Factors Regulating Cheese Shreddability

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ABSTRACT

Two sets of cheeses were evaluated to determine factors that affect shred quality. The first set of cheeses was made up of 3 commercial cheeses, Monterey Jack, Mozzarella, and process. The second set of cheeses was made up of 3 Mozzarella cheeses with varying levels of protein and fat at a constant moisture content. A shred distribution of long shreds, short shreds, and fines was obtained by shredding blocks of cheese in a food processor. A probe tack test was used to directly measure adhesion of the cheese to a stainless-steel surface. Surface energy was determined based on the contact angles of standard liquids, and rheological characterization was done by a creep and recovery test. Creep and recovery data were used to calculate the maximum and initial compliance and retardation time. Shredding defects of fines and adhesion to the blade were observed in commercial cheeses. Mozzarella did not adhere to the blade but did produce the most fines. Both Monterey Jack and process cheeses adhered to the blade and produced fines. Furthermore, adherence to the blade was correlated positively with tack energy and negatively with retardation time. Mozzarella cheese, with the highest fat and lowest protein contents, produced the most fines but showed little adherence to the blade, even though tack energy increased with fat content. Surface energy was not correlated with shredding defects in either group of cheese. Rheological properties and tack energy appeared to be the key factors involved in shredding defects.

Key words: cheese, shreddability, pressure-sensitive adhesion, surface energy

INTRODUCTION

Cheese is one of the most important foods in which shredding is used extensively by both the consumer and the manufacturer (Apostolopoulos and Marshall, 1994). Shredding allows for faster melting of cheese, as com-

pared with other methods of size reduction such as slicing and cubing (Ni and Gunasekaran, 2004).

Shreddability is a broad term that encompasses many characteristics of shredded cheese. It can take into account the ease with 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, and 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. The shredded cheese may also 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 cut uniformly and precisely, which allows the cheese to melt evenly and easily (Dubuy, 1980). Considerable importance is 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 Gunasekaran, 2004). Considerable emphasis is also put on the amount of fines produced during shredding. Production of fines causes waste that cheese processors would like to avoid (Dubuy, 1980).

Many factors regulate the production of a high-quality shred (Table 1). Composition of the cheese is one important factor that regulates cheese shreddability. Kindstedt (1995) stated that problems with surface wetness, soft body, and matting are common in Mozzarella cheeses containing high moisture. Cheese containing 45% fat in the DM (**FDM**) showed a relatively high degree of matting, whereas cheeses containing 30, 20, and 10% showed much less (Kindstedt, 1995). Increases in the fat and moisture contents of Mozzarella cheese are accompanied by a decrease in the modulus of elasticity, a softer bodied cheese, and difficulty in shredding (Masi and Addeo, 1986).

Age of the cheese at the time of shredding regulates the quality of shreds. Very young or newly manufac-

Received September 21, 2006.

Accepted December 24, 2006.

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Table 1. Factors influencing the shreddability of cheese

Factor	Effect	Shreddability	Source
Cheese-making factors			
High moisture	Matting of shreds	Decreases	Kindstedt, 1995
High fat ($\geq 45\%$ fat in DM)	Matting of shreds	Decreases	Masi and Addeo, 1986 Kindstedt, 1995
Too young (i.e., Mozzarella within the first days of manufacture)	Excessive free moisture at the surface causes matting	Decreases	Masi and Addeo, 1986 Kindstedt, 1995
Too old (i.e., Mozzarella at 20 d postmanufacture)	Soft and gummy body	Decreases	Kindstedt, 1995
Soft-bodied, pasty, or wet surface	Ragged edges, fines, matting, produces gummy balls	Decreases	Kindstedt, 1995
Too firm, too dry	Shatters into fines and small particles	Decreases	Kindstedt, 1995
Material properties ¹			
$G' > 10^5$ Pa	No pressure-sensitive adhesion	Increases	Dahlquist, 1989
$G' < 10^5$ Pa	Adhesion due to pressure-sensitive adhesion	Decreases	Dahlquist, 1989
Surface energy of cheese greater than the stainless-steel shredding blade	Adhesion of cheese due to surface energy as well as viscoelastic properties	Decreases	Saunders et al., 1992
Surface energy of the cheese less than the stainless-steel shredding blade	Adhesion of cheese due only to viscoelastic properties	Decreases if below the Dahlquist criterion; increases if above the Dahlquist criterion	Zosel, 1985
$-10 < T_g < 10$	Optimum for pressure-sensitive adhesion	Decreases if within the optimum range for pressure-sensitive adhesion	Foley and Chu, 1986

¹ G' = storage modulus; T_g = glass transition temperature.

tured Mozzarella cheese does not shred well, mostly because of excessive free moisture at the surface and within the body of the cheese (Kindstedt, 1995). The excess moisture of Mozzarella is typically absorbed back into the block of cheese after aging for a few days. To allow for moisture to absorb back into the cheese block, Mozzarella cheese is typically aged 4 to 5 d prior to shredding. On the other hand, Mozzarella cheese cannot be aged for too long before shredding because as it ages and ripens, the texture becomes too soft and gummy to produce high-quality shreds. Because Mozzarella cheese undergoes substantial changes during short-term aging, there is a window of 4 to 20 d post-manufacture to produce high-quality shreds (Kindstedt, 1995).

The physical and chemical properties of cheese responsible for poor shredding are not fully understood. Intuitively, shredding involves the rheological and adhesive properties of the cheese. Factors that influence adhesion are cheese composition, rheological properties, and surface properties, including surface energy. Texture and surface properties can combine to cause adhesion because of pressure-sensitive adhesion. Pressure-sensitive adhesives are materials that adhere

when brought in contact with a surface under light pressure but that have sufficient cohesiveness to 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 (Heddeson et al., 1993). When the adherend surface energy is less than the surface energy of the adhesive (e.g., cheese), bond formation becomes a complicated function of surface energies and viscoelasticity of the adhesive (Saunders et al., 1992; Table 1). In the opposite case, when the surface energy of the adherend is much higher than that of the adhesive, the performance of the pressure-sensitive adhesive is independent of the surface energy of the adherend (Zosel, 1985).

In addition to the surface energies of the adherend and adhesive, Dahlquist (1989) 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. Foley and Chu (1986) found that the maximum tack values of pressure-sensitive adhesives were obtained at a storage modulus

Table 2. Proximate composition for all cheeses tested

Item	Moisture (%)	Fat (% on a wet basis)	Fat (% in DM)	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
Mozzarella cheeses				
Low-FDM ¹ cheese	46.7	15.8	29.6	31.6
Medium-FDM cheese	45.9	21.5	39.7	27.4
High-FDM cheese	46.9	26.1	49.2	22.9

¹FDM = fat in DM.

range of 5×10^4 to 1×10^5 Pa, with a glass transition temperature (T_g) of between -10 and 10°C .

Because shredding is one of the most popular size-reduction methods for cheese, it is important to understand how to obtain shreds without producing fines or adhesion to the blade. Little is understood about how rheological properties and adhesion combine to influence shred quality. The objective of this experiment was to measure shred quality and describe how it is influenced by the adhesion and rheological properties of the cheese.

MATERIALS AND METHODS

Cheeses

Commercial Cheeses. Three types of cheeses, Mozzarella, Monterey Jack, and process cheese, were purchased as approximately 2.3-kg blocks from the deli section of a local grocery store and are referred to here as commercial cheeses. Proximate composition was determined by vacuum oven moisture analysis, nuclear magnetic resonance fat analysis, and Kjeldahl nitrogen analysis (Table 2). The cheeses were shredded and tested at 4, 12, and 20°C . All tests were replicated over 3 different lots of cheese.

Experimental Mozzarella Cheeses. Three different Mozzarella cheeses with varying levels of fat and protein and with a constant moisture content were made at the University of Wisconsin Dairy Plant (Madison, WI; Table 2). The milk was standardized to fat levels of 1.35, 2.35, and 3.25% for cheeses with 30 (low), 40 (medium), and 50% (high) FDM, respectively. These formulations were used as an approximation for low-, medium-, and high-fat contents for low-moisture, part-skim Mozzarella cheese in the United States. Process conditions were similar to those used in standard low-moisture, part-skim Mozzarella manufacture. Bulk starter culture (1% wt/wt C257 bulk starter, Rhodia, Madison, WI) was added to the milk at 34.4°C . Double-strength coagulant (Chymax Extra, Chr. Hansen, Mil-

waukee, WI) was added when the pH of the milk reached 6.50. The gels for the low-, medium-, and high-FDM cheeses were cut with 0.64-, 0.95-, and 1.3-cm knives, respectively. The temperature of the vats was raised to 41.3°C for 30 min, and once that temperature was achieved, cooked at 41.3°C with stirring for 30 min. After cooking, the whey was drained at pH 5.96, and the curd was cut and turned at pH 5.67, 5.52, and 5.45 for the low-, medium-, and high-fat cheeses, respectively. The low-FDM cheese curd was not stacked, whereas the medium- and high-FDM cheese curds were stacked 2 and 3 high, respectively. All cheeses were milled and dry-salted (0.25% wt of salt/wt of milk) at pH 5.25 and stretched in a cooker (Supreme Stainless Steel Fabricating Inc., Columbus, WI) at a water temperature of 70°C . The low-, medium-, and high-FDM cheeses were brined in an 85% saturated salt solution (20.9% salt) at 5°C for 30, 90, and 130 min, respectively. The brine-salted cheeses were vacuum-packed and refrigerated at $\sim 10^\circ\text{C}$.

All tests were done at 7°C except the creep and recovery test, which was done at 25°C . The day the cheeses were manufactured was labeled as d 0. Analytical tests were done on d 2, 7, 14, 21, and 28 to observe the effects of aging. All tests were performed in triplicate on 3 different batches (replications) of cheese.

Shreddability

The shreddability of cheese was assessed by shredding in a food processor (Cuisinart, East Windsor, NJ) equipped with an 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. Because 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 to control the fiber orientation. The block of cheese was shred under a constant load of 4 kg. The shredded cheese was shaken by hand in both a horizontal and a vertical direction for 5 s through 2 sieves with openings of 12.7 mm^2 (0.5 in.²) and 6.35 mm^2 (0.25 in.²). The shreds not passing through the 12.7-mm^2 sieve were classified as long shreds, shreds not passing through the 6.35-mm^2 sieve were classified as short shreds, and shreds that passed through the 6.35-mm^2 sieve were classified as fines. The percentage of cheese that adhered to the blade, the percentage of cheese that adhered to the top of the food processor, long shreds, short shreds, and fines were calculated and used to evaluate shreddability.

Tack

Cheese adhesiveness 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 4-cm squares and sliced to a thickness of 6.35 cm with a modified wire cheese slicer. The cheese was placed on a platform below the probe arm, and the probe was brought to the surface of the cheese at a speed of 1 mm/s. Upon reaching the cheese surface, a force of 2.0 N was applied, held for 5 s, and removed at a speed of 0.1 mm/s. The tack force was determined as the maximum force recorded during separation. The tack energy was measured from the area under the force-distance curve.

Surface Energy

The surface energy measurements were made with a Ramé-Hart goniometer (model 100-00 115, Ramé-Hart Inc., Mountain Lakes, NJ) by determining the contact angle of 2 solvents with different polarities, formamide and dimethyl sulfoxide. A 12- μ L drop of solvent was suspended from the tip of a 16-gauge stainless-steel needle (Popper and Sons, Inc., New Hyde Park, NY), then lowered to the surface of the cheese. Once in contact with the surface, the drop detached from the needle and the measurement started within 1 s of the drop being placed on the surface. The contact angles of both sides of the drop were measured at 1-s intervals for 5 s. This process was repeated 10 times over a total of at least 3 slices of cheese. The Drop Image software package (Ramé-Hart) was used for all data calculations. Surface energy calculations were done through a series of equations starting with the Young equation:

$$\cos \theta \times \gamma_{lv} = \gamma_{sv} - \gamma_{sl} - \pi_e, \quad [1]$$

where θ is the contact angle of the liquid on the solid, γ_{lv} is the free energy of the liquid against the 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). The contact angle (θ) and the free energy of the liquid (γ_{lv}) could be measured directly.

Fowkes (1964) 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

$$\gamma_{lv} = \gamma_l^d + \gamma_l^h, \quad [2]$$

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

$$\gamma_{sl} = \gamma_{sv} + \gamma_{lv} - 2\sqrt{(\gamma_s^d \times \gamma_l^d)}. \quad [3]$$

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:

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

Because values of γ_{lv} can be measured directly and γ_l^d has been published for many liquids, γ_s^d (the component of surface energy attributable 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

$$\gamma_{sl} = \gamma_{sv} + \gamma_{lv} - 2\sqrt{(\gamma_s^d \times \gamma_l^d)} - 2\sqrt{(\gamma_s^h \times \gamma_l^h)} \quad [5]$$

creates an assumption in which 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:

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

In this equation, the variables that can be obtained or measured are θ , through 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 Wendt (1969) explained that by measuring θ of 2 different liquids against the same solid, simultaneous equations are obtained that 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 together the components that contribute to the solid surface energy:

$$\gamma_{sv} = \gamma_s^d + \gamma_s^h. \quad [7]$$

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 2 mm (on a deli slicer) and glued to the top and bottom plates with superglue (Loctite 401, Loctite Corp., Rock Hill, CT) to avoid slip while running the creep and recovery test. A variable gap analysis was performed, and the glue was found to have no effect on the cheese rheology. 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 constant stress of 100 Pa was applied to the cheese for 10 min, and the cheese was then allowed to recover for 20 min. Initial compliance (J_0) was the first compliance value after the initial application of constant stress in the creep portion of the creep and recovery test. Maximum compliance ($J_{\max}$) was the highest compliance value during the creep portion of the test. Data were fit to the viscoelastic Burgers model, and retardation time (λ_{ret}) was calculated as the time when the strain reached 63.2% ($1 - 1/e$) of its maximum. Commercial cheeses were tested at 4, 12, and 20°C. Experimental Mozzarella cheeses were tested at 25°C to allow for the greatest differentiation between samples.

Statistical Analysis

A randomized complete split-plot design was used for the commercial and experimental Mozzarella cheeses. For the commercial cheeses, the 2.3-kg samples of cheese were the whole-plot units and the 3 different cheeses were the whole-plot treatments. Each 2.3-kg sample of cheese was split into 3 subplot units. The subplot treatments applied were the 3 different temperatures of 4, 12, and 20°C. The 3 replications acted as blocks of the experiment. The same design was used for the experimental Mozzarella cheeses. The different formulations were the whole-plot treatments, and day of testing was the subplot treatment. The 3 replications acted as blocks of the experiment.

The mixed model (PROC MIXED) in the SAS statistical software package (Version 8, SAS Institute, Inc., Cary, NC) allowed statistically significant differences between whole-plot treatments and subplot treatments to be distinguished. A correlation analysis (PROC CORR) using the SAS statistical software package allowed for determination of relationships among cheese properties.

RESULTS AND DISCUSSION

Commercial Cheeses

The shred distribution graphs (Figure 1) show the differences produced during shredding for the Monterey Jack, Mozzarella, and process cheeses. Two different

Cheese type and temperature at shredding

Figure 1. Shred distribution for Monterey Jack (MJ), Mozzarella (Mozz), and process cheese at 4, 12, and 20°C.

defects were observed that diminished cheese shreddability: 1) the production of fines and 2) adhesion of the cheese to the blade. In this case, fines were considered any shred less than 6.35 mm (0.25 in.) long. Mozzarella produced the greatest amount of fines, with greater than 20% produced at all temperatures. The fines produced when shredding Mozzarella cheese were greater ($P < 0.05$) than those from Monterey Jack and process cheese at all 3 temperatures (Table 3). Monterey Jack and process cheeses adhered to the blade more during shredding. The increase in temperature caused an increase ($P < 0.05$) in adhesion of the cheese to the blade for both Monterey Jack and process cheeses (Table 4). For the cheeses tested, Mozzarella appeared to be more sensitive to producing fines and Monterey Jack and

Table 3. Percentage of fines produced during shredding

Cheese type	4°C (%)	12°C (%)	20°C
Monterey Jack	9.6 ^b	7.5 ^b	11.9 ^b
Mozzarella	27.4 ^a	26.3 ^a	45.0 ^a
Process	9.7 ^b	8.1 ^b	9.5 ^b

^{a,b}Means within columns with different superscripts differ ($P < 0.05$).

Table 4. Percentage of cheese adhering to the blade during shredding

Cheese type	4°C (%)	12°C (%)	20°C (%)
Monterey Jack	3.4 ^c	6.1 ^b	8.5 ^a
Mozzarella	0.8 ^a	0.8 ^a	1.2 ^a
Process	2.2 ^b	3.5 ^b	10.5 ^a

^{a-c}Means within rows with different superscripts differ ($P < 0.05$).

process cheese appeared to adhere more to the shredding blade.

With reference to Table 1, cheeses with high moisture and fat contents were predicted to have lower shreddability. Mozzarella, the higher moisture cheese, produced more fines during shredding, and Monterey Jack and process cheese, the higher fat cheeses, adhered to the blade more. Cheese composition is important when evaluating shreddability, but other factors must be taken into consideration when comparing shreddability, such as cheese processing methods and age (Table 1). These factors were not considered when evaluating commercial cheeses.

From a material science approach, the shreddability of cheese can be based on the rheological and adhesive properties of the finished material. This implies that factors associated with cheese making (composition, age) are reflected in the rheological and adhesive properties. Rheological properties contribute to 2 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. Values for initial compliance (J_0), maximum compliance ($J_{\max}$), and retardation time (λ_{ret}) over all 3 temperatures can be found in Table 5. Mozzarella was the most compliant of the 3 cheeses at 12 and 20°C. The softer texture may have caused the increase in fines produced during shredding. In addition to the soft texture, a possible cause for the production of fines is the fibrous nature of Mozzarella cheese. The

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

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

Figure 2. Tack energy for (●) Monterey Jack, (○) Mozzarella, and (▼) process cheeses at 4, 12, and 20°C. Error bars represent standard error of the mean.

other 2 cheeses did not have fibrous structures, and may explain why Mozzarella produced so many more fines during shredding. The maximum compliance increased as the temperature increased for all cheeses, causing an increase in the production of fines during shredding. Kindstedt (1995) commented that soft cheese can produce many fines during shredding.

In addition to rheological properties, the adhesion of cheese to the shredding equipment surfaces may influence shreddability. Adhesive properties of the cheeses were evaluated by measuring tack, that is, the energy required to separate 2 materials that are not bound permanently (Russell and Kim, 1999). The tack energy increased for all 3 cheeses as the temperature increased from 4 to 20°C (Figure 2). Dough tack shows a similar trend (Heddleson et al., 1993). 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 did the Mozzarella cheese. It is important to note that the removal of the probe resulted in adhesive failure (no cheese remaining on the probe) rather than cohesive failure (cheese remaining on the probe). Therefore, tack energy is not a direct measure of the amount of cheese remaining on the blade. When all cheeses were taken into account, a positive correlation (0.753, $P < 0.05$) was shown between the amount of cheese adhering to the blade and tack energy (Table 6). When the cheeses were compared, an increase in

Table 6. Correlation analysis between tack energy, fines, cheese adhering to the blade, surface energy, maximum compliance ($J_{\max}$), initial compliance (J_0), and retardation time (λ_{ret}) for commercial cheeses ($n = 9$)

Item	Fines	Adherence to the 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
Adherence to the 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

* $P \leq 0.05$.

tack energy was clearly associated with an increase in the amount of Monterey Jack or process cheese adhering to the blade, but not so for Mozzarella (Figure 3). This result suggests that tack energy is one of several factors associated with cheese adhesion to blades during shredding. The other property correlated with the amount of cheese adhering to blades was retardation time (-0.723 , $P < 0.05$; Table 6). A higher retardation time indicates that a material will take longer to reach maximum strain and is flowing more slowly (Steffe, 1996). The retardation times for Monterey Jack and process cheese were in the range of 108 to 90 s at 12 to 20°C, whereas in the same temperature range, the

retardation time for Mozzarella was 131 to 135 s (Table 5). The combination of high tack energy and low retardation time appeared to cause an increase in the amount of cheese adhering 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). Applying this model to cheese adhesion is complex. Because cheese is a viscoelastic material, the storage modulus will change with the time frame of testing, with higher storage moduli values associated with shorter time frames (Brown et al., 2003). If $1/J_{\max}$ is assumed to be a ballpark indicator of the storage modulus, then 2 cheeses, Mozzarella at 4°C and process at 4°C, did not fall within the Dahlquist criterion for tack (Table 5), although they did show tack (Figure 2). This result has been seen in other viscoelastic food materials. Heddleson and others (1993) reported that the tack energy of dough decreased dramatically but did not go to zero once the storage moduli 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 (Heddleson et al., 1993). Figure 4 shows a pictorial representation of how pressure-sensitive adhesion is affected through the relationship of the surface energy of the adhered and the adhesive. Michalski et al. (1999) tested emulsions of mayonnaise-like consistency against 5 solids of increasing surface energy. The greatest amount of adhesion occurred in zone 2, where the surface energy of the adherend was greater than the surface energy of the emulsions. They also showed that at a given solid surface energy above the surface energy of the emulsions, there was no relationship between the amount of emulsion that adhered and the surface energy of the emulsion.

Figure 3. Comparison of cheese adhered to the blade and tack energy for (■) Monterey Jack 4°C, (▲) Monterey Jack 12°C; (●) Monterey Jack 20°C, (□) Mozzarella 4°C, (△) Mozzarella 12°C, (○) Mozzarella 20°C, (▼) process cheese 4°C, (◆) process cheese 12°C, and (▽) process cheese 20°C. Arrows indicate a temperature increase.

Figure 4. Mechanisms of pressure-sensitive adhesion.

When the surface energy of the adherend is less than the surface energy of the adhesive, bond formation becomes a complicated function of surface energies and viscoelasticity of the adhesive (Saunders et al., 1992), as represented by zone 1 in Figure 4. When the surface energy of the adherend was less than the surface energy of a polymer adhesive, the adhesion decreased as the surface energy of the polymer decreased and approached the surface energy of the adherend (Zosel, 1985). The surface energy of the stainless steel was experimentally determined to be 35.6 mN/m. The surface energy for all 3 cheeses at all temperatures was higher than that of stainless steel, meaning that the system was described by zone 1 (Figure 4). Therefore, the adhesion of all cheeses at all temperatures was a function of surface energy and viscoelasticity. The surface energy for all 3 cheeses over all 3 temperatures did not show any definite trends or significant differences (Figure 5). There was no universal correlation between tack and the surface energy of the cheese (Table 6).

One reason for the poor overall correlation between tack and surface energy was the different temperature-related patterns observed for the different cheeses (Figure 6). Monterey Jack cheese behaved as predicted for pressure-sensitive adhesives. Increasing the surface energy corresponded to an increase in tack energy (Figure 6), and increasing the tack energy was associated with an increase in the amount of cheese adhering to the blade during shredding (Figures 1 and 2). For Mozzarella and process cheeses, the surface energy at 4°C was higher than that at 12°C, but at 20°C, the surface

Figure 5. Surface energy for (■) Monterey Jack; (△) Mozzarella, and (●) process cheese over 4, 12, and 20°C. Dotted line represents the surface energy of stainless steel (35.6 mN/m). Error bars represent standard error of the mean.

Figure 6. Comparison of tack energy and surface energy for (■) Monterey Jack 4°C, (▲) Monterey Jack 12°C, (●) Monterey Jack 20°C, (▼) Mozzarella 4°C, (◆) Mozzarella 12°C, (▽) Mozzarella 20°C, (□) process cheese 4°C, (△) process cheese 12°C, and (○) process cheese 20°C. Arrows indicate a temperature increase.

Figure 7. Shred distribution for low-fat in DM (FDM) cheese, medium-FDM cheese, and high-FDM cheese over 28 d of aging.

energy was higher than the surface energy at 4 and 12°C. Why these 2 patterns of changes in tack and surface energy were present was not clear. One assumption in simple pressure-sensitive adhesion models is that the temperature does not change the principal chemical nature of the adhesive or adherend. This may not be the case in cheese, where increasing the temperature can cause changes such as fat melting and altered hydrophobic interactions, which may alter the chemical properties of the surface. However, precise measurement of changes in the surface chemistry of cheese is required before meaningful conclusions can be drawn.

The experiment with commercial cheeses showed that measuring the rheological and adhesive properties provided some insight into what caused shredding defects. However, further experimentation was necessary to characterize shredding behavior in one cheese when

the composition and aging varied, 2 properties associated with changes in shredding quality (Table 1). The 3 Mozzarella cheeses used in the next experiment were formulated to have similar moisture contents and altered levels of fat and protein. Shredding behavior was measured over a 28-d aging period.

Experimental Mozzarella Cheeses

The proximate compositions of the 3 experimental cheeses are found in Table 2. Fat varied from 15.8 to 26.1%, protein varied from 22.9 to 31.6%, and the moisture content remained around 46.5% for all the cheeses.

The shred distribution for all 3 cheeses is found in Figure 7. The most prominent shredding defect observed was fines, as was the case with the commercial Mozzarella used in the previous study (Figure 1).

Table 7. Initial compliance (J_0), maximum compliance ($J_{\max}$), and retardation time (λ_{ret}) for cheeses 1, 2, and 3 over 28 d of aging

Item	J_0 (1/Pa)	$J_{\max}$ (1/Pa)	λ_{ret} (s)
Low-FDM cheese ¹			
Day 2	2.74E-05	9.26E-05	175
Day 7	2.34E-05	7.72E-05	185
Day 14	2.13E-05	6.65E-05	175
Day 21	2.18E-05	6.18E-05	155
Day 28	4.68E-05	1.16E-04	125
Medium-FDM cheese			
Day 2	2.4E-05	7.83E-05	185
Day 7	3.35E-05	1.00E-04	180
Day 14	4.68E-05	1.19E-04	140
Day 21	4.47E-05	1.27E-04	150
Day 28	3.89E-05	1.02E-04	135
High-FDM cheese			
Day 2	3.94E-05	1.31E-04	325
Day 7	7.03E-05	2.42E-04	190
Day 14	5.75E-05	2.01E-04	195
Day 21	7.4E-05	2.52E-04	195
Day 28	1.26E-04	3.68E-04	160

¹FDM = fat in DM.

Among the 3 cheeses, there was no difference ($P > 0.05$) in the amount of cheese that adhered to the blade. The low-FDM and medium-FDM cheeses had very similar shred distributions, with long shreds of approximately 75%. Fines for the low-FDM and medium-FDM cheeses were slightly under 20%. The shred distribution for the high-FDM cheese had long shreds of around 60%, and fines, at around 30%, were higher than for the low-FDM and medium-FDM cheeses ($P < 0.05$). The amount of fines produced from the medium-FDM cheese was higher ($P < 0.05$) than that of the low-FDM cheese. As the cheese aged over 28 d, there was very little variation in the shred distribution among each cheese. This result appears contrary to the report by Kindstedt (1995) that very young or newly manufactured Mozzarella cheese does not shred very well, mostly because of excessive free moisture at the surface and within the body of the cheese. Free moisture was observed in the newly manufactured cheeses in this investigation; however, Kindstedt (1995) noted the defect of matting of shreds, which was not directly measured in this investigation.

Cheese rheological properties are presented in Table 7. Creep and recovery was performed at 25°C rather than at room temperature because the previous experiments with the commercial cheeses showed more differentiation at a higher temperature. The initial (J_0) and maximum compliance ($J_{\max}$) of the high-FDM cheese was found to be higher ($P < 0.05$) than for the low- and medium-FDM cheeses, but there was no difference between the low- and medium-FDM cheeses. The low- and medium-FDM cheeses had a much lower compliance than did the high-FDM cheese, meaning that the high-FDM cheese was the softest of the 3 cheeses. The high-FDM cheese was softest because of its low protein

Figure 8. Tack energy for (●) low-fat in DM (FDM) cheese; (○) medium-FDM cheese; and (▼) high-FDM cheese over 21 d of aging. Error bars represent standard error of the mean.

and high fat content. Increases in the fat and moisture contents of Mozzarella cheese are accompanied by a decrease in the modulus of elasticity and result in softening of the cheese, which can cause difficulty in shredding (Masi and Addeo, 1986).

The tack energies for all 3 cheeses can be found in Figure 8. The low-FDM cheese had little to no tack at all. The high-FDM cheese had a higher ($P < 0.05$) tack energy than the low- and medium-FDM cheeses, and the low- and medium-FDM cheeses were not different ($P > 0.05$). In comparison with the commercial Mozzarella cheese tested, the tack values for the low- and medium-FDM cheeses were much lower. The tack values for the commercial Mozzarella were similar to the tack values for the high-FDM cheese.

Initial compliance, maximum compliance, and tack energy were correlated ($P < 0.05$) with fines produced during shredding (Table 8). An examination of each property is required for proper interpretation of the correlations. Tack energy of these cheeses is a function of rheological properties and surface energy (zone 1, Figure 4). Surface energy differed only on d 2 and then remained the same for all cheeses (Figure 9). Because the moisture content was very similar for all 3 cheeses, for these cheeses surface energy appeared to be a function of moisture content. On d 2, when surface energy was the highest, the cheese was still expelling water, making the cut surface used for experimentation moist. A wet surface would have a surface energy with a higher

Table 8. Correlation analysis between fines, cheese adhering to the blade, surface energy, tack energy, maximum compliance ($J_{\max}$), initial compliance (J_0), and retardation time (λ_{ret}) for experimental Mozzarella cheeses ($n = 15$)

Item	Fines	Adherence to the 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
Adherence to the 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

* $P \leq 0.05$.

polar component, causing an increase in the total surface energy. At d 7 and thereafter, the water was drawn back into the network and the cheese surfaces became dry. The dotted line on Figure 9 represents the surface energy of the stainless steel. From d 7 on, the 3 cheeses had surface energies close to the surface energy of stainless steel. As mentioned previously, when the surface energy of the adhesive is close to the surface energy of the adherend, minimal adhesion is associated with surface energy (Zosel, 1985). Therefore, rheological properties are the main factor determining adhesion. Differences in tack energy (Figure 8) are similar to changes in rheological properties (Table 7); therefore, $J_{\max}$ and J_0 appear to be the key factors determining

the amount of fines produced in Mozzarella cheeses with varying amounts of fat and protein. In addition, $J_{\max}$ and J_0 were the only properties that correlated with the tack energy of the commercial cheeses (Table 6) and with Mozzarella (Table 8).

CONCLUSIONS

For Mozzarella, Monterey Jack, and process cheese, 2 defects in shredding were observed: the production of fines and adhesion to the blade. Mozzarella produced the most fines during shredding, whereas Monterey Jack and process cheese had the greatest amounts of cheese adhering to the blade. The combination of higher fat and lower protein caused the cheeses to be more compliant and caused an increase in the production of fines during shredding. Rheological properties were the best indicators of shredding defects. Adherence to the blade was associated with a decrease in retardation time, indicating that a faster flow increased blade adhesion. The production of fines was associated with an increased initial and maximum compliance that represented a more deformable cheese. Tack energy was also shown to be positively correlated with adherence to the blade. Surface energy was not correlated with fines or adhesion to the blade. These results suggest that factors regulating the rheological and surface tack properties of cheese are important to its shredding quality.

ACKNOWLEDGMENTS

Paper No. FSR-06-21 of the Journal Series of the Department of Food Science, North Carolina State University, Raleigh, NC 27695-7624. Support from the North Carolina Agricultural Research Service, Dairy Management Inc., and The Southeast Dairy Foods Research Center are gratefully acknowledged. This investigation is part of a collaborative project with the University of Wisconsin-Madison. We would like to thank the Department of Food Science at the University of Wisconsin for manufacturing and distributing the

Figure 9. Surface energy of (●) low-fat in DM (FDM) cheese; (□) medium-FDM cheese; and (▲) high-FDM cheese over 28 d of aging. Dotted line represents the surface energy of stainless steel (35.6 mN/m). Error bars represent standard error of the mean.

cheeses. The use of trade names in this publication imply neither endorsement by the North Carolina Agricultural Research Service of the products named nor criticism of similar ones not mentioned.

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