Mechanical Starch Damage Effects on Wheat Flour Tortilla Texture

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ABSTRACT

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To investigate the effects of mechanically damaged starch and flour particle size on the texture of fresh and stored flour tortillas, two commercial hard red winter wheat flour samples were reground four times using decreasing roll gaps. Tortillas were made with a modified hot-press procedure. Texture characteristics were measured after tortillas were stored 2 hr (fresh tortilla), 2 days, and 4 days. Damaged starch and particle size significantly affected ($P < 0.05$) flour water absorption, dough extensibility and resistance, and dough viscosity. As damaged starch increased and particle size decreased, the flour tortillas became less stretchable, the maximum force of Kramer shear decreased, and firmness and rollability increased. The effects of damaged starch and particle size on stretchability and Kramer shear were greater in fresh tortillas than in stored tortillas and became smaller as the storage time increased. However, the effects of damaged starch and particle size on rollability and firmness were smaller in fresh tortillas than in stored tortillas but became greater as the storage time increased.

Starch damage in flour results in aqueous extractability and rapid susceptibility to enzymatic digestion. Compared with undamaged starch, damaged starch increases water absorption (Evers and Stevens 1985). Undamaged starch absorbs only 30% water at 30°C, but damaged starch absorbs its own weight of water at 30°C (Farrand 1972). Intact granules have strong interchain bonds in the crystalline zone so as not to allow permeation by water, and water enters only in the amorphous zone. Upon disruption of the crystalline regions, water gains access to the whole granule (Multon et al 1980). In breadmaking, starch damage is considered one of the important factors affecting texture. Too much starch damage causes slacking dough because swollen, damaged granules release water when they are attacked by amylase and give the loaf a sticky crumb texture. However, too little starch damage gives bread low volume and heavy texture (Evers and Stevens 1985). Starch damage also has been studied in flat bread and noodle products (Oh et al 1985; Qarooni et al 1988).

Particle size is a very important concept in flour milling because it indicates the degree of fines and total surface area exposed (Kurimoto and Shelton 1988). Particle size correlates negatively with the falling number because water may penetrate into the core of the flour particle faster and will result in a more uniform and tougher gel and retard the falling of the plunger compared with flour with coarse particle sizes (Kurimoto and Shelton 1988).

Effects of flour particle size have been studied in breads, cakes, noodles, and tortillas. Gracza and Norris (1961) fractionated hard winter flour into different particle sizes by air classification. They selected two fractions (8.1 and 17.4 μm) from a single parent flour, which had equal protein contents and different particle sizes, and then used them to conduct flour and baking tests. Farinographic results showed that the flour with an average particle size of 8.1 μm had greater water absorption than the flour with an average particle size of 17.4 μm. The extensigraph showed that the flour with 8.1-μm particle size had less extensibility and more resistance than the flour with 17.4-μm particle size. The bread made from coarser flour had larger loaf volumes and higher bread score values. Shellenberger et al (1950) fractionated flour from soft red winter wheat (SRWW) into three particle size groups (<37, 37–53, and >53 μm) and found that the smallest particle size group (<30 μm) had the lowest ash and protein contents, and the intermediate particle size group (37–53 μm) had the highest. The viscosity of the cake flour increased greatly as the particle size increased. Baking tests showed that flour with small particle size produced the best cake. Oh et al (1985) reported that decreasing particle size improved the strength of uncooked noodles but did not affect noodle color or the firmness of cooked noodles.

Wang and Flores (2000) separated flours from hard red winter wheat (HRWW), hard white winter wheat (HWWW), and SRWW into <38, 38–53, 53–75, and >75 μm on the Alpine air jet sieve. They found that the protein content of medium particle size flour was higher than that of the finest and coarsest particle flours for HRWW and HWWW flours, whereas protein content increased with the increase in particle size for SRWW flour. The tortillas made from >53 μm fractions of HRWW and HWWW flour showed more stretchability. The tortillas made from <53 μm fractions of SRWW flour had more stretchability than the tortillas made from >53 μm fractions.

Research on wheat flour tortillas is necessary because of the fast growth in the tortilla industry. The tortilla market size exceeded $2 billion for 1994 (McDonough et al 1996). Tortilla sales in the U.S. were $300 million for the 1980s; however, it is estimated that the tortilla market will pass $4 billion by year 2000 (Dally and Navarro 1999). Information is needed to better understand the effects of wheat flour particle size and starch damage and of storage time on tortilla texture. Wang and Flores (2000) studied the effect of particle size on tortilla texture. Flour fractions (<38 38–53, 53–75, and >75 μm) were obtained by separating the HRWW, HWWW, and SRWW straight-grade flours on sieves with openings of 38, 53, and 75 μm on the Alpine air jet sieve, and those flour fractions had different protein contents. The objective of this study was to investigate the effects of wheat flour particle size, mechanical starch damage, and storage at room temperature on tortilla texture.

MATERIALS AND METHODS

Flour Samples

Two commercial HRWW flours that were enriched and malted with protein contents of 10.5 and 10.9% (flour 1 and flour 2, respectively) were reground four times using roller mills with decreasing roll gaps (Mao 2000).

Flour and Dough Tests

Starch damage in the flour was determined according to Approved Method 76-30A (AACC 2000) using a Chopin SD4 (Chopin Instruments, France) and a regression equation for the roll-milled samples (Rogers et al 1994). The geometric mean diameter (Dgw) of the flours was determined using Approved Method 50-11 with the Lecotrac particle size analyser (model LTS-150 Leco Corp., St. Joseph, MI). Farinograph tests were conducted according to Approved Method 54-21 using a farinograph (Brabender Instruments, South Hackensack, NJ) at 750 Brabender units (BU).

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Tortilla Making

The formula for flour tortillas was based on Wang and Flores (1999) with modification. Wheat flour tortillas were prepared from the essential ingredients of flour (100%), salt (1.5%), and baking powder (1.5%), which consisted of corn starch, bicarbonate of soda, sodium aluminum sulfate, acid phosphate of calcium, and shortening (12%). The water absorption of tortillas was based on farinograph absorption at 680 BU, which was 2.5% higher than 750 BU (Qarooni et al 1992).

A modified hot-press tortilla-making procedure described by Wang and Flores (1999) was followed. Dry ingredients and shortening were mixed at a slow speed (110 rpm) with a paddle (flat beater) in a mixer (KitchenAid K45SS. St. Joseph, MI) for 4 min. Distilled water (25 ± 2°C) was added and mixed at slow speed for 1 min for hydration of flour particles and then mixed at medium speed (176 rpm) for dough development. Mix time was based on dough development time in the farinograph. Dough was allowed to rest for 5 min in a hermetically sealed plastic food container (Rubbermaid), divided into 45-g pieces, and rounded by hand. The dough pieces were proofed for 30 min at room temperature (25 ± 2°C). The proofed dough pieces were placed between two Teflon sheets (Dawn Food Products Service) and flattened using a hot press (Doughpro, Dual/Heat, Propress Corporation, Paramont, CA) for 15 sec. The top and bottom plates of the hot press were set at 71°C. The surface temperature of the top was 75 ± 2°C and that of the bottom was 69 ± 2°C. The gap between the hot plates was set at thin, between 1.5 and 2.0 mm. The pressed doughs were baked on a griddle (Speedster, Walter & Carrel Mfg. Co., Denver, CO) set at a surface temperature of 232 ± 5°C for a total of 30 sec for each side. One side of the raw tortilla was baked for 10 sec with Teflon sheets on top to avoid shrinkage. This side was baked for another 10 sec without Teflon sheets on the top. The tortilla was turned over and baked for another 30 sec and then turned over again and baked for 10 sec. The baked tortillas were cooled for 4 min at room temperature (25 ± 2°C). Three tortillas were placed into polyethylene bags (8 H10 in Minigrip, ITW Co. Seguin, TX) for textural evaluation.

Storage Study

The textural shelf stability of the tortillas was determined by the textural change when the tortillas were stored in polyethylene bags for 2 hr (fresh), 2 days, and 4 days at room temperature (25 ± 2°C). The texture of the tortillas made from the flour with different pass times and with different storage times were analyzed using a texture analyzer.

Tortilla Physical Characteristics

The moisture content of the baked tortilla was determined using the two-stage Approved Method 44-15A (AACC 2000). The diameter

TABLE I
Properties of Tortilla Flour and Dough for Flour 1 and Flour 2 and the Combined Physical Properties of Tortillas Made from the Two Flours[a]

Properties	Original	First Pass	Second Pass	Third Pass	Fourth Pass
Flour and dough					
Starch damaged (%)					
Flour 1	13.09d	14.43c	15.40b	16.00ab	16.57a
Flour 2	10.79d	11.38c	12.12b	12.41ab	13.06a
Particle size, Dgw (μm)[b]					
Flour 1	63.9a	45.1b	41.6c	36.2d	34.2e
Flour 2	71.2a	51.2b	44.7c	40.9d	37.7e
Water absorption (14% mb)[c]					
Flour 1	51.6d	52.5c	54.5b	55.5a	55.6a
Flour 2	50.5d	50.7d	51.2c	51.4b	51.8a
Tortilla physical properties[d]					
Moisture (%, wb)	28.67c	29.15bc	29.84b	29.93b	31.01a
Whiteness (*L* value)	82.13a	82.03a	81.23b	81.45ab	81.08b
Diameter (mm)	16.68a	16.70a	16.62a	16.67a	16.69a
Weight (g)	38.27a	38.41a	38.41a	38.35a	38.39a
Thickness (mm)	1.49a	1.49a	1.47a	1.44a	1.45a
Toast spots (%)[e]	6.40a	5.56a	5.16a	5.99a	7.23a

[a] Means of two replicates. Values followed by the same letter in the same row are not significantly different ($P < 0.05$).

[b] Geometric diameters were based on particle size analysis.

[c] Water absorption was based on farinograph measurement at 750 BU.

[d] Data from tortillas from two commercial flours, $n = 6$.

[e] Percentage of tortilla area counted by a burned spot.

TABLE II
Effect of Starch Damage and Flour Particle Size on Textural Properties of Fresh Flour Tortillas[a]

Measurement	Original	First Pass	Second Pass	Third Pass	Fourth Pass
Stretchability					
Maximum force (N)	10.61a	10.25a	9.30b	9.18b	8.46c
Rupture distance (mm)	20.59a	20.68a	19.88ab	20.40ab	19.70b
Absorbed energy (Nmm)	98.67a	94.97a	84.56b	86.53b	78.19c
Elasticity modulus	0.707a	0.689a	0.639b	0.607bc	0.577c
Kramer shear					
Maximum force (N)	96.66a	89.46b	82.03c	79.15c	77.48c
Absorbed energy (Nmm)	323.13a	219.81ab	275.60bc	236.98c	279.89b
Elasticity modulus	21.72a	20.02a	17.79b	17.46b	17.77b
Rollability					
Maximum force (N)	0.199a	0.192ab	0.181ab	0.172bc	0.156c
Absorbed energy (Nmm)	6.01a	6.16a	5.90ab	4.56bc	4.02c
Firmness					
Maximum force (N)	58.57c	61.53b	61.82b	63.79a	64.41a
Absorbed energy (Nmm)	12.75b	13.37ab	13.32ab	13.70a	14.15a
Elasticity modulus	169.59a	169.81a	172.20a	173.87a	175.98a

[a] Data from tortillas from two commercial flours, $n = 6$. Values followed by the same letter in the same row are not significantly different ($P < 0.05$).

of the baked tortillas was the average of two perpendicular lines on each of three baked tortillas, and the weight was the average of three baked tortillas. The whiteness of the tortilla was determined as the *L* value using a chromameter (CR-300, Minolta Corp., Ramsey, NJ) with standard calibration plate CR-A44. The tortilla was put on white paper during measurement and three measurements for each tortilla were averaged.

Stretchability Measurements

This test was conducted using the TA-XT2 texture analyzer with a TA-108 tortilla film fixture and a 0.75 in. round-end probe technique calibrated to a distance of 60 mm from the analyzer arm to the platform. A tortilla was fixed onto the fixture and positioned with the double-baked tortilla side down. The probe traveled at 6.0 mm/sec until the tortilla surface was detected at 0.2 of maximum force (N). The probe then traveled at 2.0 mm/sec for up to 30 mm, a distance chosen to stretch all of the tortilla or until it ruptured thoroughly. The probe was withdrawn at 10.0 mm/sec. The measurements were taken of the force-deformation curve. Variables recorded were N; distance (mm) that compressed the tortilla until rupture; area or work (Nmm) under the curve; and slope or elastic (Young's) modulus (N/mm), which was the ratio of force to distance on the force-distance curve.

Kramer Shear Cell Measurements

The test was conducted using the TA-XT2 texture analyzer with a TA-91 Kramer shear cell with five blades attached. The blades were calibrated to a distance of 95 mm from the analyzer arm to the platform. A tortilla sample was cut (6 × 7.9 mm) and placed over the bottom of the sample cell. The force-deformation curve was recorded. Variables measured were N; area or work (Nmm) under the curve; and slope, which was the ratio of the force to distance on the straight line of force-distance curve.

Firmness Measurements

The test was conducted using a TA-XT2 texture analyzer with a 0.75 in. round-end probe calibrated to a distance of 10 mm from the analyzer arm to the platform. A tortilla was placed onto the flat plaform with the double-baked side down. The measurements were taken of the force-deformation curve. Variables recorded were N required to compress the tortilla until 30% strain; the distance; the area or work (Nmm) under the curve; and the slope (N/mm), which was the ratio of force to distance on the straight line of the force-distance curve. The distance (30% strain) was used for the determination of tortilla thickness.

Rollability Measurement

The rollability of flour tortillas was determined using the TA-XT2 texture analyzer with a rollability fixture (dowel 1.9 cm in diameter) set on the base platform. The probe was calibrated to a distance of 160 mm from the crossarm to the platform. The tortilla edge was gripped fully by a metal rod and the double-baked side was face down. The force and the work (Nmm) required to roll a tortilla on the dowel were recorded. The maximum force that occurs during the first turn can be related to the ease of rolling the tortilla (Suhendro et al 1998).

Tortilla Image Analysis

The SPX Speck Expert analyzer (Maztech Micro Vision Ltd.), originally developed for speck counting in semolina, was used to analyze the baked tortilla image to determine the toast spot area. The SPX Speck Expert uses digital image analysis to count black and brown specks by assigning them a gray level value within the range of 0 (black) to 255 (white) (Kim and Flores 1999).

The SPX Speck Expert analyzer is driven by Maztech's Scan ProXpert software which acquires, analyzes, and enumerates specks by gray level and particle size. Globe level 120 and particle size 1,000–9,000 µm were set. If the speck size was >9,000 µm, then it would be counted as an oversized speck, which was shown in yellow overlays. Custom sample holders (4 × 4 in.) were designed for semolina. The holder portion of the SPX analyzer was removed to easily extend the sample size. A tortilla was put directly on the glass of the scanner base. The glass was covered with food wrap film (distributed by Aldi, Inc., Batavia, IL) to keep the glass clean. The range of interest was adjusted to 8 in. for width and height with an offset of 0.02 in. and resolution of 450 dpi. The SPX analyzer was ready to count the toast spots of tortilla after the data file was named and associated with a specific setting file. Results were imported into a spreadsheet as a formatted text file.

TABLE III
Correlation Coefficients Among Flour and Tortilla Properties[a]

						Tortilla										
	Flour					MF				Modulus			Work			
	DS	PS	WA	MC	Wh	Str	KS	Firm	Roll	Str	KS	Firm	Str	KS	Firm	Roll
Flour																
PS	**–0.92**															
WA	**0.94**	–0.77														
MC	**0.94**	–0.76	**0.92**													
Wh	–0.79	0.64	**–0.86**	–0.79												
Tortilla																
MF																
Str	**–0.92**	0.77	**–0.93**	**–0.93**	**0.90**											
KS	**–0.95**	**0.95**	**–0.86**	**–0.85**	0.74	**0.89**										
Firm	**0.90**	**–0.96**	0.73	0.73	–0.60	–0.74	**–0.91**									
Roll	**–0.95**	**0.82**	**–0.89**	**–0.94**	**0.80**	**0.95**	**0.90**	**–0.86**								
Modulus																
Str	**–0.96**	**0.80**	**–0.97**	**–0.96**	**0.85**	**0.97**	**0.91**	**–0.80**	**0.97**							
KS	–0.79	**0.81**	–0.67	–0.62	0.64	0.70	**0.88**	**–0.81**	0.72	0.73						
Firm	0.35	–0.34	0.18	0.22	–0.22	–0.25	–0.42	0.49	–0.39	–0.31	–0.73					
Work																
Str	**–0.96**	**0.85**	**–0.88**	**–0.94**	0.79	**0.93**	**0.93**	**–0.82**	**0.93**	**0.93**	0.77	–0.38				
KS	–0.63	0.72	–0.56	–0.45	0.40	0.54	0.79	–0.69	0.56	0.60	**0.83**	–0.44	0.53			
Firm	0.76	–0.78	0.63	0.72	–0.37	–0.62	–0.69	0.75	–0.71	–0.66	–0.32	–0.08	–0.71	–0.31		
Roll	–0.75	0.63	–0.65	–0.77	0.47	0.76	0.77	–0.72	**0.87**	**0.80**	0.61	–0.47	0.75	0.60	–0.60	
RD	–0.71	0.57	–0.62	–0.71	0.63	0.69	0.62	–0.55	0.66	0.64	0.54	–0.37	0.83	0.09	–0.54	0.44

[a] DS = damaged starch; PS = particle size (Dgw); WA = water absorption; MC = moisture content of baked tortilla; Wh = whiteness of tortilla; MF = maximum force; Str = stretchability; KS = Kramer shear cell; Firm = firmness; Roll = rollability; Modulus = elastic modulus, the slope of the curve force vs. deformation; Work = absorbed energy; RD = rupture distance. Values in bold: $r > 0.80$.

Experimental Design and Statistic Analysis

All data were taken from the tortillas made from flours 1 and 2. Six different days of tortilla making with the two flours comprised six blocks (*b* = 6). Tortillas were made randomly from five samples (original, first pass, second pass, third pass, and fourth pass) of each flour each day as five treatments (*k* = 5).

The effects of storage time on tortilla characteristics were evaluated using one-way analysis of variance (ANOVA) in a randomized complete block design. Three treatments were composed for tortillas with storage times of 2 hr, 2 days, and 4 days. The data were analyzed statistically using the SAS program (SAS Institute, Cary, NC). Least significant difference was determined at $P < 0.05$.

The extra sum of squares *F* tests and backward elimination regression procedures for independent variables were conducted to identify the best-fit model for the tortilla's properties. A multivariate analysis of variance procedure was conducted to find partial correlation coefficients between the flour's properties and the tortilla's characteristics.

RESULTS AND DISCUSSION

Flour and Dough Properties

The means of starch damage of the five samples was 13.09–16.57% for flour 1 and 10.79–13.06% for flour 2 (Table I). For both flour samples, significant differences ($P < 0.05$) occurred among the means of starch damage in the original, first, second, and fourth pass; the third pass was not significantly different from the second and fourth passes. Comparing the geometric diameters of the samples indicates that all samples in both commercial flours were significantly different from each other ($P < 0.05$). The results of the farinograph at 750 BU show that water absorption increased as starch damage increased. Significant differences ($P < 0.05$) occurred among the means of the water absorption of the original, first, second, and third pass of flour 1 and the first, second, third, and fourth pass of flour 2. That is probably because damaged starch picked up more water than did intact starch granules at room temperature (Evers and Stevens 1985).

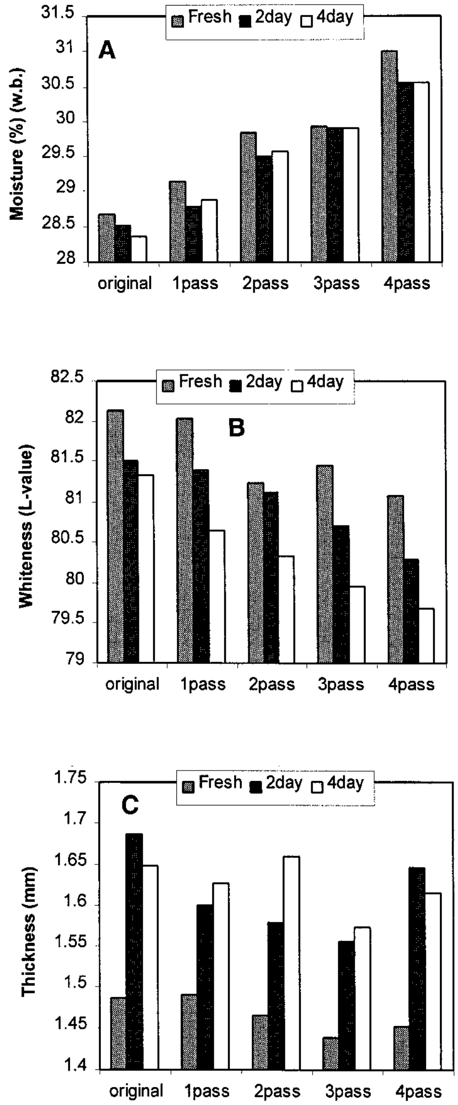

Fig. 1. Effect of storage time on tortilla physical and chemical characteristics: **A,** moisture (%, wb); **B,** whiteness (*L* value); **C,** thickness (mm).

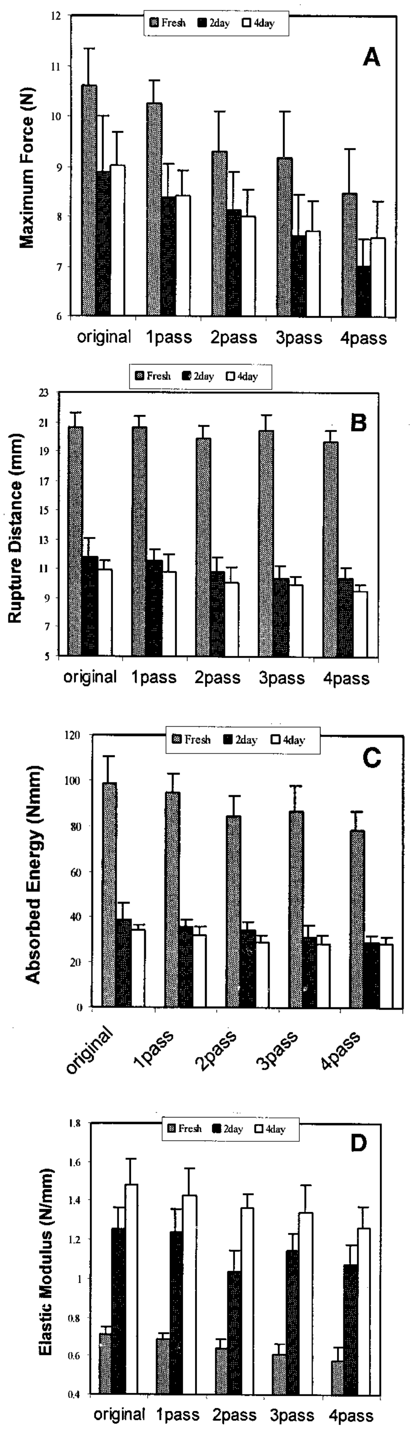

Fig. 2. Effect of storage time on tortilla stretchability at different grinding levels: **A,** maximum force (N); **B,** rupture distance (mm); **C,** absorbed energy (Nmm); **D,** elastic modulus (N/mm).

Tortilla Physical Properties

As the number of flour passes increased, the moisture content of the baked tortilla increased (28.67–31.01%, wb) (Table I). The tortilla made from fourth pass flour had a significantly higher ($P < 0.05$) moisture content. That may be accounted for by the increase in the water absorption of the tortilla (51.05–53.70, at 14% mb). However, no significant moisture differences ($P < 0.05$) occurred among the tortillas made from the first, second, and third pass flour or between the tortillas made from the original and first pass flour. The whiteness of tortillas (*L* value) decreased as the number of flour passes increased, which can be explained by browning or the Maillard reaction during the baking process due to the sugars provided by the damaged starch. But the differences in the mean *L* values were quite small (82.13 for tortillas made from the original flour, 81.08 for tortilla made from the fourth pass flour). Weight was not significantly different ($P < 0.05$) among the tortillas from all flour granulations, because all the tortillas were made from the same original weight of dough, 45 g. The diameters also were not significantly different ($P < 0.05$) among the tortillas from all flour granulations because resting times for all the tortilla doughs were the same, and the platen temperatures used to press all the tortilla doughs were the same (Bello et al 1991). The reason for no significant differences ($P < 0.05$) in thickness among the tortillas made from flours with different granulations probably was that all the tortillas were made with the same hot-press temperature, time, pressure, and gap between the plates. The toast spot areas of the tortillas made from five flours exhibited no significant differences ($P < 0.05$). That may have been the result of the same shortening level being present in all the tortilla formulations and of the same resting times being used for all the tortilla doughs (Bello et al 1991).

Tortilla Texture

The stretchability of the flour tortilla was expressed as the maximum force and the rupture distance (Table II). Greater force corresponded to the higher stretchability of the tortilla. The starch damage and particle size of flour affected stretchability. Greater force was needed to break the tortillas made from the original and first pass flour, which had lower starch damage levels and coarser particle sizes, than those made from the second and third pass flours. Less force was needed to break the tortillas made from the fourth pass flour, which had a higher level of starch damage and finer particle size. As rupture distance increased, the tortillas became stretchable. Tortillas made from the original flour had significantly larger rupture distances than those made from fourth pass flour. This result can be explained by the size of the finer flour particle, whose surface could not be bound by protein. It also can be explained by damaged starch, which increases the starch surface because it absorbs water and swells more than sound starch and, consequently, results in insufficient formation of gluten covering the surface of the starch in the tortilla dough (Farrand 1969).

Greater force of compression, shear, and extrusion was needed to break the tortillas made from original flour, whereas less was needed to break the tortillas made from third and fourth pass flours (Table II). That is probably because the original flour had a lower degree of water absorption than the others. Thus, the tortillas made from this flour had a less tender texture.

The rollability of flour tortilla was expressed by the force required to pull an axle that caused a tortilla to roll around a dowel (Table II); a lower maximum force corresponded to better rollability. Significant differences of maximum force ($P < 0.05$) occurred between tortillas made from the original and fourth pass flour, 0.199 and 0.156 N, respectively. As the level of starch damage increased and particle size decreased, the rollability of the tortillas increased, which can be accounted for by the moisture contents of the baked tortillas. The higher the moisture content, the more flexible the tortilla.

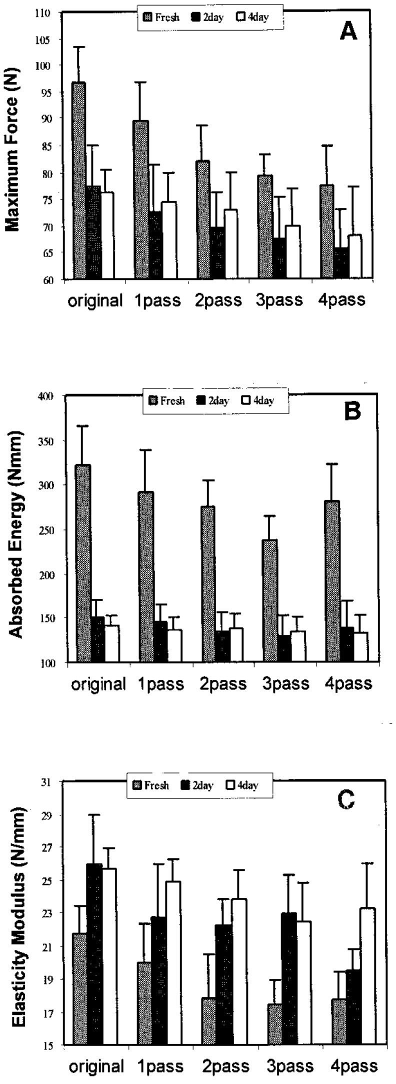

Fig. 3. Effect of storage time on tortilla Kramer shear measurement at different grinding levels: **A,** maximum force (N); **B,** absorbed energy (Nmm); **C,** elastic modulus (N/mm).

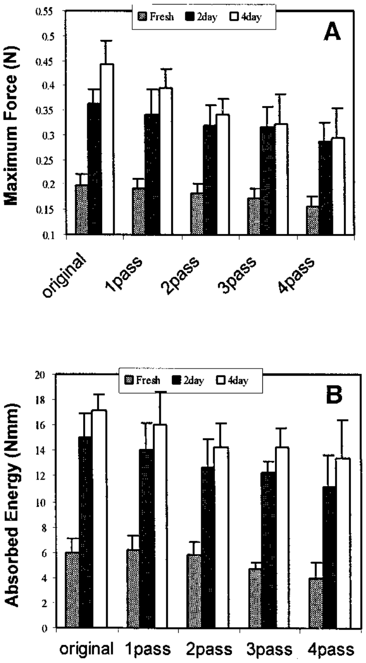

Fig. 4. Effect of storage time on tortilla rollability at different grinding levels: **A,** maximum force (N); **B,** absorbed energy (Nmm).

The firmness of the flour tortillas was expressed by maximum compression force in the force-distance curve (Table II). The higher the maximum force required to compress the tortilla up to 30% deformation, the firmer the tortilla was. The maximum forces of the third and fourth pass flour tortillas were significantly higher ($P < 0.05$) than those for the others. Original flour tortillas required the lowest maximum force to compress them up to 30% deformation, which indicated that they had more air cells, probably due to the low water absorption capacity (Wang and Flores 1999). The correlation coefficient between maximum force and water absorption was 0.73 ($P < 0.05$).

The elasticity modulus is the slope of the straight-line portion of the force deformation curve (Nmm). Tortillas made from the original and first pass flours had significantly higher elasticity moduli ($P < 0.05$) when stretched or sheared (Table II). However, no significant difference ($P < 0.05$) in the elasticity modulus occurred when the tortillas were compressed.

Correlation Coefficients of Flour and Tortilla Properties

Starch damage correlated highly with tortilla stretchability ($r = –0.92$, $P < 0.001$), the peak force of Kramer shear cell ($r = –0.95$, $P < 0.001$), firmness (0.90, $P < 0.001$), and the rollability ($r = -0.95$, $P < 0.001$) of tortillas (Table III). Starch damage also correlated highly with the elasticity or Young's modulus when tortillas were stretched ($r = –0.96$, $P < 0.001$). Particle size correlated highly with the peak force of Kramer shear cell ($r = 0.95$, $P < 0.001$), firmness ($r = –0.96$, $P < 0.001$), and the rollability ($r = 0.82$, $P < 0.01$) of the tortillas. Particle size correlated highly with the elasticity modulus when tortillas were stretched ($r = 0.80$, $P < 0.01$) or sheared ($r = 0.81$, $P < 0.01$).

A regression equation was used to predict tortilla texture in the form of maximum force ($F_{\max}$). A best-fit model was acquired by backward elimination regression procedures with the extra sum of squares F tests.

$$F_{\max(\text{stretchability})} = 25.092 + 0.032\text{PS} - 0.324\text{ WA} \qquad (1)$$
$$R^2 = 0.7069\ (P < 0.001)$$

$$F_{\max(\text{Kramer shear})} = 165.557 + 0.454\text{PS} - 1.937\text{ WA} \qquad (2)$$
$$R^2 = 0.7443\ (P < 0.001)$$

where PS = particle size (Dgw) and WA = water absorption.

The flour particle size and flour water absorption had a significant multiple linear relationship ($P < 0.001$) with the maximum force in the stretchability and Kramer shear measurements. Starch damage did not show up in Equations 1 and 2, because it was highly correlated with flour water absorption ($r = 0.94$, $P < 0.001$). Equation 1 shows that tortilla stretchability increases as the particle size of flour increases and as the water absorption of flour decreases. Equation 2 shows that tortilla tenderness, expressed by maximum force of Kramer shear, increases as the particle size of flour increases and as the water absorption of the flour decreases.

Effects of Storage Time on the Physical Properties and Texture of Tortillas

Staling occurs during the storage of tortillas. It was characterized by textural changes resulting in increased firmness and decreased flexibility. A textural change during aging is an important criterion when the consumer judges the product. Fresh tortillas have more moisture than stored tortillas, because migration of moisture occurs during storage (Fig. 1A). Gluten undergoes a transformation, resulting in the release of water (Willhoft 1971), and starch undergoes retrogradation, resulting in water being expelled from the starch matrix (Senti and Dimler, 1960). However, no significant differences occurred in the moisture contents between 2- and 4-day-old stored tortillas. Tortillas became opaque as storage time increased. The explanation for that might be that, during storage, the melted and swollen starch granules recrystallize as a result of more interaction between the starch chains with time. The crystalline area differs in its refractive index (Hoseney 1990) and light had difficultly going through the tortilla to the white paper underneath it; therefore, tortillas had a lower L value (Fig. 1B). The thickness of the tortillas was determined at 10/3 of the maximum compression distance when determining firmness of the tortillas using the compression test. Fresh tortillas were thinner than stored tortillas (Fig. 1C). Tortillas probably underwent relaxation during storage, which increased the thickness.

Fresh tortillas were more stretchable than stored tortillas (Fig. 2). The maximum forces were 10.61–8.46, 8.88–7.00, and 9.01–7.59 N for fresh 2-day-old, and 4-day-old tortillas, respectively. When the maximum force of the stetchability of tortillas from different granulations was compared within the 2- or 4-day storage time, the tortillas made from the original and first pass flours had significantly higher maximum forces, whereas those made from fourth pass flour had significantly lower maximum forces. The difference (2.15 N) in maximum force between fresh tortillas made with the original flour and with the fourth pass flour was greater than the difference (1.88 N) between 2-day-old tortillas made with original and fourth pass flour, and the difference became smaller when stored time increased. The results indicate that damaged starch and particle size had a greater effect on the stretchability of fresh tortillas, and this effect became smaller as the storage time of tortillas increased. Comparison of the maximum force of the stretchability of the tortillas among the three storage times showed that the maximum force of the fresh tortillas was significantly higher than those for 2- or 4-day-old tortillas made

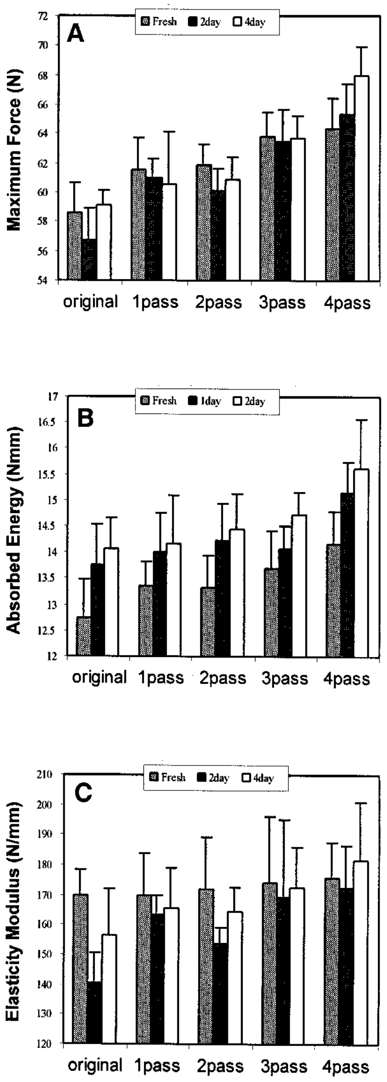

Fig. 5. Effect of storage time on tortilla firmness at different grinding levels: **A,** maximum force (N); **B,** absorbed energy (Nmm); **C,** elastic modulus (N/mm).

from the original, first, second, and third pass flours; and the maximum force of fresh tortillas was significantly higher ($P < 0.05$) than that of 4-day-old tortillas made from the fourth pass flour. However, no significant differences ($P < 0.05$) in maximum force occurred between 2- and 4-day-stored tortillas made with the original, first, second, and third pass flours; between fresh and 2-day-stored tortillas; and between 2- and 4-day-stored tortillas made with fourth pass flour. The reason that the fresh tortillas had more stretchability than the others was probably because they contained more moisture. When tortillas were stored for 2 or 4 days, their moisture was partially lost, which gave them a less stretchable texture. Starch retrogradation during tortilla storage also may have caused a decrease in the stretchability.

The stretchability of tortillas also was expressed as the rupture distance, which gave the same result as maximum force (Fig. 2B). Rupture distances ranged from 20.68 to 19.70, 11.78 to 10.35, and 10.88 to 9.50 mm for fresh, 2-day-old, and 4-day-old tortillas, respectively.

The elastic or Young's modulus of the stretchability was significantly higher ($P < 0.05$) for the 2- and 4-day-old tortillas made with original flour than that made with fourth pass flour (Fig. 2D). The elastic modulus was significantly lower ($P < 0.05$) for fresh tortillas than for tortillas stored for 2 days, and increased as storage time increased.

The design of the Kramer shear cell imitates the human mastication mechanism to a certain degree (Bedolla et al 1983). Fresh tortillas needed greater force of compression, shear, and extrusion to break them (Fig. 3). The maximum forces ranged from 96.66 to 77.77, 77.53 to 65.65, and 77.36 to 68.00 N for fresh, 2-, and 4-day-old tortillas, respectively. A significant difference ($P < 0.05$) in maximum force occurred among the 2- and 4-day-old tortillas made from different granulations. The difference (18.89 N) in maximum force between fresh tortillas made with the original and with fourth pass flour tortillas was greater than the difference (10.88 N) between 2-day-old tortillas made with original and fourth pass flour. The differences became smaller as storage time increased. The results indicated that starch damage and particle size had a greater effect on the fresh tortilla with respect to Kramer shear, and this effect became smaller as storage time of tortillas increased. When the maximum forces of Kramer shear in the tortillas were compared for the three storage times, those for the fresh tortillas were significantly higher than those for the 2- or 4-day-stored tortillas made with the original, first, second, and third pass flours, and maximum force of the fresh tortilla was significantly higher than that of the 4-day-stored tortilla made with fourth pass flour. However, no significant differences ($P < 0.05$) occurred in maximum force between 2- and 4-day-old tortillas, between fresh and 2-day-old tortillas, or between 2- and 4-day-old tortillas made with fourth pass flour.

The elastic modulus of the Kramer shear was significantly higher for the 2- or 4-day-old tortillas made with original as compared with fourth pass flour (Fig. 3C). The elastic modulus of fresh tortillas was significantly lower than that of tortillas stored for 4 days. No significant differences occurred in the elastic modulus between 2- and 4-day-old tortillas made with the original, first, second, and third pass flours or between fresh and 2-day-old stored tortillas made with fourth pass flour. The lower elastic modulus of fresh tortillas probably was due to their more tender texture.

The rollability of tortillas was described by the peak force required to pull the axle that caused a tortilla to roll around a dowel; a lower peak force indicated better rollability. The maximum forces ranged from 0.20 to 0.15, 0.36 to 0.29, and 0.41 to 0.29 N for fresh, 2-day-old, and 4-day-old tortillas, respectively. The 2- and 4-day-old tortillas made with original flour were less rollable, whereas those made with fourth pass flour were more rollable. The difference (0.05 N) in maximum force between the fresh tortillas made with original and with fourth pass flour was smaller than the difference (0.07 N) between 2-day-old tortillas made with original and with fourth pass flour, and the difference became larger as storage time increased. The results indicated that starch damage and particle size had a smaller effect on the rollability of the fresh tortilla, and this effect became greater as storage time of tortillas increased. Fresh tortillas were more rollable than 2-day-old tortillas; and, as storage time increased, the tortillas became less rollable (Fig. 4). That is because fresh tortillas were more flexible, and flexibility decreased as storage time increased (Suhendro et al 1998).

Tortilla firmness was measured by a compression test that simulated the gentle squeezing by hand. A higher peak force indicated a firmer tortilla. Fresh, 2-day-old, or 4-day-old tortillas made from flour that had a higher number of passes were firmer than those made with original or flour with a few number of passes (Fig. 5). The peak forces ranged from 58.57 to 64.41, 56.68 to 65.30, and 59.12 to 67.97 N for fresh, 2-day-old, and 4-day-old tortillas, respectively. The difference (5.84 N) of maximum force between fresh tortillas made with original and with fourth pass flour was smaller than the difference (8.62 N) between 2-day-old tortillas made with original and with fourth pass flour, and the difference became greater as storage time increased. The results indicated that starch damage and particle size had a smaller effect on the firmness of the fresh tortilla, and this effect became greater as the storage time of tortillas increased. Theoretically, during baking, starch granules are swollen and gelatinized, and the amylopectin crystallinity is disrupted. In the firming stage, the amylopectin reforms into double helical structures and reorganizes into the crystalline region. This reorganization imparts rigidity to both the swollen granules and the intergranular materials by acting as physical crosslinks in the overall structure (Zobel and Kulp 1996). However, no significant differences ($P < 0.05$) occurred among the peak forces for fresh, 2-day-old, and 4-day-old tortillas. The reason for that was not clear.

No significant differences ($P < 0.05$) in the elasticity modulus in the compression measurement occurred among the stored tortillas made from flours with different granulations or between 2- and 4-day-old storage tortillas in compression measurement.

The coefficient of variation (CV) value indicates variability; the higher CV, the lower the repeatability of measurement and the less homogenous the tortillas. Maximum force of rollability measurement had a higher CV value (10.78) than other measurements (Table IV) The results indicated that stretchability, Kramer shear, and firmness measurements are more repeatable.

CONCLUSIONS

Starch damage and particle size in flour affected the properties of tortillas. As starch damage increased and particle size decreased, flour tortillas became less stretchable, the maximum force of Kramer

TABLE IV
Coefficient of Variation (%) of Textural Properties for Flour Tortilla[a]

Flour	Stretchability	Stretchability RD	Kramer Shear	Rollability	Firmness
Original	6.89	4.68	7.00	10.08	3.64
First pass	4.28	3.45	8.22	10.43	3.61
Second pass	8.64	4.20	8.13	9.01	2.34
Third pass	10.14	5.17	4.93	10.17	2.55
Fourth pass	10.54	3.43	9.31	14.23	3.14
Average	8.10	4.19	7.52	10.78	3.06

[a] Values given are for maximum force except for Stretchability RD (rupture distance).

shear decreased, and firmness and rollability increased. Tortillas became less flexible after storage at room temperature for 2 days. The staling rates were faster during the first 2 days of storage than the next 2 days. The effects of starch damage and particle size on strechability and Kramer shear were greater in the fresh tortillas than in the stored tortillas, and these effects became smaller as the storage time of the tortillas increased. However, the effects of starch damage and particle size on the rollability and firmness were smaller in fresh tortillas than in stored tortillas, and these effects became greater as the storage time increased. To make a tortilla with acceptable rollability, starch damage should not be too high and particle size should not be too fine.

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LITERATURE CITED

American Association of Cereal Chemists. 2000. Approved Methods of the AACC, 10th ed. Methods 44-15A, 50-11, 54-21, 76-30A. The Association: St. Paul, MN.

Bedolla, S., de Palacios, M. G., Rooney, L. W., Diehl, K. C., and Khan, M. N. 1983. Cooking characteristics of sorghum and corn for tortilla preparation by several cooking methods. Cereal Chem. 60:263-268.

Bello, A. B., Serna-Saldivar, D. O., Waniska, R. D., and Rooney, L. W. 1991. Method to prepare and evaluate wheat torillas. Cereal Foods World 36:315-322.

Dally, V., and Navarro, L. 1999. Flour tortillas: A growing sector of the U.S. food industry. Cereal Foods World 44:457-459.

Evers, A. D., and Stevens, D. J. 1985. Starch damaged. Pages 321-349 in: Advances in Cereal Science and Technology, Vol. VII. Y. Pomeranz, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.

Farrand, E. A. 1969. Starch damage and α-amylase as bases for mathematical models relating to flour water-absorption. Cereal Chem. 46:103.

Farrand, E. A. 1972. The influence of particle size and starch damage on the characteristics of bread flours. Baker's Dig. 46(1):22-26.

Gracza, R., and Norris, C. G. 1961. Flour strength and particle size. Baker's Dig. 35(3):56-62, 64.

Hoseney, R. C. 1990. Cereal starch. Pages 33-56 in: Principles of Cereal Science and Technology. Am. Assoc. Cereal Chem.: St. Paul, MN.

Kim, Y. S., and Flores. R. A. 1999. Determination of bran contamination in wheat flours using content, color, and bran speck counts. Cereal Chem. 76:957-961

Kurimoto, Y., and Shelton. D. R. 1988. The effect of flour particle size on baking quality and other flour attributes. Cereal Foods World 33:429-433.

Mao, Y. 2000. Effects of starch damage and particle size on the texture of wheat flour tortillas. MS thesis. Department of Grain Science and Industry. Kansas State University: Manhattan, KS.

McDonough, C. M., Seetharaman, K., Waniske, R. D., and Rooney, L. W. 1996. Changes in microstructure of wheat flour tortilla during baking. J. Food Sci. 61:995-999.

Multon, J. L., Bizot, H., and Savet, B. 1980. Water absorption in cereal foods and water activity measurement. Pages 97-110 in: Cereals for Food and Beverages. G. E. Inglertt and L. Munck, eds. Academic Press: New York.

Oh, N. H., Seib, P. A., Ward, A. B., and Deyoe, C. W. 1985. Noodles. IV. Influence of flour protein, extraction rate, particle size, and starch damage on the quality characteristics of dry noodles. Cereal Chem. 62:441-446.

Qarooni, J., Moss, R. A., and Wootton, M. 1988. The effect of flour properties on the quality of Arabic bread. J. Cereal Sci. 7:95-107.

Qarooni, J., Ponte, J. G., Jr., and Posner, E. S. 1992. Test baking procedure for evaluating flour tortilla quality. Assoc. Operative Millers Bull. (Dec):6136-6138.

Rogers, D. E. Gelroth, J. A. Langemeier, J. M., and Ranhotra, G. S. 1994. Evaluation of starch damage values determined enzymatically or amperometrically. Cereal Chem. 71:578-518.

Senti, F. R., and Dimler, R. J. 1960. Changes in starch and gluten during aging of bread. Baker's Dig. 33(1):28-31.

Shellenberger, J. A., Wichser, F. W., and Lakamp, R. C. 1950. Cake properties in relation to flour particle size fractions. Cereal Chem. 27:106-113

Suhendro, E. L., Almeida-Dominguez, H. D., Rooney, L. W., and Waniska, R. D. 1998. Objective rollability method for corn tortilla texture measurement. Cereal Chem. 75:320-324.

Wang, L., and Flores, R. A. 1999. Effect of different wheat classes and flour milling streams on the textural properties of flour tortilla. Cereal Chem. 76:496-502.

Wang, L., and Flores, R. A. 2000. Effects of flour particle size on the textural properties of flour tortillas. J. Cereal Sci. 31:263-272.

Willhoft, E. M. A. 1971. Bread staling. I. Experimental study. II. Theoretical study. J. Sci. Food Agric. 22:176.

Zobel, H. F., and Kulp, K. 1996. Staling mechanism. Pages: 1-64 in: Baked Goods Freshness. R. E. Hebeda and H. F. Zobel, eds. Marcel Dekker: New York.

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