

# Rheological and Sensory Evaluation of Wheat Flour Tortillas During Storage

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## ABSTRACT

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Texture of wheat flour tortillas over 15 days at room temperature was evaluated using an expert sensory panel, consumer panels, subjective rollability test, large deformation rheological methods (i.e., bending, extensibility [1-D and 2-D], and puncture tests), and stress relaxation method. Most of the changes in texture occurred during the initial 8 days of storage, while texture of tortillas changed slowly thereafter. Differences in texture between fresh and 1-day-old tortillas were detected by many objective rheological methods but not by either sensory panel. The expert sensory panel observed a rapid decrease in tortilla extensibility and

an increase in staleness between 1 and 8 days of storage and smaller changes in sensory scores after 8 days of storage. Most objective rheological parameters changed rapidly between 0 and 5 days, and slowly after 5 days of storage. Significant correlations and factor analysis reveal that changes occurring in flour tortillas during staling are estimated better by subjective rollability, sensory evaluation (expert and consumer panels), and 2-dimensional extensibility test than by other methods. Hence, some rheological methods are useful to estimate sensory properties of flour tortillas.

Good quality tortillas should be flexible without tearing and cracking when folded, soft without sticking together, light colored, and puffed (Bello et al 1991). Fresh tortillas are soft, extensible, and flexible. When tortillas stale, the texture becomes firmer, less extensible, and less rollable. The reassociation of starch molecules during storage corresponds to loss of freshness and increased structure or firmness of bakery products (Zobel and Kulp 1996). Such phenomenon is generally referred to as staling. Cracking and breaking of tortillas during rolling can be delayed by using flour with higher protein quality, and adding gluten and some hydrocolloids (Friend et al 1993). Storage temperature has a significant influence on the rate of staling of tortillas. Tortillas stored at  $-12^{\circ}\text{C}$  for 15 days had texture comparable to that of the 1-day-old tortillas stored at  $22^{\circ}\text{C}$  (Kelekci et al 2003).

Staling begins as soon as baking is complete and the product begins to cool. The rate of staling is dependent on the formulation, the process conditions, and the product storage conditions. Staling is mainly due to the gradual transformation of amorphous starch to a partially crystalline, retrograded state. During tortilla production, there is enough time and moisture to gelatinize starch granules, to disperse some of the starch, and to have much of the amylose become insoluble (retrograde) by the time the product has cooled to room temperature (Seetharaman et al 2002). Retrogradation of amylopectin is believed to involve association of its outer branches and requires a longer time and a lower temperature than amylose to retrograde (Kelekci et al 2002). Thus, retrogradation of amylopectin occurs with time after the product has cooled and corresponds to the staling process. However, there were indications that amylopectin in tortillas crystallizes more quickly and to a greater extent than does amylopectin in hamburger buns (Seetharaman et al 2002).

The subjective rollability test is often used to evaluate changes of tortilla texture during storage. In this method, tortillas are rolled using a dowel, and textural changes and the extent of cracking is evaluated subjectively. Waniska (1976) rolled a strip of chapati around a dowel and evaluated the extent of breaking subjectively. Bello et al (1991) and Suhendro et al (1993) used this method to monitor texture changes of flour tortillas during

storage. It is a simple method and reflects the way tortillas are handled before consumption. However, rollability score can be different from person to person and the method is not sensitive to changes in texture during the initial days of storage of corn tortillas, when the tortilla is “fresh” (Suhendro et al 1998).

Sensory evaluation is another subjective method to monitor texture changes of food products. Sensory methods can be divided into two main categories: effective and analytical. Effective tests measure the average person’s responses to a food; responses like acceptance, preference, and degree of liking or disliking. Paired preference, ranking, and hedonic rating are commonly used as effective tests. Analytical tests can be discriminative and descriptive and are commonly called “expert panels”.

Another way to measure texture of foods is by using large deformation rheological methods. These procedures can imitate subjective measurements and are sensitive, reliable, and appropriate to differentiate the changes in flexibility and rollability of tortillas resulting from storage or changes in processing or formulations. Objective texture measurements can characterize the rheology of wheat flour dough (Srinivasan et al 2000) or tortillas. Suhendro et al (1998) used objective rheological methods to measure corn tortilla texture, which changed during storage. Their objective texture measurements significantly correlated with subjective rollability scores. The same authors also showed that the some of the objective techniques were more sensitive to changes in texture of corn tortillas than subjective evaluations, which do not detect differences in tortilla texture during the first 24 hr after baking.

An example of an objective rheological technique is the extensibility method. It is a simple, fast, and repeatable method where a tortilla strip is pulled apart by a tensile force during the test. The tensile characteristic of sorghum chapati (Waniska 1976), corn tortillas (Suhendro et al 1999b), and wheat flour tortillas (Bejosano and Waniska 2004) were evaluated using this method. Parameters of force, modulus, and work of deformation and force and distance to rupture are provided by extensibility methods.

The bending method was developed to imitate and isolate the bending action of a tortilla during rolling. During the test, a tortilla strip is bent up to  $40^{\circ}$  angle. The force and work required to bend the tortilla strip and modulus of deformation are calculated. The bending method detected differences in uniformity, thickness, and puffing of corn tortilla (Suhendro et al 1998). Thick tortillas required more force to bend and had greater moduli of deformation than thin tortillas.

The stress relaxation technique is another method to evaluate the texture of food materials. In this test, the sample is given an instantaneous strain, and the stress required to maintain deformation is observed as a function of time. Ideal elastic materials do not show relaxation, but ideal viscous materials relax instantan-

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ously. Viscoelastic materials relax gradually with the end point depending on the molecular structure of the material (Steffe 1996).

The objective of this study was to determine the textural changes that occur during storage of flour tortillas using both objective and subjective methods. We hope to learn which objective rheological methods best characterize the staling of flour tortillas. Then the best procedures to evaluate staling of flour tortillas will be used in future studies.

## MATERIALS AND METHODS

### Tortilla Processing

Tortillas were made according to the method of Bello and co-workers (1991). Hot-press wheat flour tortillas were prepared from a standard formula of 1.0 kg of flour (bleached, enriched, and malted flour with 13.4% moisture content, 0.50% ash, 10.4% protein, 254 falling number, 58.6% farinograph absorption) (ADM Arkady, Enid, OK), 60 g of all-purpose shortening (Bunge Foods, Bradley, IL), 15 g of salt (United Salt Corporation, Houston, TX), 6 g of sodium bicarbonate (Arm and Hammer, Church & Dwight Co., Princeton, NJ), 5.8 g of sodium aluminum phosphate (Monsanto Co., St. Louis, MO), 3.3 g of fumaric acid (Bartek Ingredients, Stoney Creek, ON, Canada), 4 g of sodium propionate (American Ingredients, Grandview, MO), 4 g of potassium sorbate (Ashland Chemical Co., Columbus, OH), 2.5 g of sodium 2 stearoyl lactylate (American Ingredients Co., Grandview, MO), 2.5 g of succinylated monoglycerides/distilled monoglycerides (Eastman Chemical Co., Kingsport, TN), and distilled water at 38°C.

Dough balls were formed in a dough ball rounder, allowed to rest in a proof chamber, and transferred to the processing line, where each dough ball was hot-pressed between warm Teflon-coated platens to a thickness of ≈2 mm. The pressed disks were passed into a three-tier oven (model OP01004-02, Lawrence Equipment, El Monte, CA) and baked at 180°C, allowed to cool, and then packed in polyethylene bags.

### Subjective Rollability Test

Tortillas were evaluated subjectively by rolling around a 1-cm diameter dowel at different stages during storage. Rollability score was rated from 1 (unrollable) to 5 (rolls easily) (Cepeda et al 2000).

### Objective Rheological Methods

Large deformation rheological measurements were conducted using a texture analyzer (model TA XT2, Texture Technologies Corp., Scarsdale, NY).

### Extensibility Test

The one-dimensional tortilla extensibility test was based on the method used by Suhendro et al (1999b) using two clamps. The lower clamp was attached to the texture analyzer platform and the upper clamp was attached to the analyzer arm. The distance between the two clamps was adjusted to 2.2 cm. A tortilla strip was cut to 75 × 35 mm from the center of a tortilla. The strip was aligned vertically by two clamps. Extensibility was tested using the “return to start” option with tension mode and trigger force of 0.05N. Pretest, test, and posttest speeds were adjusted to 5.0 mm/sec, 1.0 mm/sec, and 5.0 mm/sec, respectively.

Fresh (2 hr)	Stale (15 d)	Id#	Id#	Name	Score Sheet for Descriptive Analysis of Flour Tortillas
3	4			APPEARANCE	
				Evenness (color)	0 = even, 7 = moderately even, 15 = extremely uneven
10	11			Opacity	0 = translucent, 7 = moderately opaque, 15 = opaque
7	7			Shape	0 = round, 15 = oval
8	8			Surface (single bake)	0 = none, 7 = blistered, 15 = puffed
		Rating	Rating	TEXTURE	(in the hand)
4	5			Roughness (double bake side)	0 = gelatin, 5 = orange peel, 8 = potato chip, 12 = hard granola bar; (0 = smooth, 15 = rough)
15	7			Bending (angle of bend)	0 = none, 3 = 15°, 7 = 45°, 11 = 60°, 15 = 90°
15	11			Rollability	0 = unrollable, 3 = breaks along axis, 7 = both sides break, 11 = one side breaks, 15 = rollable with no breaks
12	5			Extensibility	0 = none, 7 = moderately extended, 15 = completely extended
		Rating	Rating	ODOR	
9	9			Overall	2 = soda, 7 = potato, 10 = grape
1	1			Acidic	0 = none, 15 = acidic
		Rating	Rating	FLAVOR	
1	1			Acidic / Sour	2 = 0.05 % solution, 5 = 0.4 % solution, 10 = 0.15 % solution, 15 = 0.2 % solution
2	2			Salty	2.5 = 0.2 % solution, 5 = 0.4 % solution, 8.5 = 0.8 % solution, 15 = 1.6 % solution
1	1			Sweet	2 = 2 % solution, 5 = 5 % solution, 10 = 10 % solution, 15 = 15 % solution
1	1			Bitter	2 = 0.05 % solution, 5 = 0.08 % solution, 10 = 0.15 % solution, 15 = 0.20 % solution
		Rating	Rating	TEXTURE	(by the mouth)
9	8			Springiness	0 = not springy, 15 = very springy; 0 = cream cheese, 5 = frankfurter, 9.5 = marshmallow; Compress partially without breaking, degree to which sample returns to original shape
6	7			Hardness	0 = soft, 15 = hard; 1 = cream cheese, 4.5 = cheese, 6 = olives, 9 = peanuts; Bite down evenly, force to attain a given deformation.
7.5	6.5			Cohesiveness	0 = rupturing, 15 = deforming; 1 = corn muffin, 5 = cheese, 8 = soft pretzel, 10 = raisins; Compress fully, degree to which sample deforms rather than cracks or crumbles
1	2			Fracturability	0 = crumbly, 15 = brittle; 1 = corn muffin, 2.5 = egg, 4.2 = graham cracker, 6.7 = toast; Bite down evenly until food crumbles/cracks, force with which sample breaks
4	5			Moisture Absorption	0 = No absorption, 15 = large amount; 0 = licorice, 7.5 = popcorn, 10 = potato chips, 15 = cracker; Amount of saliva absorbed during chew down.
9.5	8.5			Cohesiveness of Mass	0 = loose mass, 15 = tight mass; 2 = carrots, 4 = mushroom, 9 = cheese, 13 = soft brownie; Chew sample, degree to which chewed sample holds together in a mass.
8	7			Tooth Packing	0 = none stuck, 15 = very much; 1 = carrots, 3 = mushroom, 7.5 = graham cracker, 9 = cheese, 15 = candy; Swallowed, degree to which product sticks on the teeth surface.
		Rating	Rating	OVERALL STALING	
1	10				1 = fresh taste/smell/texture, 10 = stale (off) taste/smell and/or hard texture

Fig. 1. Format of expert panel score sheet for descriptive analysis of flour tortillas.

During the test, force (N), and distance (mm) were recorded. The test continued until the strip was ruptured.

### Two-Dimensional Extensibility

The two-dimensional extensibility test measured the extensibility and the force required to rupture the tortilla (Kelekci et al 2003). The TA-108 fixture was held on the analyzer platform and an acrylic probe (7/16-in. diameter) with a flat edge was attached to the analyzer arm. The two-dimensional extensibility test was conducted using the “return to start” option with compression mode and trigger force of 0.05N. Pretest, test, and posttest speeds were adjusted to 5.0 mm/sec, 1.0 mm/sec, and 5.0 mm/sec, respectively. The test was conducted until the distance reached 7.5 mm. Force (N) and distance (mm) were recorded.

### Puncture Test

A metal probe 3.2 cm in length and 3.0 mm in diameter was used to puncture the tortillas. Tortillas were placed on an aluminum plate 1.3 cm thick with a hole 6.0 mm in diameter that accepted the metal probe as it is punched through the product. The metal probe was calibrated to a distance of 50 mm above the platform. The setting was the same as two-dimensional extensibility test. Force (N) and distance (mm) were recorded.

### Bending Test

A tortilla strip 30 × 35 mm was evaluated in the bending test. The strip was placed horizontally in a setup that consisted of a lower grip attached to the texture analyzer platform and an aluminum guillotine attached to the analyzer arm. The probe was calibrated to a distance of 50 mm from platform to guillotine. The test was run with the same setup as the two-dimensional extensibility test. The probe moved down for 5.0 mm at a test speed of 1.0 mm/sec until the guillotine bent the tortilla strip to a controlled 40° angle (Suhendro et al 1999a).

### Stress Relaxation Test

The stress relaxation procedure of Limanond et al (2002) for corn tortillas was used for flour tortillas. The tortilla strip size and texture analyzer setup were the same as for the one-dimensional extensibility test. The texture analyzer system was set in tension mode and the samples were tested at 3% strain levels (linear viscoelastic region). The 3% strain was effective for both fresh and staled tortillas. Maximum and minimum forces (N) initial, middle, and end modulus were recorded. Initial and final stiffness and energy dissipation values were calculated using a seven-element Maxwell model.

### Sensory Evaluation of Tortillas

In the descriptive analysis, only five panelists participated, which is less than the minimum of seven panelists recommended by Larmond (1977). They were trained following the Spectrum method (Meilgaard et al 1999). The lexicon to evaluate flour tortillas was generated by them and included parameters related to appearance, odor, flavor, and texture of tortillas such as hardness, bending, extensibility, rollability, springiness, fracturability, cohesiveness, and moisture absorption (Fig. 1). The intensity of each attribute was evaluated using a 15-point scale. The panelists were trained using tortillas that were fresh (2 hr) and “stale” (10 days). The panelists were provided samples of tortillas (8 days) at the beginning of each session as a reference. A completely randomized block design was used to arrange the serving order of tortillas for each panelist. Tortillas that were 0, 1, 8, and 15 days old were evaluated. Drinking water and unsalted soda crackers were used to cleanse the mouth between samples.

In the consumer acceptability test, >30 members participated in each of two sensory evaluations. Consumers were randomly selected from the Soil and Crop Sciences Department. A brief interview was used to screen for panelists that were familiar with flour tortillas. Consumer panelists rated tortillas on a 10-cm, like-dislike

<b>CONSUMER PANEL DATA SHEET</b>	
Consumer panel instructions for evaluation of wheat flour tortillas	
<b>DEMOGRAPHICS:</b> Please answer the following questions. Gender:    ___ female   ___ male Age:       ___ under 30   ___ over 30 Origin:    ___ Hispanic   ___ non-Hispanic   ___ Asian   ___ other	
<b>INSTRUCTIONS:</b> Wheat flour tortillas will be evaluated. Please MARK through the line “- -” to record your evaluation. Please evaluate near the center of the tortilla (not near the edge).	
* Using your hands and fingers, stretch the tortilla: => “Stretchiness”       Rate: [low --- high]	
* Smell the tortilla. Take a bite from the center of the tortilla. Continue the normal eating process: => “Acceptability”       Rate: [dislike --- like]	
* Rinse your mouth with water after each sample. Evaluate the next tortilla using the same procedure.	
<b>Taste Panel Questionnaire for Wheat Flour Tortillas</b>	
ID# _____	<b>Stretchiness by Hand</b>
Low	----- ----- High
Dislike	----- ----- Like
Comments for ID# _____	

Fig. 2. Format of consumer panel score sheet for sensory evaluation of flour tortillas.

scale; and tortillas were scored for acceptability, taste, stretchiness, and staleness (Fig. 2). Tortillas that were 0, 1, 8, and 15 days old were evaluated. A complete randomized block design was used to arrange the serving order of tortillas for each panelist.

### Statistical Analysis

At least 144 tortillas were prepared on eight days to conduct replicated consumer and expert panels and texture measurements. Rheology of tortillas was evaluated in duplicate from at least four of these replicates. The effects of storage time on tortilla texture were evaluated using one-way analysis of variance in a completely randomized experimental design. Protected Fisher's LSD was used for multiple mean comparisons ( $\alpha = 0.05$ ). Pearson's correlation and factor analysis were used to determine relationships between the objective and subjective measures of tortilla texture and with storage time of flour tortillas. Statistical software was used to conduct statistical analysis (SAS Institute, Cary, NC).

## RESULTS AND DISCUSSION

### Sensory Evaluation

Both the expert and consumer sensory panels detected that most of the loss of tortilla freshness occurred during the first eight days of the 15-day storage period (Table I). The expert sensory panel did not detect differences in texture between fresh (0 day) and 1-day-old tortillas. The expert sensory panel noted increased staleness in tortillas on day 8 of storage. The range of values was greater for staleness, extensibility, and pliability than for the other parameters measured by sensory analysis. Expert panel staleness score significantly correlated with objective rheological measurements of bending, extensibility, puncture, rollability score, and stress relaxation (Table II). Thus, the expert panel detected changes such as staling that occur in flour tortillas during storage.

The consumer panel did not detect differences between 0 and 1-day-old tortillas (Table I). Tortilla stretchiness, taste, and acceptability scores decreased and staleness of tortillas increased with storage time. The consumer panel detected a significant change in staleness scores between 1 and 8 days of storage, but did not detect a further increase in staleness between 8 and 15 days of storage. The expert panel, however, was able to detect texture changes in tortillas between 8 and 15 days of storage. The staleness score significantly correlated with tortilla taste, stretchiness, and acceptability (Table II), which suggests that changes that occur to flour tortillas during storage include more than firming of the structure. The consumer panel staleness scores significantly correlated with objective rheological measures of extensibility, puncture, rollability score, and stress relaxation (Table II).

### Subjective Rollability

Subjective rollability was significantly affected by storage time with decreased scores observed during storage (Table I). Subjective rollability scores differentiated the age of tortillas and detected fresh (0 day) over 1-day-old tortillas, which neither expert nor consumer sensory panels accomplished. Subjective rollability scores of flour tortillas over the 15 days of storage significantly correlated to sensory parameters measured by the expert and consumer panels, as well as most of the objective rheological measurements (Table II). Tortilla rollability is a simple and easy technique that produces reliable measurement of changes in tortilla properties during storage without the need of a sensory panel and use of expensive instrumentation.

### Rheological Measurements

Most of the parameters of the one-dimensional extensibility, two-dimensional extensibility, bending, puncture, and stress relaxation tests changed rapidly from day 0 to day 5 and less rapidly after 5 days of storage at 22°C (Table III). In most cases, objective force, work, and modulus values were significantly

different from day 0 to day 5, after which no significant changes were detected.

Changes in tortilla texture were detected by the one-dimensional extensibility test (Table III). All rheological parameters of fresh (0 day) tortillas were significantly different from those of 1-day-old tortillas. However, no significant changes in texture were observed from 5 to 15 days of storage. The subjective rollability and expert panel staleness ratings significantly correlated with the one-dimensional extensibility rupture force and work at 2-mm deformation (Table III). These findings are consistent with those of Suhendro et al (1999b), who found that the one-dimensional extensibility test detects changes in texture of corn tortillas during storage. They noted that subjective measurements (tortilla rollability and flexibility) significantly correlated with objective rheological parameters such as rupture force, force at 1 mm, and modulus of deformation, but not with distance or work.

Changes in tortilla texture over time were also detected by the two-dimensional extensibility test (Table III). However, fresh (0 day) and 1-day-old tortillas had similar texture values, which were significantly different from those of older tortillas. The subjective rollability and staleness ratings (expert and consumer panels) significantly correlated with all rheological parameters from this test (Table II). Kelekci et al (2003) used this method to determine that flour tortillas firm more rapidly during ambient temperature storage (22°C) than at other storage temperatures. They also concluded that fresh wheat flour tortillas were less firm and more extensible compared with staled tortillas and that subjective rollability scores correlated significantly with the two-dimensional extensibility parameters.

The objective bending test detected differences in tortillas of different ages (Table III). Some parameters (i.e., force at 1 mm, modulus, and work at 1 mm) detected significant differences between fresh and 1-day-old tortillas, while others (i.e., force, distance, and work) did not. Rheological parameters measured from this test did not significantly correlate with subjective rollability or consumer panel staleness scores (Table II). In contrast, Suhendro et al (1999b) detected texture changes in corn tortillas during ageing using the bending test. Parameters of the bending test correlated significantly with subjective rollability scores. The objective puncture test detected texture changes in flour tortillas during storage (Table III). Some parameters from this test (rupture

**TABLE I**  
Changes in Subjective Textural and Sensory Properties of Flour Tortillas During Storage at 22°C<sup>a</sup>

Subjective Parameters	Storage Time (days)			
	0	1	8	15
Rollability score <sup>b</sup>	5.0a	4.9b	4.8bc	4.6c
Expert panel <sup>c</sup>				
Bending	10.7b	13.0a	9.3b	7.6b
Rollability	15.0a	15.0a	12.7b	12.3b
Extensibility	11.1a	11.3a	7.2b	6.4b
Pliability	14.5a	15.0a	10.0b	9.9b
Hardness	6.5ab	6.0a	7.1b	6.9b
Cohesiveness	7.4a	7.4a	6.9a	6.8b
Fracturability	1.4ab	1.0a	1.7b	1.8b
Acidic odor	1.1a	1.0a	1.1a	1.2b
Sweet taste	0.9a	1.0a	1.0a	0.9a
Sour taste	1.2a	1.1a	1.4b	1.4b
Bitter taste	1.0a	1.0a	1.3b	1.2b
Staleness	1.0a	1.1a	7.7b	9.1c
Consumer panel <sup>d</sup>				
Stretchiness	6.1a	4.4a	2.3b	2.0b
Acceptability	6.6a	6.3a	3.7b	2.6b

<sup>a</sup> Values followed by the same letter in the same row are not significantly different ( $P \leq 0.05$ ).

<sup>b</sup> Rated from 1 (unrollable, breaks easily) to 5 (rolls easily without cracking).

<sup>c</sup> Expert panel scores on a 15-point scale (see Fig. 1).

<sup>d</sup> Consumer panel scores on a 10-point scale (see Fig. 2).

force, modulus, and work at 1 mm) detected changes in tortilla texture between 0 and 1 day, 1 and 5 days, and 5 and 12 days of storage. Most of the other rheological tests were unable to differentiate these textural changes. Many puncture test parameters correlated significantly with subjective rollability and staleness scores (expert and consumer sensory panels). Perry et al (2003) measured differences in texture of cookies with different formulations using the puncture test but found significant correlations only between sensory attributes and the area under the force-distance curve and not with the other puncture test parameters.

The stress relaxation parameters of initial force, final force, initial stiffness, and final stiffness increased with tortilla age (Table III). Initial and final stiffness correlated significantly with subjective rollability and staleness scores (expert and consumer panels) (Table II). Limanond et al (2002) used stress relaxation measurements to quantify degree of staling in corn tortillas and

they found significant correlations between stiffness, tortilla age, and subjective rollability score.

### Subjective vs. Objective Methods of Tortilla Evaluation

Tortilla texture measured by objective rheological parameters changed rapidly from 0 to 5 days of storage, after which the rate of change dramatically decreased, thus progressing in a logarithmic manner. In contrast, the rates of change in tortilla attributes measured by the sensory panels progressed in a linear manner because the sensory panels (expert and consumer) did not detect significant changes between fresh (0 day) and 1-day-old flour tortillas. Therefore, objective rheological parameters had higher correlation coefficients with the logarithmic age of tortillas (Table II). Fresh tortillas had soft and extensible texture with low force values required to rupture or puncture, low moduli of defor-

TABLE II  
Pearson's Correlation Coefficients<sup>a</sup> of Physical and Sensory Parameters of Flour Tortillas

Rheology and Sensory Parameters	Age (days)			
	Linear	Log	Expert Staleness	Rollability Score <sup>b</sup>
One-dimensional extensibility				
Rupture force (N)	<b>0.81</b>	<b>0.98</b>	<b>0.82</b>	<b>-0.82</b>
Rupture distance (mm)	-0.68	<b>-0.92</b>	-0.68	0.66
Rupture work (Nm)	-0.71	<b>-0.93</b>	-0.70	0.68
Force at 2 mm (N)	0.79	<b>0.98</b>	0.79	<b>-0.80</b>
Modulus (N/mm)	0.63	<b>0.90</b>	0.64	-0.61
Work at 2 mm (Nm)	<b>0.84</b>	<b>0.99</b>	<b>0.86</b>	<b>-0.83</b>
Two-dimensional extensibility				
Rupture force (N)	<b>0.91</b>	<b>0.91</b>	<b>0.88</b>	<b>-0.96</b>
Rupture work (Nm)	<b>0.91</b>	<b>0.89</b>	<b>0.87</b>	<b>-0.96</b>
Force at 2 mm (N)	<b>0.88</b>	<b>0.85</b>	<b>0.85</b>	<b>-0.96</b>
Modulus (N/mm)	<b>0.84</b>	<b>0.90</b>	<b>0.84</b>	<b>-0.93</b>
Work at 2 mm (Nm)	<b>0.89</b>	<b>0.95</b>	<b>0.92</b>	<b>-0.88</b>
Bending				
Force (N)	0.79	<b>0.92</b>	<b>0.84</b>	-0.76
Distance (mm)	-0.45	-0.61	-0.55	0.34
Work (Nm)	0.75	<b>0.92</b>	0.76	-0.74
Force at 1 mm (N)	0.52	0.77	0.60	-0.45
Modulus (N/mm)	<b>0.80</b>	<b>0.92</b>	<b>0.85</b>	-0.77
Work at 1 mm (Nm)	0.76	<b>0.90</b>	<b>0.82</b>	-0.73
Puncture				
Rupture force (N)	<b>0.91</b>	<b>0.96</b>	<b>0.91</b>	<b>-0.83</b>
Rupture distance (mm)	<b>-0.83</b>	<b>-0.97</b>	<b>-0.82</b>	<b>0.81</b>
Rupture work (Nm)	0.14	-0.22	0.12	-0.05
Force at 1 mm (N)	<b>0.98</b>	<b>0.96</b>	<b>0.97</b>	<b>-0.95</b>
Modulus (N/mm)	<b>0.96</b>	<b>0.98</b>	<b>0.95</b>	<b>-0.94</b>
Work at 1 mm (Nm)	<b>0.95</b>	<b>0.98</b>	<b>0.96</b>	<b>-0.91</b>
Stress relaxation				
Initial force (N)	<b>0.88</b>	<b>0.98</b>	<b>0.86</b>	<b>-0.89</b>
Final force (N)	0.13	0.49	0.21	-0.07
Initial stiffness (N/m <sup>2</sup> )	<b>0.96</b>	<b>0.98</b>	<b>0.97</b>	<b>-0.94</b>
Final stiffness (N/m <sup>2</sup> )	<b>0.94</b>	<b>0.98</b>	<b>0.94</b>	<b>-0.91</b>
Energy dissipated (kJ/m <sup>2</sup> )	-0.64	<b>-0.87</b>	-0.63	0.61
Expert panel <sup>c</sup>				
Bending	<b>-0.97</b>	<b>-0.87</b>	<b>-0.97</b>	<b>0.96</b>
Rollability	<b>-0.90</b>	-0.70	<b>-0.92</b>	<b>0.80</b>
Extensibility	<b>-0.97</b>	<b>-0.93</b>	<b>-0.97</b>	<b>0.97</b>
Pliability	<b>-0.98</b>	<b>-0.85</b>	<b>-0.99</b>	<b>0.96</b>
Hardness	<b>0.93</b>	<b>0.85</b>	<b>0.92</b>	<b>-0.99</b>
Cohesiveness	-0.79	<b>-0.87</b>	-0.78	<b>0.87</b>
Fracturability	0.64	0.32	0.63	-0.71
Acidic odor	0.69	0.36	0.63	-0.62
Sweet taste	-0.09	0.21	-0.01	0.12
Sour taste	0.90	0.74	<b>0.92</b>	<b>-0.85</b>
Bitter taste	0.89	0.79	<b>0.89</b>	<b>-0.94</b>
Consumer panel <sup>d</sup>				
Stretchiness	<b>-0.94</b>	<b>-0.92</b>	<b>-0.95</b>	<b>0.98</b>
Acceptability	<b>-0.95</b>	<b>-0.83</b>	<b>-0.94</b>	<b>0.98</b>

<sup>a</sup> Correlation coefficients in bold type are significant at  $P = 0.05$ .

<sup>b</sup> Rated from 1 (unrollable, breaks easily) to 5 (rolls easily without cracking).

<sup>c</sup> Expert panel scores on a 15-point scale (see Fig. 1).

<sup>d</sup> Consumer panel scores on a 10-point scale (see Fig. 2).

mation, and longer distances of extension before the deformation. In contrast, stale tortillas were harder, as indicated by higher force values, had higher moduli of deformation, and shorter distances of extension before deformation (Table III). The objective bending method was the least sensitive of the objective rheological techniques in detecting changes in tortilla texture during storage.

The rheological and sensory parameters used to evaluate the changes in tortilla properties during storage correlated with time and with each other (Table II). Objective rheological parameters had higher correlation coefficients with logarithmic age than the arithmetic age of tortillas. This corresponds to the rapid changes in texture measurements from 0 to 5 days and then much smaller changes afterwards. This may be related to the rapid crystallization of amylopectin during the initial day of storage of flour tortillas as suggested by Seetharaman et al (2002). In contrast, subjective sensory parameters correlated at the same level of significance with both the arithmetic and logarithmic age of tortillas. Rheological techniques were more sensitive to textural changes than sensory evaluation, especially during the early stages of staling. Thus, rheological techniques maybe useful to determine and understand the mechanisms involved in the staling phenomenon.

All of the parameters measured by the two-dimensional extensibility test and some of the parameters of the puncture and stress relaxation tests significantly correlated with tortilla age, logarithmic age, expert panel staleness, consumer panel staleness, and subjective rollability score (Table II). On the other hand, most of the parameters from the one-dimensional extensibility and bending tests did not correlate significantly with those of the other tests (Table II). This may explain why Bejosano and Waniska (2004) found that one-dimensional extensibility measurements did not differentiate between tortillas leavened with various types and

grades of leavening base, while the subjective rollability test detected differences between treatments.

Except for tortilla fracturability, all the parameters measured by the expert sensory panel correlated significantly with the other parameters. The overall tortilla sensory attributes (texture, taste, and general acceptability) significantly correlated with storage time (Table II). Sensory attributes of flour tortilla obtained from the consumer panel correlated significantly with many rheological parameters (subjective and objective) of flour tortillas during storage. This shows that, if done properly, a consumer panel can be as useful as an expert panel in determining changes in tortilla attributes during storage.

Cronbach's alpha (Santos 1999) was used to select parameters within each test that give the most reliable and consistent response. In the objective rheological methods, the distance parameter was consistently rejected by the Cronbach's test, whereas, in the subjective test parameters (combined subjective rollability, expert, and consumer panel scores) it retained all the texture attributes but not staleness scores (Table IV). This is because textural changes are only partially responsible for staleness. Sensory perception of staleness is an overall combination of texture, taste, and odor attributes.

Factor analysis was done on the combined objective and subjective tests parameters that were retained by the Cronbach's test (Table IV). This will indicate whether subjective texture test parameters are parallel to those of objective rheological tests. Principal component factor analysis grouped most of the sensory and rheological parameters in one cluster (Factor 1). This cluster appears to be measuring tortilla texture that relates to hardness and stiffness. The evaluation methods in this cluster include two-dimensional extensibility, subjective rollability, expert and consumer sensory panels, puncture, and stress relaxation tests. None of the

**TABLE III**  
Changes in Objective Rheological Properties of Flour Tortillas During Storage at 22°C<sup>a</sup>

Rheological Parameter	Storage Time (days)					
	0	1	5	8	12	15
<b>One-dimensional extensibility</b>						
Rupture force (N)	3.67a	5.04b	6.79c	7.35c	7.17c	7.03c
Rupture distance (mm)	13.56a	4.40b	2.32c	2.01cd	1.90d	1.85d
Rupture work (Nm)	38.68a	17.54b	12.69c	12.03cd	11.22cd	1.46d
Force at 2 mm (N)	1.89a	4.33b	6.67c	7.29c	7.03c	6.91c
Modulus (N/mm)	0.66a	1.37b	1.72c	1.67bc	1.67bc	1.56bc
Work at 2 mm (Nm)	2.45a	6.16b	10.56c	10.87c	11.68c	11.58c
<b>Two-dimensional extensibility</b>						
Rupture force (N)	0.96a	1.02a	2.12b	2.94bc	2.41bc	3.31c
Rupture work (Nm)	2.55a	2.43a	4.88b	7.08bc	5.70bc	7.80c
Force at 2 mm (N)	0.19a	0.16a	0.28b	0.44bc	0.35b	0.45c
Modulus (N/mm)	0.03a	0.04ab	0.05b	0.08c	0.07bc	0.07bc
Work at 2 mm (Nm)	0.04a	0.05a	0.06ab	0.08b	0.08b	0.07b
<b>Bending</b>						
Force (N)	0.15a	0.21a	0.37b	0.38b	0.47b	0.35b
Distance (mm)	5.63a	5.18a	4.92a	5.25a	4.39a	5.29a
Work (Nm)	0.57a	0.71a	1.53b	1.41b	1.35b	1.40b
Force at 1 mm (N)	0.04a	0.11b	0.21bc	0.15b	0.22bc	0.13b
Modulus (N/mm)	0.05a	0.10b	0.16b	0.16b	0.21b	0.15b
Work at 1 mm (Nm)	0.07a	0.11b	0.21cd	0.21cd	0.28cd	0.19c
<b>Puncture</b>						
Rupture force (N)	1.01a	1.18b	1.42bc	1.33b	1.49c	1.57c
Rupture distance (mm)	3.81a	2.86b	2.57b	2.40b	2.30bc	2.17c
Rupture work (Nm)	1.63a	1.45ab	1.52ab	1.44b	1.51ab	1.62ab
Force at 1 mm (N)	0.25a	0.49b	0.66bc	0.83cd	1.00d	1.16d
Modulus (N/mm)	0.15a	0.33b	0.44bc	0.55cd	0.63d	0.72d
Work at 1 mm (Nm)	0.16a	0.34b	0.47c	0.54cd	0.68d	0.69d
<b>Stress Relaxation</b>						
Initial force (N)	2.14a	4.54b	6.37c	7.52cd	6.84c	8.57d
Final force (N)	1.06a	2.67c	2.58c	2.06b	2.58c	1.47a
Initial stiffness (N/m <sup>2</sup> )	0.55a	1.15b	2.20c	2.66c	3.26cd	3.34d
Final stiffness (N/m <sup>2</sup> )	0.53a	1.57b	2.66c	2.59c	3.15cd	3.24d

<sup>a</sup> Values followed by the same letter in the same row are not significantly different ( $P \leq 0.05$ ).

TABLE IV  
Results of Factor Analysis of Rheological and Sensory Properties of Tortillas During Storage<sup>a</sup>

Parameters	Alpha <sup>b</sup>	Factor 1	Factor 2
One-dimensional extensibility	0.88		
Rupture force (N)		0.67	0.69
Force at 2 mm (N)		0.64	<b>0.73</b>
Modulus (N/mm)		0.42	<b>0.87</b>
Work at 2 mm (Nm)		0.69	0.68
Two-dimensional extensibility	0.62		
Rupture force (N)		<b>0.89</b>	0.31
Rupture work (Nm)		<b>0.90</b>	0.27
Force at 2 mm (N)		<b>0.90</b>	0.21
Modulus (N/mm)		<b>0.81</b>	0.44
Bending	0.75		
Force (N)		0.64	0.69
Work (Nm)		0.62	0.65
Force at 1 mm (N)		0.30	<b>0.86</b>
Modulus (N/mm)		0.64	0.69
Work at 1 mm (Nm)		0.60	<b>0.70</b>
Puncture	0.90		
Rupture force (N)		<b>0.74</b>	0.53
Rupture work (Nm)		0.26	<b>-0.73</b>
Force at 1 mm (N)		<b>0.87</b>	0.38
Modulus (N/mm)		<b>0.85</b>	0.45
Work at 1 mm (Nm)		<b>0.81</b>	0.51
Stress relaxation	0.84		
Initial force (N)		<b>0.77</b>	0.53
Final force (N)		-0.12	<b>0.95</b>
Initial stiffness (N/m <sup>2</sup> )		<b>0.85</b>	0.47
Final stiffness (N/m <sup>2</sup> )		<b>0.80</b>	0.52
Rollability score <sup>c</sup>		<b>-0.95</b>	-0.20
Expert panel <sup>d</sup>	0.81		
Bending		<b>-0.94</b>	-0.19
Rollability		<b>-0.81</b>	-0.08
Extensibility		<b>-0.91</b>	-0.33
Pliability		<b>-0.94</b>	-0.16
Hardness		<b>0.94</b>	0.18
Cohesiveness		<b>-0.73</b>	-0.48
Fracturability		<b>0.80</b>	-0.44
Consumer panel <sup>e</sup>			
Stretchiness		<b>-0.91</b>	-0.34
Explained variation		18.02	9.13
Proportion total (%)		58	29

<sup>a</sup> Loadings of rotated factors, significant factors (>0.70) are in bold type. Loadings are interpreted as the correlation between each variable and the factor. Higher loadings (absolute value) indicate that the variable shares more variance with that factor. The sign of the loading determines the direction of the relationship of each variable to the factor.

<sup>b</sup> Cronbach's alpha of parameters within each evaluation method.

<sup>c</sup> Rated from 1 (unrollable, breaks easily) to 5 (rolls easily without cracking).

<sup>d</sup> Expert panel scores on a 15-point scale (see Fig. 1).

<sup>e</sup> Consumer panel scores on a 10-point scale (see Fig. 2).

parameters from the one-dimensional extensibility and bending tests were in this cluster.

## CONCLUSIONS

The most suitable rheological methods to analyze textural changes in tortillas during storage are the two-dimensional extensibility, puncture, and stress relaxation tests. Tortilla staling is a function of time and its textural manifestations can be suitably measured by the subjective rollability test, sensory evaluation, and the objective texture measurements using the two-dimensional extensibility, puncture, and stress relaxation methods.

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