Melt Analysis of Process Cheese Spread or Product Using a Rapid Visco Analyzer

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ABSTRACT

The objective of this study was to evaluate a rapid visco analyzer (RVA) method for measuring the melting characteristics of process cheese spread or product. The melt properties of 32 commercial process cheese spread and process cheese product samples from 4 manufacturers were analyzed with the RVA, tube melt test, texture profile analysis (TPA) hardness, and dynamic stress rheometry (DSR). For the RVA melt test, a 15-g disc of cheese was packed into the RVA canister and subjected to a heating, holding, and cooling profile during continuous mixing. During the test, the apparent viscosity was continuously measured and several data points (melt time, hot viscosity, time at 5000 cP during cooling, and solidification time) were collected from the viscosity vs. time curve. There was a high correlation ($R^2 = 0.91$) between the DSR melt temperature and the tube melt test. There was also a high correlation between the RVA melt time and the DSR melt temperature or the tube melt test ($R^2 = 0.84$ and 0.74 , respectively). The RVA hot viscosity had a low correlation ($R^2 < 0.44$) with the DSR melt temperature and the tube melt test but had a high correlation ($R^2 = 0.74$) with DSR G'' at 85°C . The results of this study indicate that RVA melt analysis of process cheese spread/product is correlated with the results from other melt tests and is capable of measuring the melt properties quantified by other methods. The RVA melt test may also provide additional information on the melt characteristics of process cheese spread/product not measured in other tests.

(Key words: process cheese, melt analysis, rapid visco analyzer)

Abbreviation key: DSR = dynamic stress rheometry, PCS = process cheese spread, PCP = process cheese product, RSD = relative standard deviation, RVA = rapid visco analyzer, TPA = texture profile analysis.

INTRODUCTION

Pasteurized process cheese spread (PCS) is a standardized category of process cheese that is defined by the Code of Federal Regulations (CFR, 2003). Process cheese spread is required to have at least 20% fat, must be between 44 and 60% moisture, and at least 51% of the PCS must be cheese ingredients. The ingredients that may be used in PCS include natural cheese, emulsifying salts, acid, salt, milk fat, color, spices or flavorings, milk, skim milk, buttermilk, whey (whey protein concentrate, whey protein isolate, liquid whey, etc.), sweetening agents (dextrose, corn syrup, etc.) as well as several food grade hydrocolloids (up to 0.8%). Pasteurized process cheese product (PCP) is a nonstandardized process cheese. It is nutritionally equivalent to PCS, but the ingredients that can be used are not defined, nor is it required to contain a minimum amount of these ingredients (Zehren and Nusbaum, 2000).

Process cheese spread and PCP are used in a variety of applications and may be sliced on crackers or other foods as well as used in dips, sauces, or spreads. In several of these applications, the melt and flow properties of the PCS or PCP are critical for consumer acceptance (Lefever et al., 2000). The melt properties of PCS or PCP are typically analyzed using empirical melt tests such as the tube melt test (Olson and Price, 1958; Wang et al., 1998). In the tube melt test, 20 g of process cheese spread is packed to a set height in a glass tube. The tube is then placed horizontally in a tube rack and inserted into a preheated forced draft oven. The meltability of the cheese is determined by measuring cheese flow after being heated under controlled conditions. The test is simple to perform and provides a measure of cheese meltability under specific conditions. Although it is simple to perform, this method suffers from high variability.

Rheological based analysis techniques such as dynamic stress rheometry (DSR) can be used to measure the viscoelastic properties of cheese. In this analysis, the elastic modulus (G'), viscous modulus (G''), and $\tan \delta$ ($G''/G' = 1$) are determined and used to quantify cheese melt and flow properties (Sutheerawattananonda and

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Bastian, 1998; Zhou and Mulvaney, 1998). Rheological methods are typically not used as quality control techniques because they require technical expertise, are difficult to interpret, and require expensive equipment.

Consequently, there is a need for methodology capable of quantifying the melt and flow properties of PCS and PCP that is also simple to perform. An additional instrument that may fit this need is called the rapid visco analyzer (**RVA**). The RVA is a computer-integrated instrument designed by Newport Scientific (Warriewood, Australia) that is capable of rapidly measuring the apparent viscosity of products over a range of temperatures and mixing conditions. The RVA has been primarily used to analyze the viscous properties of starch and other grain products. However, it has been adapted for use in dairy products including process cheese (Metzger et al., 2002; Kapoor et al., 2004). The RVA test conditions and data collection are controlled by a computer; consequently, minimal skill is required to operate the instrument. Additionally, cleaning and analysis time is minimized by the use of disposable canisters and paddles.

The objective of the current study was to determine if an RVA-based method could be used to measure the melt and flow properties of PCS and PCP. Additionally, the apparent viscosity data obtained with the RVA was compared with an empirical method as well as a rheological based method.

MATERIALS AND METHODS

Experimental Design and Compositional Analysis

Thirty-two commercial PCS and PCP samples from 4 manufacturers (9 PCP samples from manufacturer 1, 8 PCS samples from manufacturer 2, 5 PCS samples from manufacturer 3, and 10 PCS samples from manufacturer 4) were analyzed for composition and functionality. Moisture content of the samples was determined using the vacuum oven method developed by Bradley and Vanderwarn (2001). Fat content was determined using the Mojonnier fat extraction for percentage fat in cheese (Case et al., 1985). The pH was measured with a Corning pH/ion meter 450 (Corning Glass Works, Medfield, MA) and Sentron streamline intelliprobe (Sentron, Gig Harbor, WA). Protein content was determined using the Dumas method with a Leco TruSpec N analyzer (Leco, St. Joseph, MI; Wiles et al., 1998).

Functionality Analysis

RVA analysis. The RVA melt test was performed in triplicate on cheese disks (15 mm high, 34 mm in diameter, 15 g) cut from a cross-section of process cheese spread using a cork borer. All samples were

tempered at 4°C for at least 1 h before testing. The cheese disk was placed into the bottom of the canister, a paddle was inserted into the canister, and the canister was placed into the RVA for testing. Once placed into the RVA, the samples were analyzed using a 14-min test. During the test the temperature was raised from 25 to 90°C over 5 min, held for 3 min at 90°C, and then cooled from 90 to 25°C over 6 min. In the first 2 min of the test, the stirring speed was sequentially increased from 0 to 300 rpm and was then held at 300 rpm for the remainder of the test. The apparent viscosity of the cheese during the entire test was collected. The features of interest obtained from the apparent viscosity data are identified in Figure 1, including melt time, hot viscosity, time at 5000 cP during cooling, and solidification time. The data obtained during the first 2 min of the test when the stirring speed is being increased is meaningless and was ignored. However, once the maximum stirring speed of 300 rpm is reached, meaningful data was collected. During the temperature increase from 25 to 90°C the cheese melts, which results in a peak in the apparent viscosity profile referred to as the melt peak (point A in Figure 1). After the melt peak, the apparent viscosity decreases as the temperature of the melted cheese increases. During the holding period at the maximum temperature (at 5 to 8 min of the test) a minimum in the apparent viscosity curve is observed (point B in Figure 1). This point on the apparent viscosity curve is referred to as the hot viscosity. During the cooling phase of the test (from 8 to 14 min), the apparent viscosity of the cheese increases until the cheese begins to solidify. As the cheese solidifies, a peak in the apparent viscosity curve is observed (point D in Figure 1). Additionally the time required to reach an apparent viscosity of 5000 cP (point C in figure 1) during cooling was also recorded.

Tube melt test. Five replicates of the tube melt test were performed on each sample using the method developed by Olson and Price (1958). Twenty grams of PCS and PCP were weighed into 38 × 200-mm glass tubes and tamped to a set height in the bottom of the tube. The tubes were then sealed with a screw cap and tempered, cheese end down, at 4°C for at least 30 min. The screw caps were removed, the tubes were sealed with a one-hole rubber stopper, placed horizontally on a tube rack, and inserted into a preheated Lindberg/Blue (model OV-490A-2; Blue M, Blue Island, IL) forced draft oven at 110°C for 10 min. The tubes were removed from the oven, tilted to prevent further cheese flow, and allowed to cool for 30 min. The extent of cheese flow from the etched line was determined.

Dynamic rheological analysis. A dynamic stress rheometer (Rheometrics, Inc., Piscataway, NJ) was used to analyze process cheese meltability using 25-mm

Figure 1. Example of a typical rapid visco analyzer (RVA) graph showing apparent viscosity, stirring paddle (speed) rpm, and temperature. The points of interest include: melt time (A), hot viscosity (B), time at 5000 cP (C), and solidification time (D).

parallel plate geometry. Dynamic rheological analysis was performed using serrated plates as specified in the method developed by Sutheerawattananonda and Bastian (1998). Process cheese spread and PCP test samples were prepared by sectioning with a wire cutter to obtain uniform slices 3 mm thick. Then, a round disk, 25 mm in diameter, was cut from the cheese slice using a cork borer. All cheese disks were tempered to room temperature before testing, and silicone oil (Dow Corning Corporation, Midland, MI) was applied to the edges of each sample to prevent drying.

Before determining test conditions, a dynamic stress sweep was performed at 25°C to determine the linear viscoelastic range of the sample. The dynamic moduli were recorded as the stress increased from 0.4 to 6000 Pa at a frequency of 5 rad/s. The linear region where G' is constant as a function of the frequency was found from 0.388 to 0.776% strain. A dynamic frequency sweep was performed at 25°C to find the appropriate frequency range. For the frequency sweep, the maximum stress was set at 1000 Pa and the frequency was set at an initial frequency of 100 rad/s and a final frequency of 0.1 rad/s. Using a frequency of 5 rad/s produced a strain of 0.732%, which was within the linear viscoelastic range. The dynamic rheological properties of the cheese were then analyzed with a dynamic temperature ramp test. The ramp test was run from 25 to 85°C with a ramp rate of 10°C/min using a frequency

of 5 rad/s. The maximum stress was set at 150 Pa, with 0.4 to 0.8% strain using a stress adjustment of 30%. The temperature at which $\tan \delta = 1$ (G''/G') was used as the cheese melting point, and is referred to as the DSR melt temperature. In addition, $\tan \delta$ max was used to evaluate maximum flowability, and G'' at 85°C was used to evaluate the viscous properties at high temperature. Duplicate analysis was performed on each cheese sample.

Texture profile analysis hardness. Texture profile analysis (TPA) hardness was performed using the TA.XT2i Texture Analyzer (Texture Technologies Corp., Scarsdale, NY/Stable Microsystems, Godalming, United Kingdom) as described by Antoniou et al. (2000). Process cheese spread and PCP were cut into 20-mm³ cubes using a cheese slicer, wrapped in Reynolds food service film (Nogg Chemical and Paper, Omaha, NE) to prevent moisture loss, and tempered at 4°C for at least 1 h before testing. Five replicates of each sample were analyzed with a crosshead speed of 0.8 mm/s, and the peak force was recorded at 70% compression.

Statistical Analyses

A one-way ANOVA was performed with manufacturer as the factor for each functional and compositional test. Because the total number of process cheese samples analyzed from each manufacturer was not the

Table 1. Mean¹ (and relative standard deviation, RSD) composition of process cheese spread and process cheese product from 4 manufacturers.

Manufacturer	Protein, %		Moisture, %		Fat, %		pH	
	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD
1	16.69 ^b	2.94	46.00 ^c	1.43	21.69 ^b	1.86	5.84 ^b	0.50
2	17.61 ^a	1.52	47.15 ^b	1.51	22.68 ^a	3.26	5.81 ^b	2.03
3	16.52 ^b	2.30	47.00 ^b	1.32	22.57 ^a	3.96	5.65 ^c	0.69
4	15.73 ^c	1.96	49.02 ^a	2.11	21.29 ^b	2.83	5.96 ^a	1.60

^{a,b,c}Means within the same column not sharing common superscripts are significantly different ($P < 0.05$).

¹For manufacturers 1, 2, 3, and 4, $n = 9, 10, 8$, and 5, respectively.

same, Type III ANOVA was performed to obtain the mean squares and the P values for the functionality tests using Macanova (version 4.12, School of Statistics, University of Minnesota, St. Paul, MN). Paired comparison using Fisher's LSD was performed to compare the functional properties of process cheese samples obtained from each manufacturer, for each of the functional and compositional tests individually and thus rank the process cheese functional and compositional properties on the basis of the manufacturer as identified by the different tests.

Moreover, within each manufacturer, one-way ANOVA and paired comparisons using Fisher's LSD were also performed, with each process cheese sample as the factor for each functional test. This analysis allowed for a comparison of the sensitivity of the different techniques for differentiating the process cheese samples within each manufacturer. The comparisons were made at a 0.05 level of significance and the results were considered significant at $P < 0.05$. Relative standard deviation (**RSD**) of the composition and functionality values as well as correlation coefficients between the functional properties were determined using Excel (Microsoft Corp., Redmond, WA).

RESULTS AND DISCUSSION

Comparisons Between Manufacturers

Compositional analysis. The mean and RSD for the protein, moisture, fat, and pH of the process cheese from each manufacturer are shown in Table 1. Samples from manufacturer 1 had intermediate values for protein, fat, and pH but had significantly ($P < 0.05$) lower moisture content compared with those of other manufacturers. Samples from manufacturer 2 had intermediate values for moisture and pH but had significantly ($P < 0.05$) higher protein content compared with samples from other manufacturers. Samples from manufacturer 3 had intermediate values for protein and moisture but had significantly ($P < 0.05$) lower pH compared with those of the other manufacturers. Samples from

manufacturer 4 had significantly ($P < 0.05$) lower protein and higher moisture content compared with those from the other manufacturers.

Functionality testing. The mean and RSD for the hardness, DSR melt temperature, DSR G'' at 85°C, tube melt test, and RVA parameters of the process cheese from each manufacturer are shown in Table 2. In general, samples from manufacturers 1 and 3 had similar functional properties; no significant difference ($P > 0.05$) in DSR G'' at 85°C, tube melt test, RVA melt time, RVA time at 5000 cP, or RVA solidification time was observed between these manufacturers. However, there were significant ($P < 0.05$) differences in hardness, RVA hot viscosity, and DSR melt temperature between samples from these 2 manufacturers. Samples from manufacturer 2 had intermediate values for most functional properties including hardness, DSR melt temperature, tube melt test, and RVA melt time. However, samples from manufacturer 2 did have the lowest RVA time at 5000 cP and RVA solidification time. Samples from manufacturer 4 stood out from the other manufacturers and had significantly lower hardness, DSR melt temperature, DSR G'' at 85°C, RVA melt time, and significantly higher tube melt, RVA time at 5000 cP, and RVA solidification time compared with samples from the other manufacturers.

Relationship between composition and functionality. There appeared to be some relationship between composition and functionality. For example, samples from manufacturer 4 had the lowest hardness, DSR melt temperature, RVA melt time, and highest tube melt test, RVA time at 5000 cP, and RVA solidification time. This matches well with the compositional values, because we would expect a cheese with lower protein, higher moisture, and higher pH to be softer and more meltable. Samples from manufacturer 1 also had moderate functionality values, matching the overall composition. However, process cheese functionality is not solely controlled by cheese composition. For example, samples from manufacturer 3 had moderate compositional values, but was the least meltable, and had the highest DSR melt temperature, RVA melt time, and

Table 2. Mean¹ (and relative standard deviation, RSD) functionality of process cheese spread and process cheese product from 4 manufacturers using dynamic stress rheometry (DSR), tube melt test, and rapid visco analyzer (RVA).

Manufacturer	Hardness (N)		DSR melt temp ² (°C)		DSR G'' at 85° C (Pa)		Tube melt (mm)		RVA melt time (min)		RVA hot viscosity (cP)		RVA time at 5000 cP (min)		RVA solid ³ time (min)	
	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD
1	26.5 ^b	23.80	63.9 ^{bc}	5.46	48.59 ^a	39.18	30 ^c	50.75	3.51 ^a	6.42	1002 ^a	21.67	11.01 ^b	2.97	12.26 ^b	1.17
2	28.4 ^{ab}	14.66	62.1 ^c	6.29	49.49 ^a	29.34	39 ^b	30.44	3.31 ^b	4.44	1060 ^a	12.98	10.81 ^c	1.95	11.98 ^c	2.78
3	29.9 ^a	7.25	65.7 ^a	1.99	39.16 ^a	48.08	25 ^c	9.97	3.52 ^a	1.62	814 ^b	11.91	11.10 ^b	1.74	12.18 ^b	1.16
4	20.8 ^c	9.45	50.9 ^d	5.60	25.37 ^b	31.16	80 ^a	22.93	2.99 ^c	3.26	774 ^b	16.22	11.49 ^a	1.46	13.32 ^a	2.03

^{a,b,c}Means within the same column not sharing common superscripts are significantly different ($P < 0.05$).

¹For manufacturers 1, 2, 3, and 4, $n = 9, 10, 8$, and 5, respectively.

²Temp = Temperature.

³Solid = Solidification.

lowest tube melt values. Consequently, the relationship between composition and functionality is not straightforward and other factors will affect functionality (Rayan et al., 1980). Previous researchers have indicated that manufacturing conditions, type of emulsifying salt, cooking time and temperature, and ingredient changes influence process cheese functionality (Templeton and Sommer, 1932; Harvey et al., 1982; Shimp, 1985; Gupta and Reuter, 1992; Fox et al., 2000; Kuo et al., 2001).

In this study, all cheeses within each manufacturer were the same type of process cheese. The variability in composition and functionality within a manufacturer is represented by the relative standard deviation (RSD) shown in Tables 1 and 2. The RSD of all the composition parameters tested was less than 2.94 for all manufacturers. This indicates that all manufacturers had excellent control of cheese composition. However, the RSD for the functional parameters was much larger and varied substantially depending on the functionality test. These results indicate that controlling the functional properties of process cheese is difficult and that the

various functionality tests measure different cheese properties.

Functionality Comparisons Within Manufacturer

The functionality parameters of the individual process cheese samples from manufacturers 1, 2, 3, and 4 are shown in Tables 3, 4, 5, and 6, respectively. Significant ($P < 0.05$) differences between the individual samples from each manufacturer were observed for all the functionality parameters tested except for the tube melt test and the RVA melt time for manufacturer 3. The absence of significant differences for the RVA melt time and the tube melt test for manufacturer 3 may have been the result of the smaller number of samples that were analyzed from this manufacturer.

The tube melt test, DSR melt temperature, and RVA melt time are all measures of the initial melt characteristics of process cheese. A cheese that melts easily will have a low DSR melt temperature, a short RVA melt time, and a high tube melt test value, whereas a cheese that does not melt easily will have a high DSR melt

Table 3. Mean [$n = 5, 2, 5$, and 3, respectively for hardness, dynamic stress rheometry (DSR), tube melt, and rapid visco analyzer (RVA)] functionality and relative standard deviation (RSD) for process cheese product samples from manufacturer 1.

Sample	Hardness (N)		DSR melt temp ¹ (°C)		DSR G'' at 85° C (Pa)		Tube melt (mm)		RVA melt time (min)		RVA hot viscosity (cP)		RVA time at 5000 cP (min)		RVA solid ² time (min)	
	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD
1	24.1 ^c	3.94	63.9 ^{de}	0.58	51.85 ^b	14.05	26 ^{cd}	10.57	3.60 ^{abc}	8.06	1111 ^b	5.72	11.02 ^c	0.73	122.25 ^{bc}	0.33
2	35.3 ^a	6.94	67.0 ^b	0.51	52.26 ^b	1.12	17 ^d	26.14	3.75 ^a	4.00	1046 ^{bc}	4.43	10.82 ^d	0.74	12.07 ^c	0.58
3	36.6 ^a	5.12	64.7 ^{cd}	0.54	83.57 ^a	3.01	18 ^d	15.65	3.76 ^a	2.66	1420 ^a	2.46	10.42 ^e	0.38	12.13 ^{bc}	1.40
4	30.8 ^b	7.43	62.7 ^e	1.43	55.73 ^b	5.43	25 ^d	4.37	3.40 ^{cd}	3.82	1095 ^{bc}	2.05	10.71 ^d	0.28	12.20 ^{bc}	0.98
5	20.5 ^d	2.24	56.7 ^g	4.99	28.23 ^c	7.93	63 ^a	15.00	3.07 ^e	0.00	907 ^d	5.64	11.20 ^b	0.63	12.24 ^{bc}	1.72
6	24.1 ^c	2.82	68.4 ^a	0.15	50.55 ^b	3.39	19 ^d	16.96	3.62 ^{abc}	1.10	961 ^d	3.67	11.07 ^c	0.63	12.18 ^{bc}	0.33
7	26.0 ^c	9.86	65.8 ^{bc}	0.56	62.37 ^b	20.57	22 ^d	31.32	3.42 ^{bcd}	4.09	1044 ^c	1.30	11.02 ^c	0.36	12.27 ^b	0.57
8	21.1 ^d	9.56	65.1 ^{cd}	0.08	25.15 ^c	5.06	37 ^{bc}	41.09	3.65 ^{ab}	1.10	657 ^f	3.65	11.51 ^a	0.87	12.47 ^a	0.00
9	19.8 ^d	5.81	60.9 ^f	0.15	27.55 ^c	6.45	46 ^b	31.77	3.33 ^d	2.10	781 ^e	4.39	11.31 ^b	0.71	12.50 ^a	0.24

^{a,b,c,d,e,f,g}Means within the same column not sharing common superscripts are significantly different ($P < 0.05$).

¹Temp = Temperature.

²Solid = Solidification.

Table 4. Mean [$n = 5, 2, 5$, and 3 , respectively, for hardness, dynamic stress rheometry (DSR), tube melt, and rapid visco analyzer (RVA)] functionality and relative standard deviation (RSD) for process cheese spread samples from manufacturer 2.

Sample	Hardness (N)		DSR melt temp ¹ (°C)		DSR G'' at 85° C (Pa)		Tube melt (mm)		RVA melt time (min)		RVA hot viscosity (cP)		RVA time at 5000 cP (min)		RVA solid ² time (min)	
	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD
10	31.6 ^b	5.16	64.7 ^a	1.11	66.46 ^a	5.77	27 ^c	13.20	3.31 ^b	2.42	1286 ^a	3.46	10.49 ^e	0.76	11.67 ^d	0.00
11	24.7 ^{ef}	5.96	65.3 ^a	4.34	40.04 ^{bc}	14.33	36 ^{bc}	31.50	3.40 ^{ab}	3.53	932 ^d	1.83	10.95 ^b	0.37	12.11 ^b	0.25
12	29.6 ^{bc}	4.77	63.9 ^{ab}	1.08	49.17 ^{abc}	4.29	27 ^c	13.60	3.38 ^{ab}	2.37	1103 ^b	2.61	10.67 ^d	0.66	11.82 ^c	0.34
13	22.6 ^f	7.70	64.8 ^a	2.55	51.15 ^{ab}	16.23	40 ^b	23.87	3.33 ^b	4.20	1054 ^{bc}	4.76	10.82 ^c	0.92	11.64 ^d	0.69
14	35.9 ^a	6.35	57.2 ^c	2.29	53.99 ^{ab}	15.11	52 ^a	22.71	3.11 ^{cd}	5.47	950 ^d	1.64	10.93 ^{bc}	0.64	12.47 ^a	0.00
15	28.9 ^{bcd}	17.08	56.1 ^c	3.57	25.76 ^c	20.21	61 ^a	22.48	3.09 ^d	3.24	910 ^d	6.01	11.13 ^a	0.63	12.42 ^a	0.32
16	26.2 ^{de}	5.77	59.4 ^{bc}	3.80	39.51 ^{bc}	27.45	33 ^{bc}	24.82	3.29 ^{bc}	0.91	1022 ^c	5.45	10.91 ^{bc}	0.27	12.04 ^b	0.83
17	27.7 ^{cd}	3.65	65.5 ^a	6.75	69.81 ^a	35.84	37 ^{bc}	15.65	3.53 ^a	3.40	1225 ^a	3.32	10.60 ^{de}	0.66	11.69 ^d	1.20

a,b,c,d,e,f Means within the same column not sharing common superscripts are significantly different ($P < 0.05$).

¹Temp = Temperature.

²Solid = Solidification.

temperature, long RVA melt time, and a low tube melt test value. As expected, with most of the manufacturers, these 3 tests generally ranked the relative meltability of the individual samples from each manufacturer in a similar manner (Tables 3, 4, and 5). However, this was not the case for the RVA melt time for the samples from manufacturer 4 (Table 6). All of the samples from this manufacturer had a short melt time (<3.13 min), which indicates that all the samples melted easily during the initial temperature increase in the RVA test. These results indicate that the temperature ramp rate in the RVA may need to be adjusted for samples that melt easily to detect differences between samples.

The RVA hot viscosity, RVA time at 5000 cP, and G'' at 85°C are all measures of process cheese flow properties after the cheese has completely melted. A high RVA hot viscosity, RVA time at 5000 cP, or G'' at 85°C would be observed in a cheese that has minimal flow after melting, whereas a low RVA hot viscosity, RVA time at 5000 cP, or G'' at 85°C would be observed in a cheese that flows easily after melting. As expected, all 3 of these tests generally ranked the individual samples

from each manufacturer in a similar manner (Tables 3, 4, 5, and 6).

The RSD of the various functional tests varied substantially and was highest in the tube melt test. The variability in this functional test is well known and is the reason the test is typically replicated 5 times for each sample. Additionally, the G'' data for some of the samples (1 and 7 from manufacturer 1, numerous samples from manufacturer 2, and samples 30 and 31 from manufacturer 4) had a high RSD (>10). The high RSD in these samples was most likely due to differences in sample loading, which caused the G' and G'' curves to be shifted up or down due to differences in the excess edge material (Giles and Hooper, 1999). However, this shift in the G' and G'' curves has no effect on the $\tan \delta = 1$ data. Consequently, the RSD for the $\tan \delta = 1$ data was small (<5.0) for the majority of the samples. The RSD for the RVA parameters (melt time, hot viscosity, time at 5000 cP, and solidification time) was higher than the DSR melt temperature data and lower than the tube melt test. In the majority of the samples from all manufacturers, the RSD of all the RVA parameters

Table 5. Mean [$n = 5, 2, 5$, and 3 , respectively, for hardness, dynamic stress rheometry (DSR), tube melt, and rapid visco analyzer (RVA)] functionality and relative standard deviation (RSD) for process cheese spread samples from manufacturer 3.

Sample	Hardness (N)		DSR melt temp ¹ (°C)		DSR G'' at 85° C (Pa)		Tube melt (mm)		RVA melt time (min)		RVA hot viscosity (cP)		RVA time at 5000 cP (min)		RVA solid ² time (min)	
	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD
18	30.11 ^{ab}	7.31	67.80 ^a	0.65	26.66 ^c	6.71	22	15.00	3.56	4.21	698 ^c	4.68	11.29 ^a	0.27	12.16 ^{ab}	0.82
19	30.28 ^{ab}	9.94	64.48 ^c	0.34	35.60 ^b	1.86	28	26.06	3.42	4.09	746 ^{bc}	5.05	11.11 ^{ab}	0.72	12.38 ^a	0.32
20	32.39 ^a	9.32	65.15 ^{bc}	0.11	29.35 ^c	4.44	24	13.94	3.55	4.79	928 ^a	2.59	10.91 ^b	0.27	12.27 ^{ab}	0.57
21	30.43 ^{ab}	4.73	64.98 ^{bc}	0.18	72.32 ^a	3.59	26	26.20	3.51	2.85	894 ^a	7.88	10.89 ^b	0.92	12.07 ^b	0.58
22	26.41 ^b	7.04	66.03 ^b	1.47	31.86 ^{bc}	12.77	26	12.05	3.54	3.39	804 ^b	4.25	11.28 ^a	2.75	12.04 ^b	2.08

a,b,c Means within the same column not sharing common superscripts are significantly different ($P < 0.05$).

¹Temp = Temperature.

²Solid = Solidification.

Table 6. Mean [$n = 5, 2, 5$, and 3 , respectively, for hardness, dynamic stress rheometry (DSR), tube melt, and rapid visco analyzer (RVA)] functionality and relative standard deviation (RSD) for process cheese spread samples from manufacturer 4.

Sample	Hardness (N)		DSR melt temp ¹ (°C)		DSR G'' at 85° C (Pa)		Tube melt (mm)		RVA melt time (min)		RVA hot viscosity (cP)		RVA time at 5000 cP (min)		RVA solid ² time (min)	
	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD
23	21.4 ^{bc}	6.82	52.3 ^b	0.67	22.46 ^{cd}	8.17	76 ^{bc}	9.10	3.13 ^a	2.24	757 ^{cd}	3.30	11.55 ^{bc}	0.35	13.11 ^{def}	0.76
24	21.7 ^{bc}	3.60	55.7 ^a	0.90	35.82 ^b	1.81	54 ^d	16.22	3.02 ^{ab}	8.94	934 ^a	4.87	11.31 ^{de}	0.27	12.89 ^f	1.63
25	23.7 ^a	4.98	55.7 ^a	1.02	42.04 ^a	1.65	53 ^d	24.34	3.09 ^{ab}	4.53	942 ^a	6.90	11.31 ^{de}	0.88	13.00 ^{ef}	1.00
26	22.8 ^{ab}	11.49	51.3 ^{bc}	2.85	20.79 ^d	7.67	83 ^{bc}	19.93	3.04 ^{ab}	4.61	662 ^{ef}	7.98	11.56 ^{bc}	0.69	13.16 ^{cde}	0.76
27	18.5 ^{ef}	5.02	49.8 ^{cd}	1.53	21.85 ^{cd}	0.86	83 ^{bc}	4.66	2.98 ^{ab}	4.70	812 ^{bc}	2.50	11.49 ^c	0.26	13.42 ^{ab}	1.42
28	20.1 ^{cde}	3.49	49.0 ^{ef}	0.84	24.80 ^{cd}	9.14	80 ^{bc}	14.84	2.91 ^{ab}	1.03	834 ^{bc}	8.04	11.38 ^d	0.35	13.62 ^a	0.73
29	22.3 ^{ab}	5.84	49.7 ^{cd}	0.08	26.37 ^c	1.81	73 ^c	28.34	2.93 ^{ab}	2.39	881 ^{ab}	7.62	11.27 ^c	0.62	13.40 ^{abc}	1.34
30	17.5 ^f	5.37	48.9 ^{ef}	1.94	22.51 ^{cd}	16.31	89 ^{bc}	16.13	2.84 ^b	7.04	644 ^{ef}	6.10	11.71 ^a	0.26	13.62 ^a	1.03
31	19.4 ^{de}	7.02	48.8 ^{ef}	1.23	22.39 ^{cd}	18.68	91 ^b	12.68	2.89 ^{ab}	1.04	682 ^{de}	1.63	11.60 ^b	0.00	13.29 ^{bcd}	0.75
32	20.3 ^{cd}	4.34	47.7 ^f	2.62	14.65 ^e	7.51	116 ^a	8.21	3.09 ^{ab}	8.74	591 ^f	3.77	11.72 ^a	0.00	13.64 ^a	1.03

^{a,b,c,d,e,f}Means within the same column not sharing common superscripts are significantly different ($P < 0.05$).

¹Temp = Temperature.

²Solid = Solidification.

was less than 5.0. However, a few samples had an RSD for at least one of the RVA parameters that was between 5.0 and 10.0. Overall, the variability in the RVA test was moderate and substantially less than in the tube melt test.

Analysis of the Complete Data Set

Linear regression analysis was performed on the entire data set (all samples from all manufacturers) to determine if cheese composition was correlated with functionality. Furthermore, linear regression analysis was performed to determine if the results from dynamic rheological analysis, tube melt analysis, and RVA analysis were correlated. The correlation coefficients obtained are shown in Table 7.

Correlation between composition and functionality. There was a moderate correlation between cheese composition and the results of some of the functional tests performed in this study. The highest correlation ($R^2 = 0.74$) was between RVA time at 5000 cP and protein content. This parameter is a measure of how quickly the apparent viscosity of the melted cheese increases during cooling. Because protein plays a critical role in the formation of the structural network in process cheese (Green et al., 1981), it is not surprising that protein content was correlated with RVA time at 5000 cP. Protein content was also moderately correlated with RVA solidification time, RVA hot viscosity, and TPA hardness ($R^2 = 0.64, 0.53$, and 0.48 , respectively). Moisture content was moderately correlated with several functional tests including DSR melt temp, RVA solidification time, $\tan \delta$ max, tube melt, and RVA melt time ($R^2 = 0.59, 0.56, 0.50, 0.48$, and 0.47 , respectively). Previous research also observed a correlation between moisture and process cheese functional properties

(Templeton and Sommer, 1932), although Arnott et al. (1957) found no relation between the melting properties of process cheese and the amount of moisture or fat. Process cheese pH was moderately correlated with several functional tests including DSR melt temperature, RVA solidification time, and tube melt ($R^2 = 0.48, 0.44$, and 0.41 , respectively). Again, previous research has observed a relationship between process cheese functionality and pH (Templeton and Sommer, 1932). There was a low correlation ($R^2 < 0.37$) between fat content and all of the functional tests. This is not surprising because there was a minimal difference in fat content between the samples evaluated in this study.

Correlation between the functional tests. The highest correlation ($R^2 = 0.91$) found in this study was between the DSR melt temperature and the tube melt test. A plot of this data is shown in Figure 2. Using DSR to measure the transition temperature where $\tan \delta$ (G''/G') = 1 is a convenient measure of the melting point of cheese, because this temperature is where a material changes from primarily elastic to primarily viscous (Zhou and Mulvaney, 1998). This transition temperature has been used by other researchers to quantify the melt characteristic of process cheese (Sutheerawattananonda and Bastian, 1998). The tube melt test is a measure of the extent of initial cheese flow during melting. As shown in Figure 2, samples that had a high DSR melt temperature had a low tube melt value, whereas samples with a low DSR melt temperature had a high tube melt value.

However, Mounsey and O'Riordan (1999) used an alternative method to correlate DSR data to the tube melt test of imitation process cheese. In their evaluation, a local $\tan \delta$ maximum was highly correlated ($R^2 = 0.96$) to the tube melt test. Use of a local $\tan \delta$ maximum will give the point at which the cheese has the greatest

Table 7. Correlation coefficients between all samples from all manufacturers for compositional and functional testing of 32 process cheese spread and process cheese product samples from 4 manufacturers.

	Protein, %	Moisture, %	Fat, %	DSR melt (°C)	G'' at 85°C (Pa)	Tan δ max (°C)	Tube melt (mm)	TPA hardness (N)	RVA hot viscosity (cP)	RVA melt time (min)	RVA solid ¹ time (min)	RVA time at 500cP (min)
pH	0.13	0.22	0.15	0.48	0.07	0.24	0.41	0.12	0.03	0.32	0.44	0.14
Protein, %		0.24	0.20	0.41	0.45	0.26	0.44	0.48	0.53	0.27	0.64	0.74
Moisture, %			0.08	0.59	0.26	0.50	0.48	0.18	0.18	0.47	0.56	0.29
Fat, %				0.24	0.06	0.27	0.22	0.11	0.05	0.07	0.37	0.16
DSR melt (°C)					0.40	0.59	0.91	0.39	0.26	0.84	0.81	0.48
G'' at 85°C (Pa)						0.12	0.47	0.43	0.74	0.34	0.47	0.75
Tan δ max (°C)							0.47	0.30	0.06	0.51	0.49	0.23
Tube melt (mm)								0.49	0.37	0.74	0.75	0.58
Texture profile analysis hardness (N)									0.34	0.39	0.41	0.59
RVA hot viscosity (cP)										0.21	0.43	0.84
RVA melt time (min)											0.57	0.36
RVA solid time (min)												0.68

¹Solid = Solidification. **Figure 2.** Linear correlation between dynamic stress rheometry (DSR) melt temperature and tube melt distance (flow), showing samples from manufacturer 1 (□), manufacturer 2 (○), manufacturer 3 (●), and manufacturer 4 (■).

viscous character, which should be its softest and most flowable point. In addition, a local $\tan \delta$ maximum has been observed at the mobilization of the protein phase (Olson et al., 1996; Mounsey and O'Riordan, 1999). However, in our study this parameter had an R^2 value of 0.46 when compared with the tube melt test. The large difference in the correlation of these tests between our study and the study conducted by Mounsey and O'Riordan (1999) is most likely due to differences in the samples analyzed and the tube melt testing conditions. In the Mounsey and O'Riordan (1999) study, the imitation process cheese contained starch. The addition of starch resulted in a reduction in meltability. Consequently, the conditions used by the researcher for the tube melt test were modified and the test was performed at 180°C for 15 min.

There was a high correlation ($R^2 = 0.84$) between DSR melt temperature and RVA melt time. A plot of this data is shown in Figure 3. The RVA melt time is a measure of the time required for the cheese to completely melt as it is heated from 25 to 90°C. Consequently, cheese that melts quickly has a shorter melt time, whereas cheese that melts slowly has a longer melt time. As expected, samples that had a low DSR melt temperature had a low RVA melt time, and samples with a high DSR melt temperature had a high RVA melt time.

A plot of the correlation between RVA melt time and the tube melt test is shown in Figure 4. The correlation between RVA melt time and tube melt test was lower ($R^2 = 0.74$) compared with the correlation between the RVA melt time and the DSR melt temperature ($R^2 = 0.84$) or between the DSR melt temperature and the tube melt test ($R^2 = 0.91$). This difference was largely a result of the samples from manufacturer 4 (filled squares in Figure 4), which had a small range in RVA

Figure 3. Linear correlation between dynamic stress rheometry (DSR) melt temperature and rapid visco analyzer (RVA) melt time, showing samples from manufacturer 1 (□), manufacturer 2 (○), manufacturer 3 (●), and manufacturer 4 (■).

melt time but had a large range in tube melt values. Again, these results indicate that the temperature ramp used in the RVA may need to be adjusted for samples that melt easily to detect difference between the samples that correlate with results from the tube melt test.

In addition to the correlation between RVA melt time and the tube melt test, a similar correlation ($R^2 = 0.75$) was found between the RVA solidification time and the tube melt test. A plot of this data is shown in Figure 5. The RVA melt time is a measure of how quickly the cheese melts during heating with continuous mixing in the RVA, whereas the RVA solidification time is a measure of how quickly the melted cheese solidifies during cooling with continuous mixing in the RVA. It is not surprising that both of these RVA parameters were correlated with the tube melt test because they

Figure 4. Linear correlation between rapid visco analyzer (RVA) melt time and tube melt distance (flow), showing samples from manufacturer 1 (□), manufacturer 2 (○), manufacturer 3 (●), and manufacturer 4 (■).

Figure 5. Linear correlation between rapid visco analyzer (RVA) solidification time and tube melt distance (flow), showing samples from manufacturer 1 (□), manufacturer 2 (○), manufacturer 3 (●), and manufacturer 4 (■).

are both measures of the transformation of cheese from a primarily viscous material to a primarily elastic material (or vice versa) with a change in temperature. However, the RVA solidification time measures this transition after the sample has been completely melted and held at 90°C for several minutes with continuous mixing. Any changes in the cheese properties because of mixing the melted cheese at 90°C would result in a difference between the RVA melt time and the RVA solidification time. These 2 RVA parameters were moderately correlated ($R^2 = 0.57$), which indicates that continuous mixing of the melted cheese at 90°C has an effect on its melt and flow properties. In addition, the small difference between samples for the RVA melt time for manufacturers 3 and 4 may have contributed to a lower correlation. Other researchers have determined that applying mixing to melted pasteurized process cheese at high temperatures during manufacture results in a decrease in meltability (Glenn et al., 2003). This reduction in meltability is thought to be a result of increased fat-protein interactions. Additionally, in process cheese spread or product, the food grade hydrocolloids used as an ingredient are known to be influenced by mixing and heat and could contribute to the differences between RVA melt time and RVA solidification time.

The RVA hot viscosity and time at 5000 cP were both correlated ($R^2 = 0.74$ and 0.75 respectively) with DSR G'' at 85°C. A plot of RVA hot viscosity and DSR G'' at 85°C is shown in Figure 6. All of these parameters are a measure of cheese flow properties after melting, and good mutual correlation was expected. None of these 3 parameters were highly correlated with DSR melt temperature or the tube melt test, which indicates that they provide additional information on process cheese functional properties that are not measured with the

Figure 6. Linear correlation between the viscous modulus (G'') at 85°C and rapid visco analyzer (RVA) hot viscosity, showing samples from manufacturer 1 ($\square$), manufacturer 2 ($\circ$), manufacturer 3 ($\bullet$), and manufacturer 4 ($\blacksquare$).

tube melt test or DSR melt temperature. However, the DSR G'' at 85°C data had a high RSD compared with the RVA hot viscosity and time at 5000 cP data. As mentioned previously, this variability is thought to be the result of edge effects, which result in shifts of the G' and G'' curves obtained during DSR analysis (Giles and Hooper, 1999).

The TPA hardness was not highly correlated with any of the other functional tests performed in this study. Texture profile analysis hardness is a measure of unmelted cheese firmness, and these results indicate that unmelted cheese texture is not related to process cheese melt properties. In a previous study by Harvey et al. (1982), a number of textural properties including hardness were analyzed. The only textural property with good correlation to melt was cohesiveness, which had a positive correlation with melt.

Comparison of the Melt Tests

The RVA melt test has an advantage over DSR in that minimal expertise is required to perform the RVA melt test. The RVA methodology uses disposable canisters and paddles, which eliminates cleaning and minimizes analysis time. However, unlike DSR, the RVA does not provide fundamental rheological information and simply measures the apparent viscosity of cheese at various temperatures. Compared with the tube melt test, the RVA is a more precise test and provides additional information about cheese flow properties after complete melting, which are not quantified in the tube melt test. However, the tube melt test requires a minimal amount of low-cost equipment, whereas both the RVA and DSR tests require the purchase of relatively expensive equipment. No information is available regarding how each of these melt tests relates to actual home or food service performance of PCS or PCP. How-

ever, because in the RVA melt test the cheese is exposed to a range of temperatures during continuous mixing, the data obtained may provide information on PCS or PCP performance in applications where the cheese is melted, stirred, and held at a high temperature (e.g., when used as a sauce for nachos).

CONCLUSIONS

An RVA-based method for measuring PCS and PCP melt properties was evaluated. In this test, the apparent viscosity of the cheese is measured as it is heated from 25 to 90°C over 5 min, held for 3 min, and cooled from 90 to 25°C over 6 min. Select parameters (melt time, hot viscosity, time at 5000 cP, and solidification time) obtained from the apparent viscosity curve were correlated with other established melt tests (DSR and tube melt test). Consequently, the RVA melt test provides useful information on the melt characteristics of PCS or PCP.

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