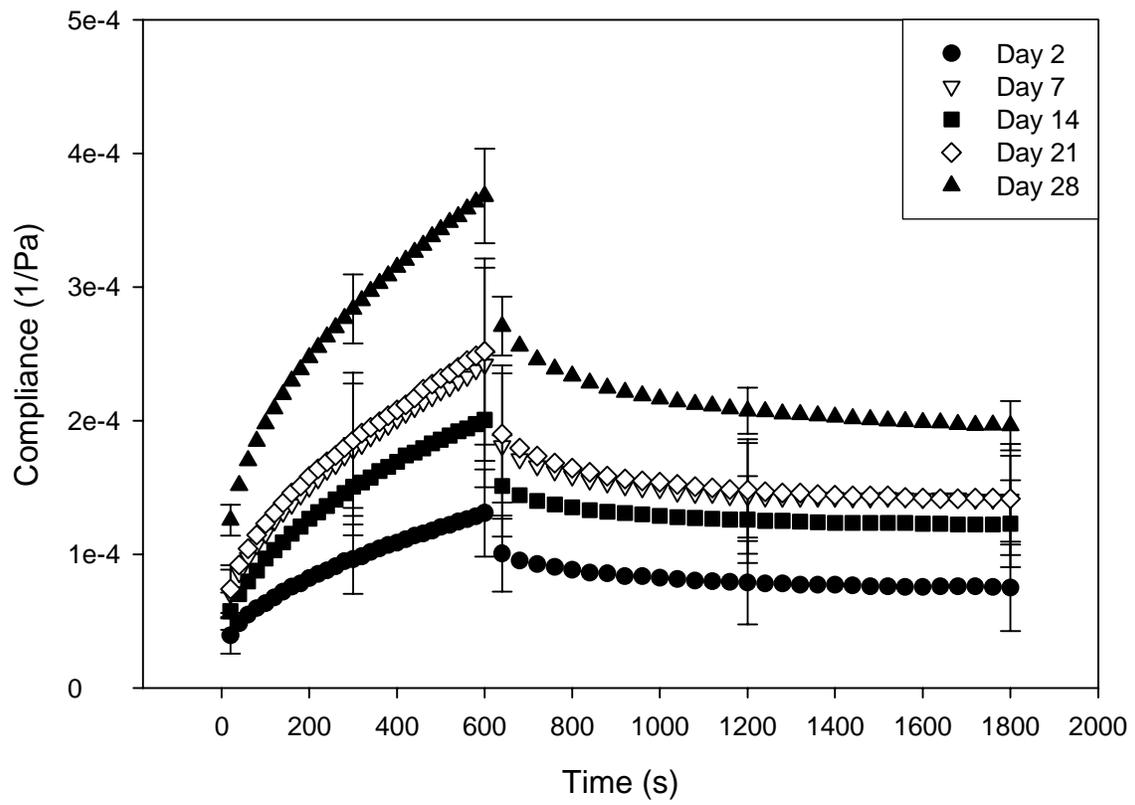


Figure 14c. Creep and recovery for Cheese 3 over 28 days of aging.

Table 6. Correlation analysis between fines, cheese adhered to the blade, surface energy, tack energy, maximum compliance (J_{\max}), initial compliance (J_0) and retardation time (λ_{ret}) for Experimental Cheese Set A

	Fines	Adhered to Blade	Surface Energy	Tack Energy	J_{\max}	J_0	λ_{ret}
Fines	1.000	0.409	-0.293	0.576*	0.657*	0.571*	0.267
Adhered to Blade		1.000	-0.040	0.444	0.541*	0.502	0.107
Surface Energy			1.000	-0.266	-0.260	-0.306	0.701*
Tack Energy				1.000	0.804*	0.819*	-0.099
J_{\max}					1.000	0.979*	0.072
J_0						1.000	-0.047
λ_{ret}							1.000

*significant correlation at $p \leq 0.05$

Table 7. Initial compliance (J_0), maximum compliance (J_{\max}), storage modulus (G') and retardation time (λ_{ret}) for Cheeses 1, 2 and 3 over 28 days of aging.

	J_0 (1/Pa)	J_{\max} (1/Pa)	G' (Pa)	λ_{ret} (s)
Cheese 1				
Day 2	2.74E-05	9.26E-05	1.08E+04	175
Day 7	2.34E-05	7.72E-05	1.30E+04	185
Day 14	2.13E-05	6.65E-05	1.50E+04	175
Day 21	2.18E-05	6.18E-05	1.62E+04	155
Day 28	4.68E-05	1.16E-04	8.66E+03	125
Cheese 2				
Day 2	2.4E-05	7.83E-05	1.28E+04	185
Day 7	3.35E-05	1.00E-04	1.00E+04	180
Day 14	4.68E-05	1.19E-04	8.43E+03	140
Day 21	4.47E-05	1.27E-04	7.86E+03	150
Day 28	3.89E-05	1.02E-04	9.84E+03	135
Cheese 3				
Day 2	3.94E-05	1.31E-04	7.64E+03	325
Day 7	7.03E-05	2.42E-04	4.13E+03	190
Day 14	5.75E-05	2.01E-04	4.98E+03	195
Day 21	7.4E-05	2.52E-04	3.97E+03	195
Day 28	1.26E-04	3.68E-04	2.72E+03	160

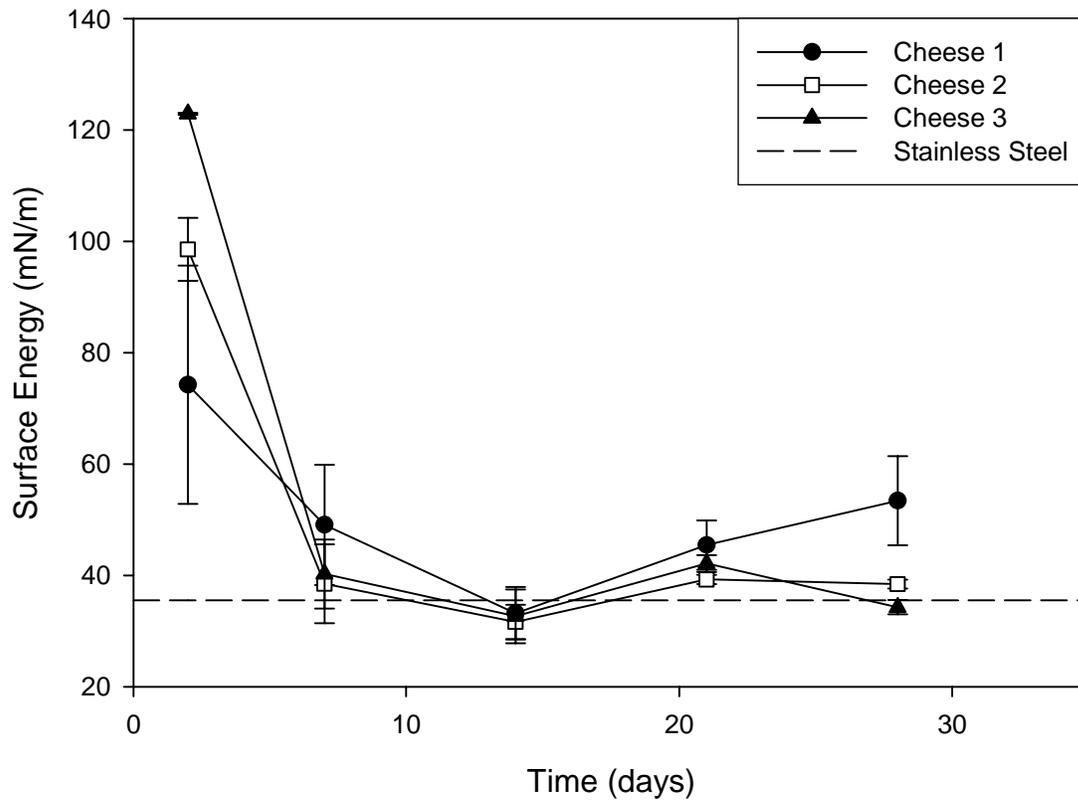


Figure 15. Surface energy of Cheeses 1, 2 and 3 over 28 days of aging. Error bars represent standard error of the mean.

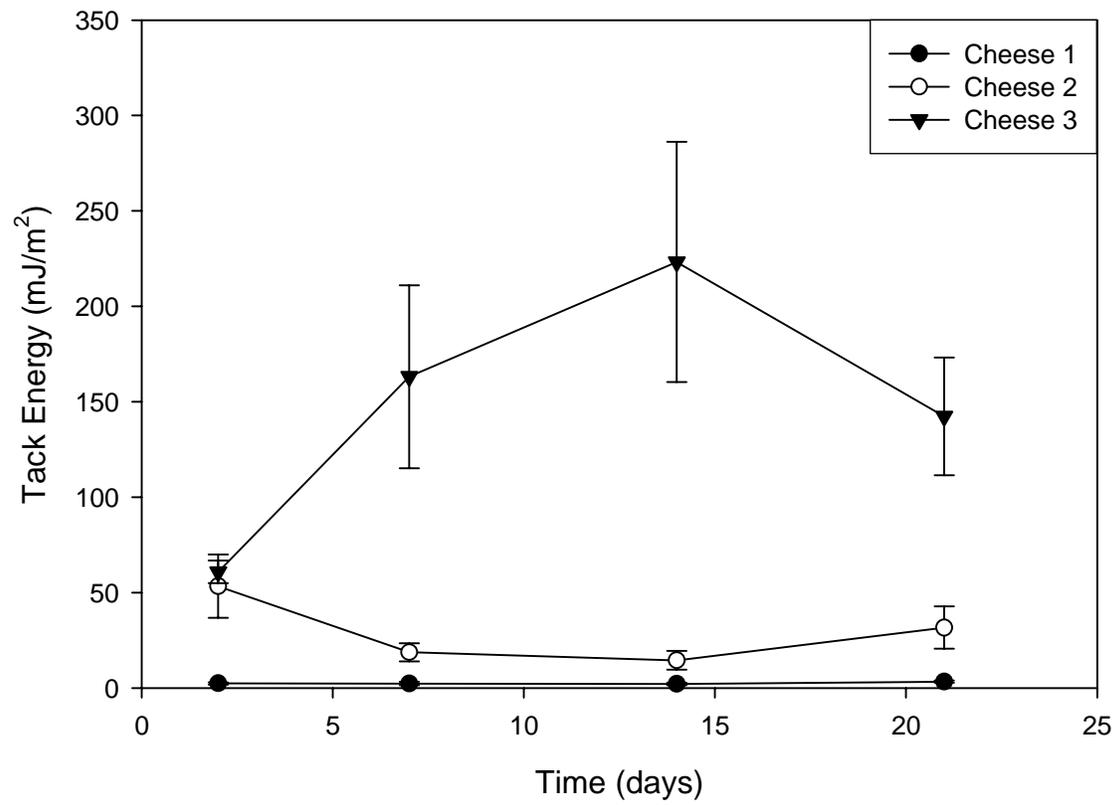


Figure 16. Tack energy for Cheeses 1, 2 and 3 over 21 days of aging. Error bars represent standard error of the mean.

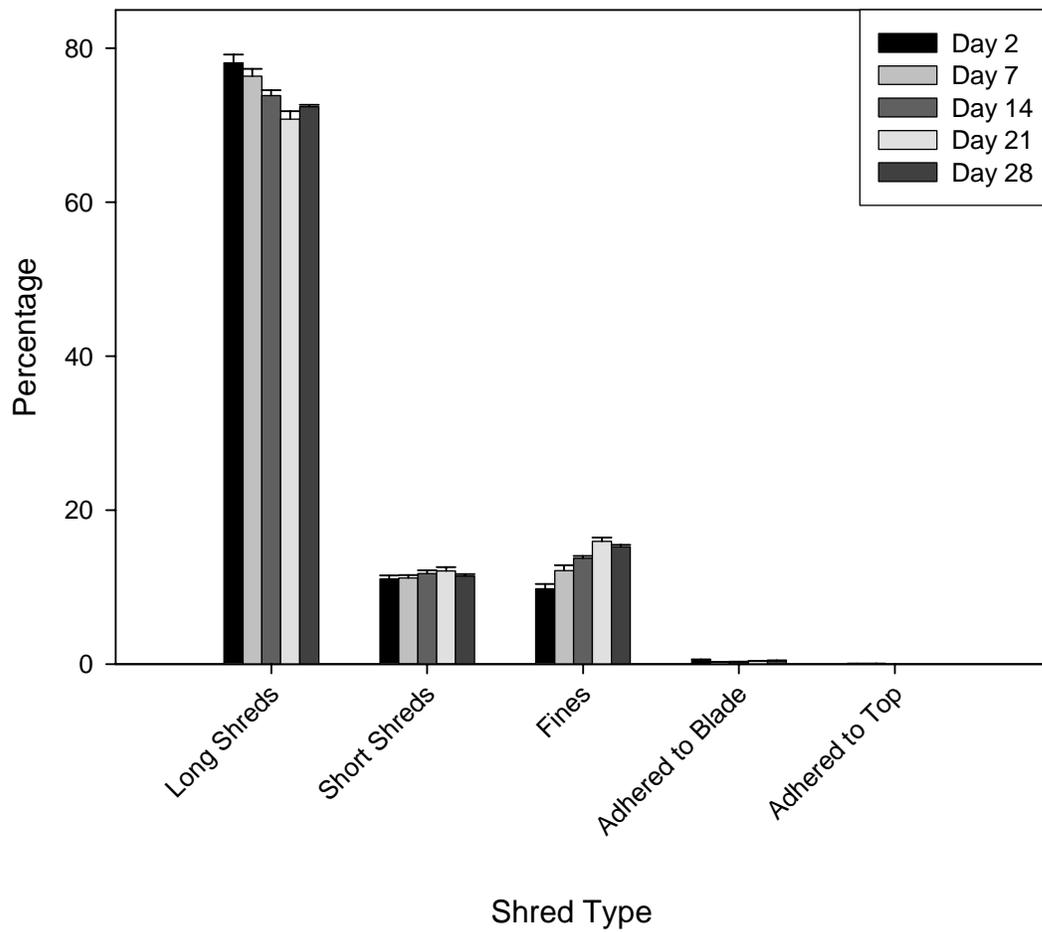


Figure 17a. Shred distribution for low calcium-low moisture (LC-LM) cheese over 28 days of aging. Error bars represent standard error of the mean.

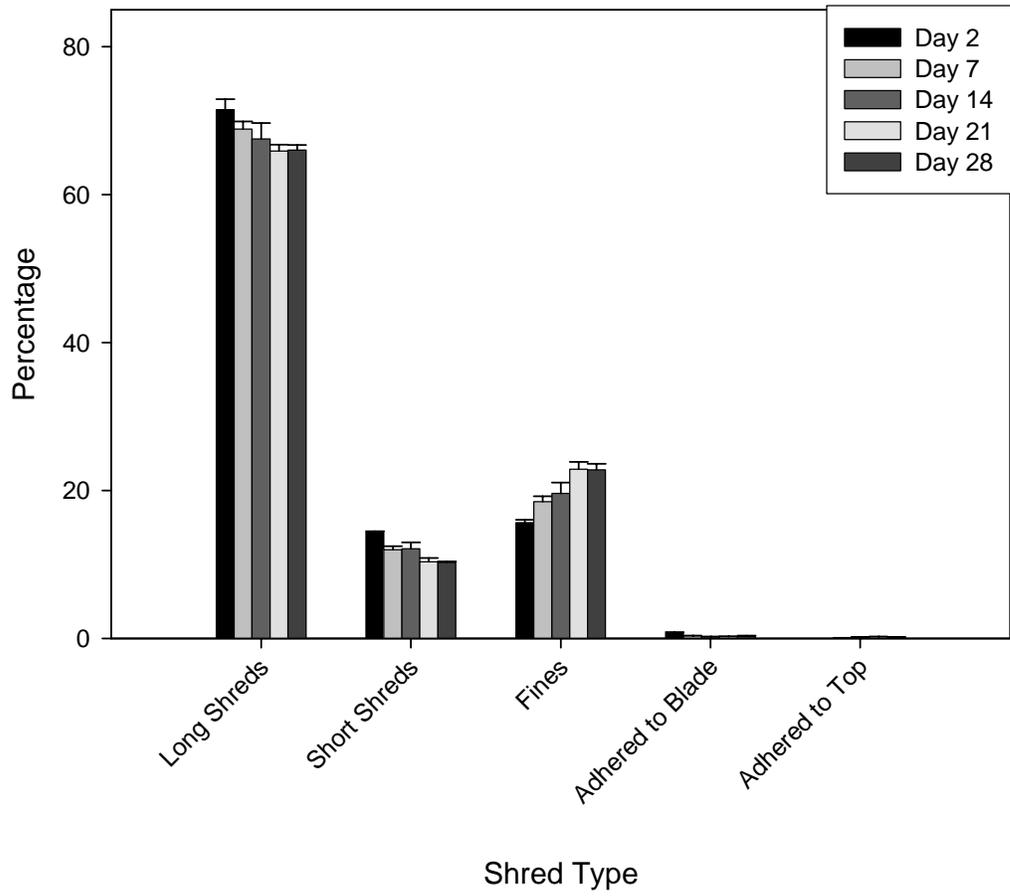


Figure 17b. Shred distribution for low calcium-high moisture (LC-HM) cheese over 28 days of aging.

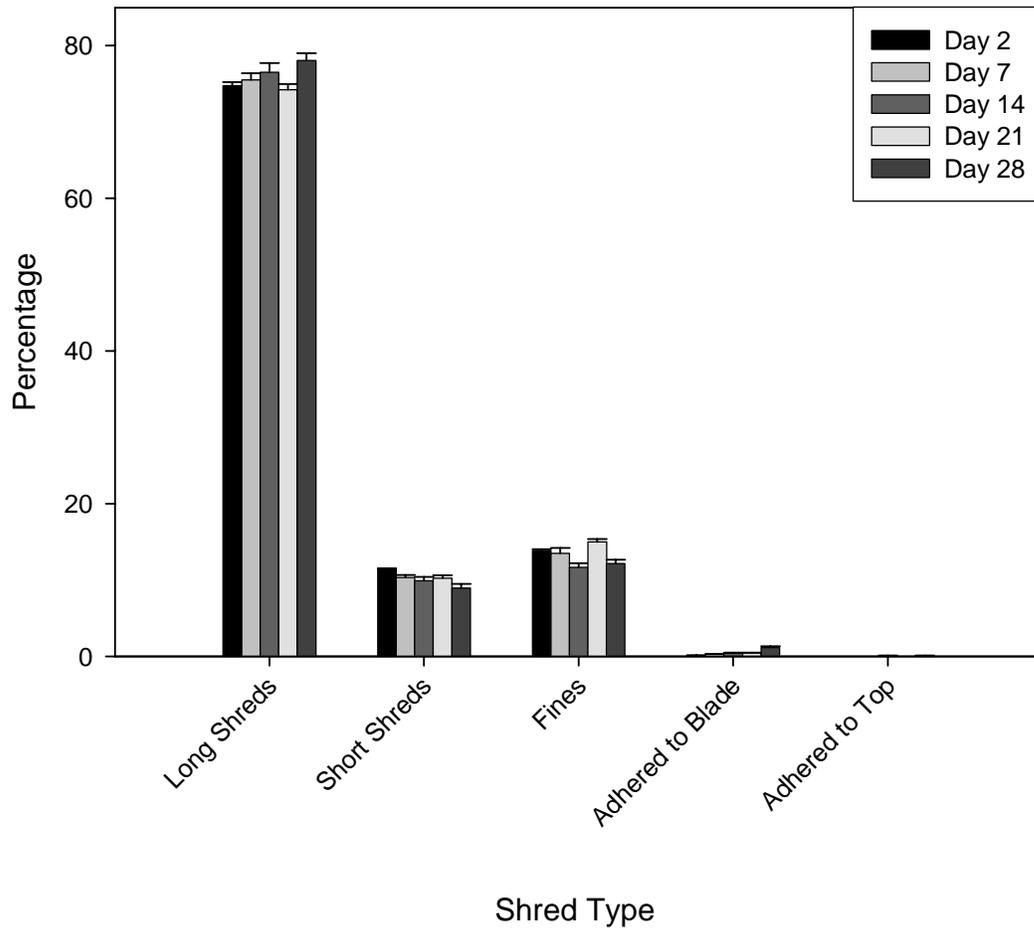


Figure 17c. Shred distribution for high calcium-low moisture (HC-LM) cheese over 28 days of aging.

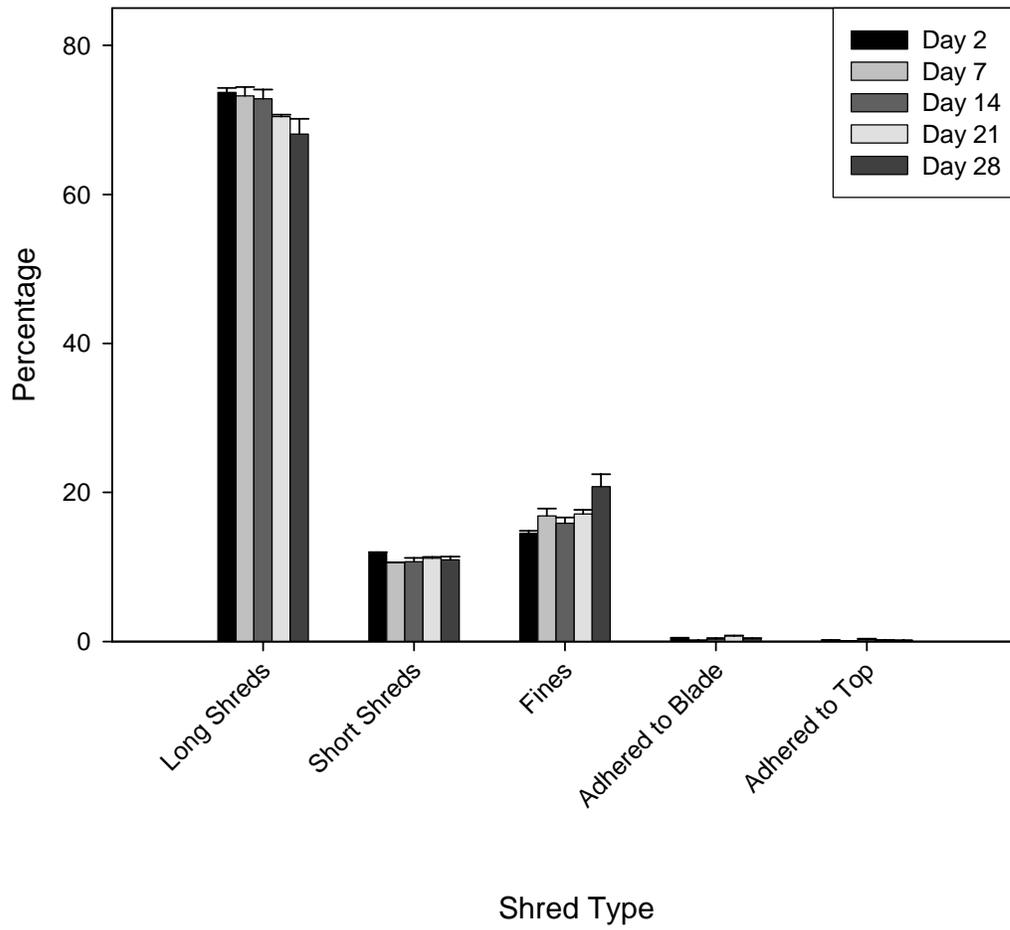


Figure 17d. Shred distribution for high calcium-high moisture (HC-HM) cheese over 28 days of aging.

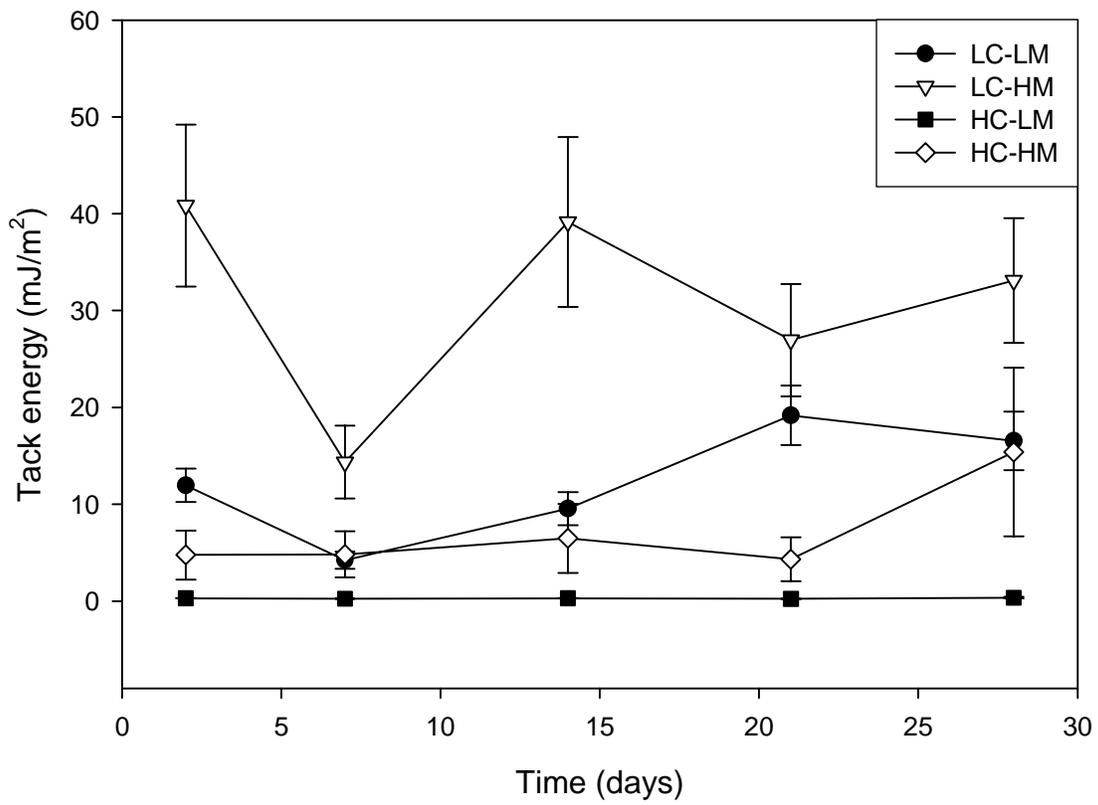


Figure 18. Tack energy for low calcium-low moisture (LC-LM), low calcium-high moisture (LC-HM), high calcium-low moisture (HC-LM), and high calcium-high moisture (HC-HM) cheeses over 28 days of aging. Error bars represent standard error of the mean.

Table 8. Correlational analysis between fines, cheese adhered to the blade, surface energy, tack energy, maximum compliance (J_{\max}), initial compliance (J_0) and retardation time (λ_{ret}) for Experimental Cheese Set B.

	Fines	Adhered to Blade	Surface Energy	Tack	J_{\max}	J_0	λ_{ret} (s)
Fines	1.000	-0.353	-0.004	0.678*	0.500*	0.423	-0.312
Adhered to Blade		1.000	0.329	-0.088	-0.049	-0.024	0.162
Surface Energy			1.000	0.390	-0.113	-0.057	0.233
Tack				1.000	0.057	-0.036	0.210
J_{\max}					1.000	0.971*	-0.495*
J_0						1.000	-0.604*
Retardation Time							1.000

*significance correlation at $p \leq 0.05$

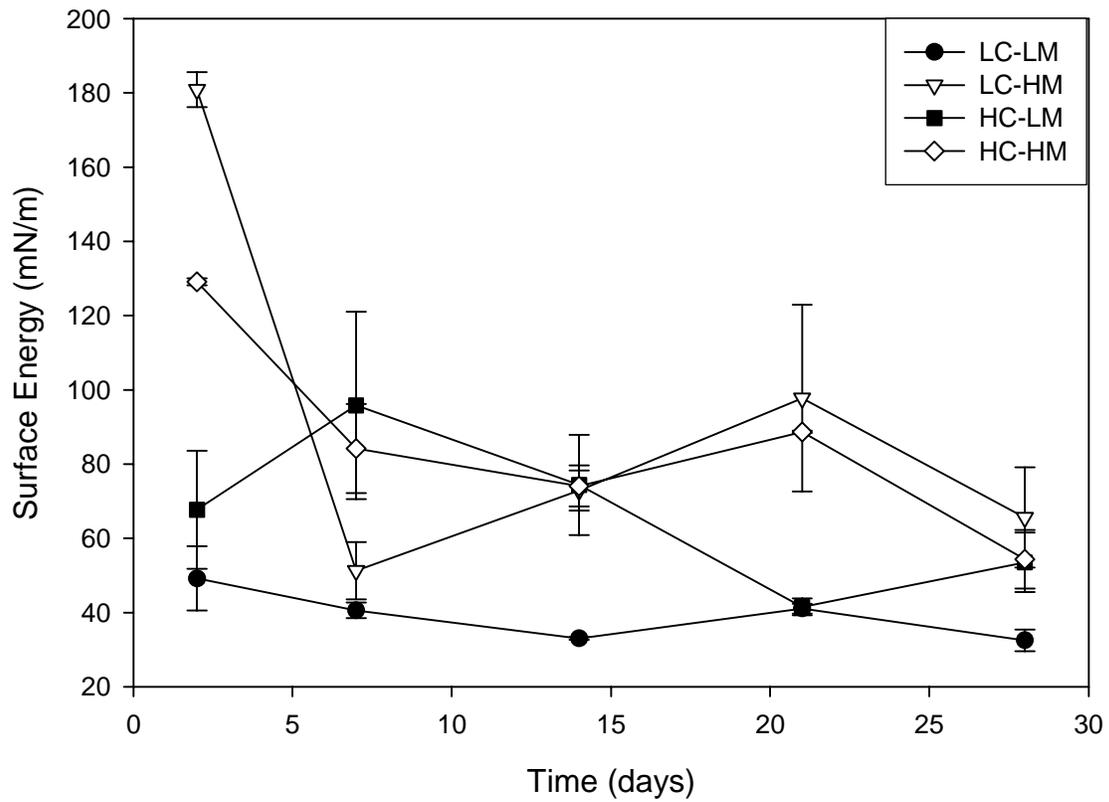


Figure 19. Surface energy for low calcium-low moisture (LC-LM), low calcium-high moisture (LC-HM), high calcium-low moisture (HC-LM), and high calcium-high moisture (HC-HM) cheeses over 28 days of aging. Error bars represent standard error of the mean.

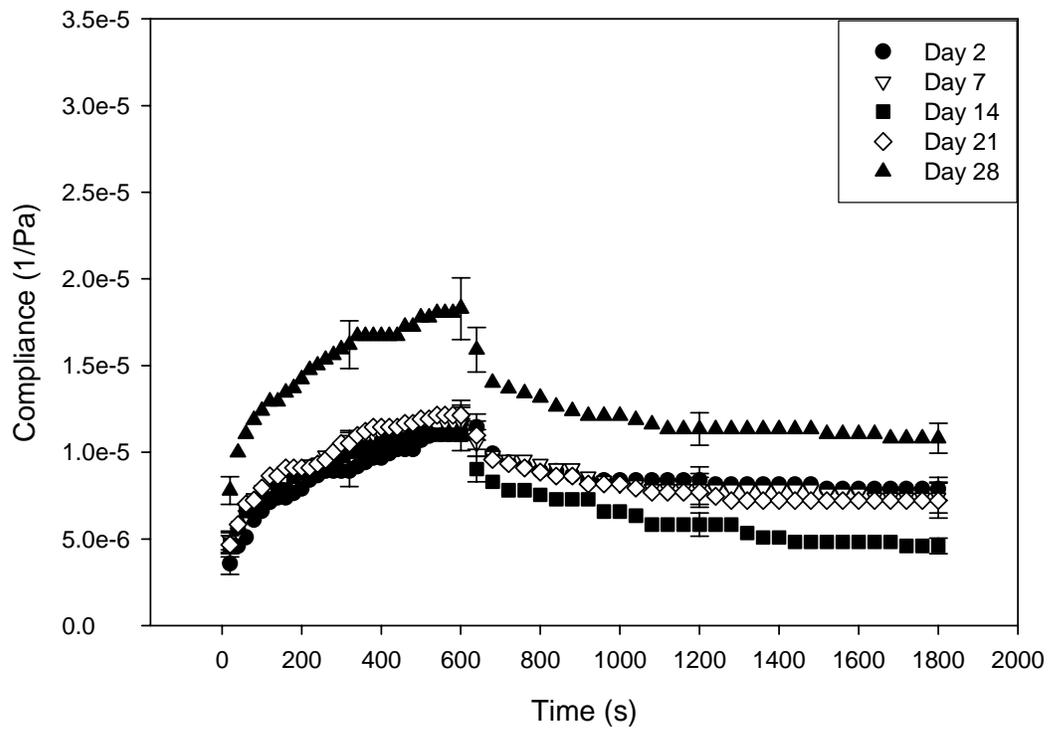


Figure 20a. Creep and recovery for low calcium-low moisture (LC-LM) cheese over 28 days of aging. Error bars represent standard error of the mean.

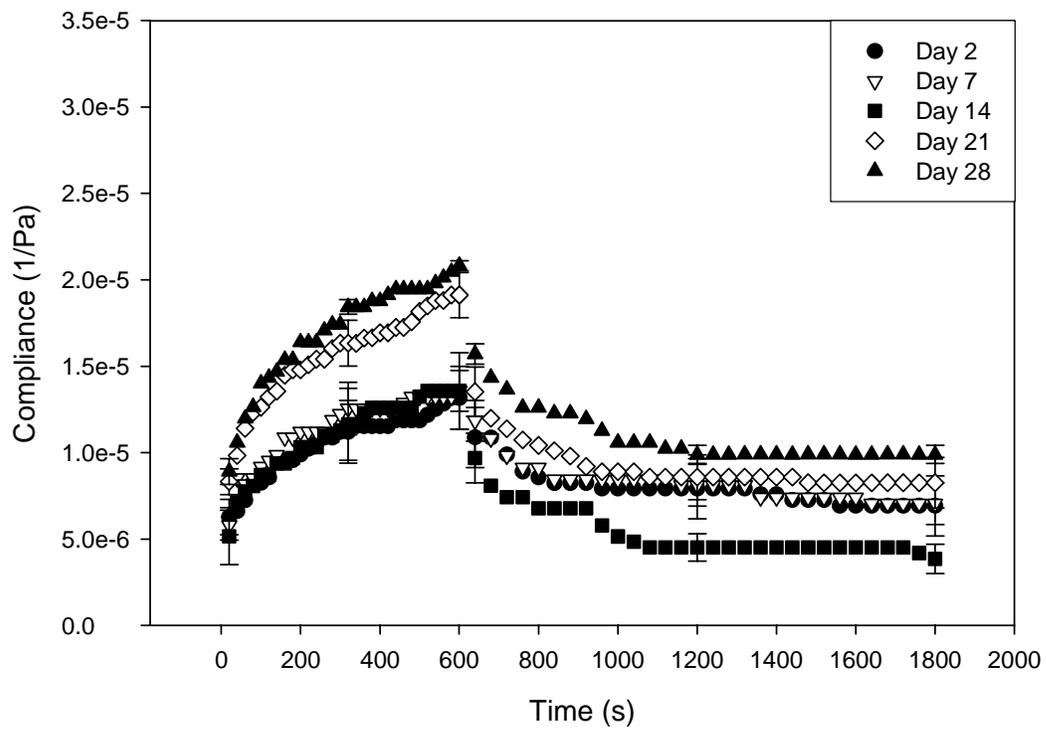


Figure 20b. Creep and recovery for low calcium-high moisture (LC-HM) cheese over 28 days of aging.

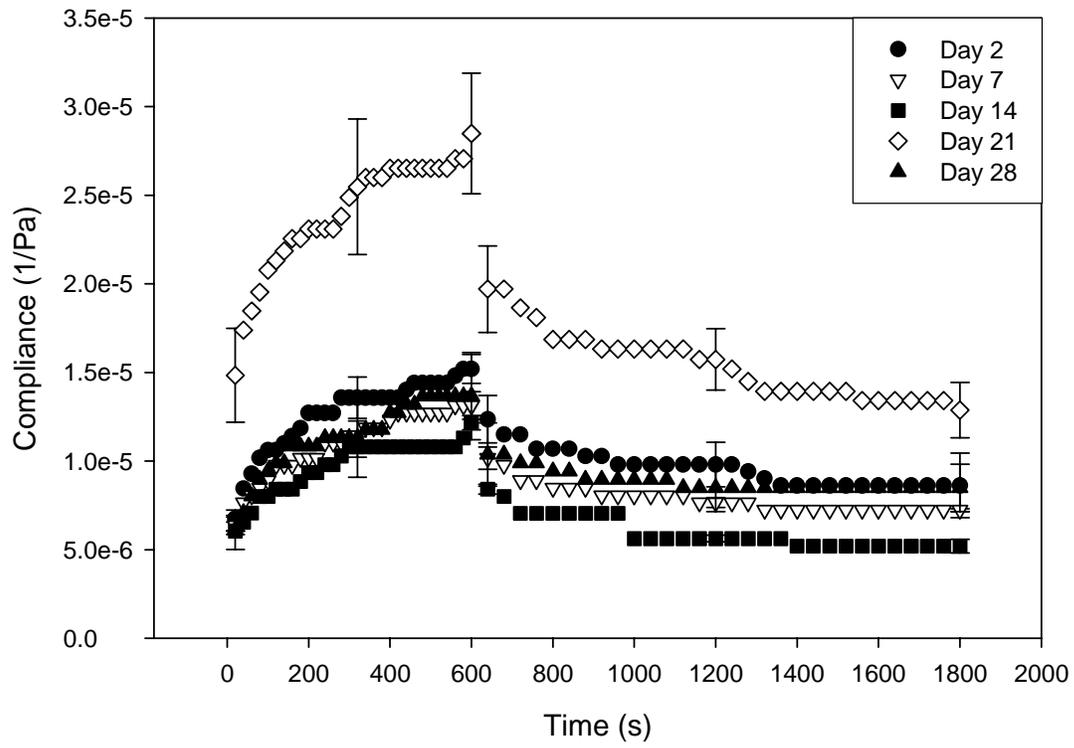


Figure 20c. Creep and recovery for high calcium-low moisture (HC-LM) cheese over 28 days of aging.

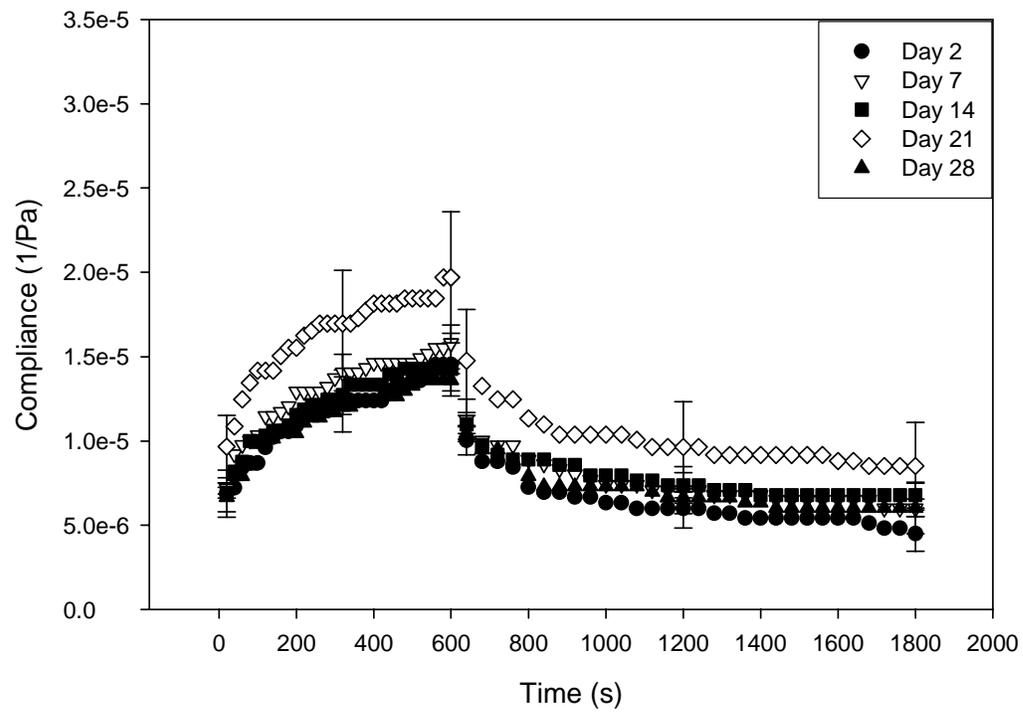


Figure 20d. Creep and recovery for high calcium-high moisture (HC-HM) cheese over 28 days of aging.

Table 9. Initial compliance (J_0), maximum compliance (J_{\max}), storage modulus (G') and retardation time (λ_{ret}) for Low Calcium-Low Moisture (LC-LM), Low Calcium-High Moisture (LC-HM), High Calcium-Low Moisture (HC-LM), High Calcium-High Moisture (HC-HM) Cheeses from Experimental Cheese Set B over 28 days of aging.

Day	J_0 (1/Pa)	J_{\max} (1/Pa)	G' (Pa)	λ_{ret} (s)
Low Calcium-Low Moisture				
2	3.58E-06	1.17E-05	8.54E+04	212
7	4.90E-06	1.17E-05	8.53E+04	102
14	4.66E-06	1.1E-05	9.08E+04	98
21	4.66E-06	1.21E-05	8.24E+04	118
28	7.79E-06	1.83E-05	5.47E+04	88
Low Calcium-High Moisture				
2	6.26E-06	1.32E-05	7.60E+04	138
7	5.8E-06	1.36E-05	7.36E+04	70
14	5.15E-06	1.36E-05	7.37E+04	131
21	8.32E-06	1.91E-05	5.23E+04	104
28	8.91E-06	2.08E-05	4.80E+04	85
High Calcium-Low Moisture				
2	6.74E-06	1.52E-05	6.58E+04	70
7	6.35E-06	1.31E-05	7.62E+04	78
14	6.05E-06	1.22E-05	8.22E+04	67
21	1.48E-05	2.85E-05	3.51E+04	73
28	6.12E-06	1.37E-05	7.32E+04	83
High Calcium-High Moisture				
2	6.88E-06	1.45E-05	6.88E+04	130
7	7.18E-06	1.58E-05	6.33E+04	91
14	6.94E-06	1.43E-05	7.00E+04	56
21	9.67E-06	1.97E-05	5.07E+04	63
28	6.66E-06	1.36E-05	7.34E+04	89

APPENDIX A

Method Development for Measurement of Cheese Surface Energy

To obtain a measurement of surface energy on a solid it is important that the surface of the solid is flat and smooth. The heterogeneous nature of cheese does not allow for a perfectly flat surface of cheese. In order to get the surface of the cheese as flat and smooth as possible, a custom cheese slicer was constructed at the NC State University Biological and Agricultural Engineering Machine Shop. The cheese slicer has a wall one quarter of an inch to the right of the cutting wire. The cheese can be pushed up against the wall and when cut with the cheese wire a flat, 1/4" slice of cheese is produced. Even with the use of the custom cheese slicer, there are still some pinholes and crevices that exist in the cheese. Since this is the nature of the cheese, it worked best to work around the holes in the cheese and find portions in a slice of cheese that were flat.

The piece of equipment used in measuring the surface energy of the cheese is called a goniometer. The goniometer is equipped with a camera, a light source and a stage. The samples are placed on the stage that lies between the camera and the light source. The camera feeds into the computer so that a live picture of the sample being measured can be seen. Once the cheese is cut into a flat surface, it is placed on the stage. The cheese surface is balanced with a level so when the solutions are dropped on the cheese they are not skewed and measurements can be made more easily. Once the cheese is balanced on the stage, 12 μL of solution are dispensed and suspended from a 16-gauge

needle. The drop of solution that is suspended from the needle is brought down to the surface of the cheese and gently placed on the surface of the cheese. Once the drop is on the surface of the cheese the surface energy can be measured.

In order to measure the surface energy of cheese, it is necessary to obtain a contact angle measurement of two different solutions of different polarity on the surface of the cheese. When measuring the surface energy of solid materials, the two typical solutions used are water and methylene iodide. The cheeses used in developing a method for measuring surface energy of cheese were purchased from a grocery store and will be referred to as commercial cheeses. When water was dropped on the surface of the cheese, it began to soak up into the surface of the cheese. Since the drop has to be stable on the surface of the solid when measuring surface energy, water was not an option for measuring surface energy of the cheese. When methylene iodide was dropped on the surface of the cheese it wetted the surface of the cheese completely. The contact angle was very difficult to measure and therefore another solution that did not wet the surface of the cheese completely had to be investigated. When measuring the contact angle of the solutions, a measurement of each side of the drop was taken every second for one minute. The values from each side were then averaged to give the value for the contact angle.

Other solutions that could be used to measure the surface energy of a solid were listed within the Drop Image Software (Ramè-Hart Inc., Mountain Lakes, NJ). The values for polarity were present within the software program and the process of selecting the two new solutions was started on a basis of the polarity. The solutions, other than water and methylene iodide, that were listed in the software program and tested (in order

of decreasing polarity) were glycerol, formamide, ethylene glycol, dimethyl sulfoxide, and aniline. First, the solution that had a polarity closest to water, which was glycerol, was chosen and tested on the cheese. Since glycerol is very viscous, it proved to be problematic since it could not be dispensed easily from the needle onto the cheese. Glycerol's viscous nature supported the drop and caused it to sit up tall on the surface of the cheese and then creep downward very rapidly. This caused the measurement of the contact angle to be very inconsistent. The benefit of glycerol is that it did not soak up into the cheese, so the possibility of a solution that did not soak up into the cheese did exist. The next solution that was tried was formamide. This solution did not soak into the cheese, but the contact angle slowly decreased over the minute that the contact angle was measured. Ethylene glycol and dimethyl sulfoxide behaved similarly to the formamide. Due to the decreasing contact angle over the minute that the contact angle of the solutions was measured, the amount of time that contact angles were measured was reduced to five seconds. Since there was not much variability in the measurements over the five seconds after the initial placement of the drop on the cheese, it appeared that this length of time for measurement was suitable for the experiment. A measurement was taken every second for the five second period.

Through further evaluation of the solution drop stability on the cheese, the two solutions chosen for the surface energy measurement of cheese were formamide and dimethyl sulfoxide. These two solutions had the greatest range of polarity and produced a stable drop on the surface of the cheese long enough to make the necessary contact angle measurements.