Characterization of facial tissue softness

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ABSTRACT: Tissue softness is one of the most consumer-desired properties, but quantifying that quality is challenging. Softness is a multidimensional perception that includes sight, sound, and touch. It is believed that the sensation of softness is influenced by surface and bulk softness. This study systematically investigated the effects of various tissue physical properties contributing to human tactile sensation of facial tissue. We developed a three-parameter softness model based on the cross direction-to-machine direction tensile ratio, surface arithmetic roughness, and average elastic modulus. The model was able to predict facial tissue softness for traditional commercial creping technology; however, it does not predict well on tissue softness scores for through-air-drying samples.

Application: This model, coupled with enabling technologies, opens the possibility of development of on-line softness monitoring capabilities.

The tissue market worldwide is estimated to be US$ 17 billion, and is extremely competitive, which leads to continued efforts to improve the tissue product quality. Among these properties, softness is considered the most consumer-desired property [1]. Tissue softness has been extensively studied by the tissue industry [2-4], however, quantitative characterization of tissue softness is challenging. The most accurate method to evaluate softness to date is still the "panel" test.

Although quantitative prediction of tissue softness is difficult, we've learned a lot about the factors that affect tissue softness. Tissue softness is a complex function of various physical and psychological interactions [5, 6]. It is believed that the sensation of softness is influenced by surface and bulk softness [7, 8]. Surface softness is the softness perception generated when the customer gently brushes his or her fingertips over the tissue surface. Bulk softness is the perception of softness they feel when they crumple the tissue sample in their hands. Softness is a multidimensional perception [9, 10] that includes sight, sound, and touch [11]. In practice, however, research on characterizing softness usually focuses on the study of important factors affecting human tactile sensations [6].

From previous research, properties such as tissue bulk or thickness, compressibility, modulus, and surface texture have been correlated to softness sensation. A bulkier sheet usually seems to feel softer, as long as other properties remain the same. Compressibility (the ratio of the bulk measured at a lower vs. a higher pressure [12]) is a measure of the tissue cushion [13]. It is generally believed that tissue stiffness is inversely related to tissue softness [7, 8, 14]. Stiffness could be described in terms of Young's modulus and tensile strength. In general, at the same breaking elongation, tissue with low Young's modulus also has low tensile strength. Tissue surface texture also plays an important role in human tactile sensation. Numerous free fiber ends protruding from the tissue surface could simulate the velvety surface of cloth, giving the customer the sense of surface softness [15]. Stylus profilometry is commonly used to study tissue surface texture. Various authors have defined factors that significantly contribute to tissue softness [14-18].

Quantitative models that relate softness to these properties are rare. A good softness model would help quality control efforts and reinforce subjective ("panel") testing. Existing models usually lack predictive power because they are not tissue-grade specific. Customers also tend to evaluate tissue properties differently for different tissue grades [19]. In this study, we had two goals:

1. To quantitatively determine the effect of individual physical property on softness of facial tissue
2. To develop a softness model specifically for facial tissue made by creping technology.

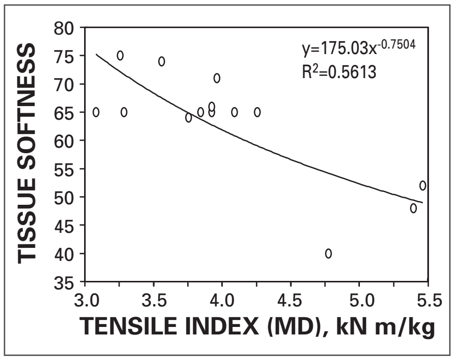
EXPERIMENTAL

We used 14 facial tissue samples made by creping technology for the softness model development and used another five samples to test the model validity. The tissue samples remained in a conditioning room overnight per TAPPI 402 om-88. The softness evaluation and physical property tests were performed under standard testing conditions.

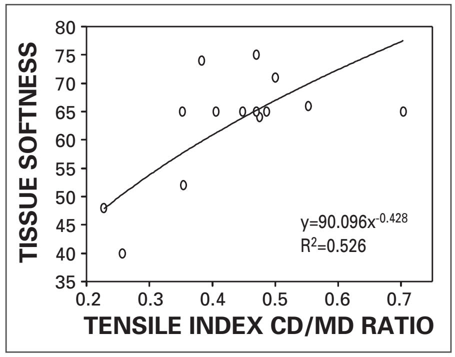
An experienced panelist evaluated the softness of each labeled tissue sample using a "direct comparison" method. Standard tissue samples were carefully selected and evaluated, and softness scores from 0 to 100 were assigned. Then, two folded pads of tissue samples were prepared; the standard sample with known softness score, and the tissue sample to be tested. The panelist determined the softness by holding each pad on their fingers with the thumb being pressed down on the sample and simultaneously brushing it over the sample surface. The panelist then compared the test sample to a series of standard tissue samples. If the panelist sensed that the test sample was softer than the tissue standard with the softness of X, but was harsher than the tissue standard with a score of Y, the test sample was assigned a softness score between X and Y. The softness perception generated could be considered to be a surface softness. In practice, the effects of surface and bulk on softness sensation cannot be entirely separated; it is probably a combination of bulk and surface softness.

The softness score for each sample was the average of five softness evaluations. All samples were preconditioned in the same way before taking measurements the same day. The experienced panelist results were corroborated by having several students make the same direct comparison tests.

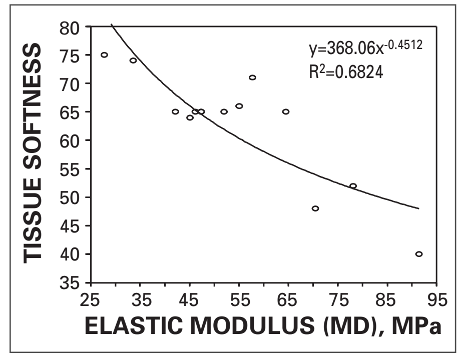
We tested most physical properties in machine direction (MD) and cross direction (CD). Tensile strength and Handle-O-Meter



1. The correlation of tissue softness with the tensile index in the machine direction. R^2*=0.5613.*



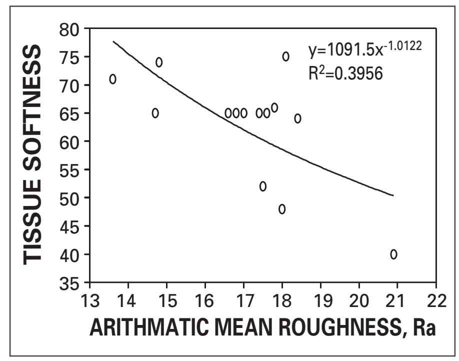
2. The correlation of tissue softness with the tensile strength ratio in the machine direction. R^2*=0.526.*



3. The power law correlation of tissue softness with elastic modulus in the MD; R^2*=0.6824.*

Tissue properties	B (Corr. #)	K (Corr. #)	$R^2_{(adj)}$,%	F (Stat. #)	P (Stat. #)
Tensile index (MD), N m/g	51.6	-0.75	52.5	15.35	0.002
Tensile index (CD), N m/g	0.298	3.98	7.2	2.01	0.182
Mean tensile index, N m/g	5.16	-1.50	52.5	15.35	0.002
CM, Tensile index CD/MD ratio	4.50	0.428	48.7	13.32	0.003
Elastic modulus(MD), MPa	5.91	-0.451	65.6	25.78	0.000
Elastic modulus (CD), MPa	4.53	-0.093	0.0	0.81	0.387
Mean elastic modulus, MPa	5.32	-0.290	26.0	5.56	0.036
Elastic modulus ratio	4.09	-0.139	4.3	1.59	0.231
Tensile stiffness, N/m	6.24	-0.284	15.1	3.32	0.093

I. Correlation between measured physical properties and softness ranking.



4. The power law correlation of tissue softness with arithmetic mean roughness.

testing followed the TAPPI test method (T498-cm 85).

The tissue surface profile was evaluated with a Hommelwerke LV-50 Surface Profilometer (Alte Tuttlinger, Western Germany) equipped with a TKL300-3312 diamond probe with the diameter of 5 µm. The probe velocity was set to 1 mm/s, and the maximum height was 300 µm. The total scanned distance was 48 mm. The tissue surface profile data were collected and analyzed using the Turbo Roughness for Windows 2.17a software package. The sample was placed on the Hommelwerke LV-50 scanning block, and the tissue sample surface was kept tight and free of waviness. We manually positioned the probe by adjusting the screw until the probe altitude value was between –7 µm and +7 µm.

The coefficients of friction (COF) of tissue samples, with plies unaltered, were measured using Amontons I (Mu Measurement, Madison, Wisconsin). Both the table and sled were covered with a soft, foam rubber backing material to reduce potential effects on paper sample friction. A 2 in x 2 in sample was placed on the table facing up. An equal size sample was placed on the sled facing down. A normal force was applied with the sled sample on the table sample, and a COF measurement was taken to evaluate the friction between the samples. We took 10 measurements for each sample.

Tissue thickness was measured using an electronic thickness tester (capable of measuring thickness at various pressures) with a pressure foot 5.08 cm in diameter (Model 89-100, Thwing-Albert Instrument Company, Philadelphia, Pennsylvania, USA). The lowest measurement pressure was 0.689 kPa. We increased the pressure by increments of 0.48 kPa up to 3.571 kPa. We used a TAPPI standard micrometer (E. J. Cady Co., Wheeling, Illinois) to measure the thickness of tissue samples at 50 kPa. Then we determined the ratio of thickness at low pressure to the one at 50 kPa loading, which reflects the compressibility of the tissue sample.

Thermal conductivity of tissue samples was measured with a thermal conductivity probe (Mathis Instruments Ltd., Fredericton, New Brunswick, Canada). The test time was set at 30 seconds (s) and sampling frequency was set at 10 Hz. After testing, the sample's thermal bulk value (square root of the product of thermal conductivity, density, and heat capacity) was calculated. The instrument was set to cool for 10 min. We performed five repetitions for each tissue sample.

RESULTS AND DISCUSSION

In this study, we performed a power law regression between tissue softness and physical properties. A power law model was previously used to correlate tissue properties with subjective bulk softness [8]. We assumed that the power relationship exists between softness S and n tissue physical properties (x_1 …xn), as shown in Eq. 1. Taking the logarithm of both sides of Eq. 1 led to Eq. 2:

$$S = a\prod_{i=1}^{n} x_i^{k_i} \quad (1)$$

$$\ln(S) = b + \sum_{i=1}^{..} k_i \ln(x_i) \quad (2)$$

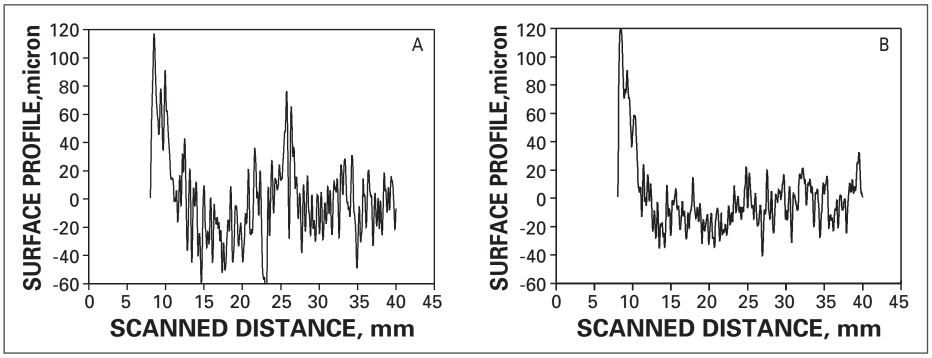
Where S is the panel softness score, x_i is the measured tissue physical property, k_i

is the exponent of x_i by regression, and a and b are the constants in the regression relationship.

The physical properties that showed statistically significant correlation with the subjective softness score were then considered in the multivariable model formation. **Table I** shows the correlation results of softness with tissue strength properties. Tensile index was used to exclude the effect of basis weight variation. Because of the difficulties in normalizing the softness and elastic modulus, we did not attempt to adjust these values. **Figures 1–3** show the correlation of tissue softness with MD tensile index, tensile strength ratio, and MD elastic modulus, Eavg, respectively. The mean elastic modulus was also significant in correlating with softness with F value 5.56 (p-value <0.05). Those results are purely the mathematical correlation and do not consider any mechanistic theory.

In this study, the softness correlation with tensile stiffness was poor (R^2 of 15.1%). Previous studies have shown a high degree of correlation of tensile stiffness with bulk softness of tissue and towel [8]. Our study did not specifically determine a bulk softness score; therefore, we can not anticipate the correlation with the bulk softness of the tissue samples. However, this suggests that surface softness plays an important role in the tactile sensation of tissue products. The underlining reasoning is that the softness scores the panelist measured were some combination of bulk and surface softness. The perception of softness is thought to be a strong function of surface softness. That has a different effect on the perceived softness than bulk softness alone, so this perceived softness does not correlate with tissue stiffness. Perhaps another reason why tissue softness does not correlate well with tensile stiffness is that tensile stiffness is not a fundamental mechanical property, but simply an indication of one (elastic modulus).

Next, we examined the surface texture properties of the tissue samples. The total scanned distance was 48 mm, and the data on the first and last 8 mm of each scan was discarded. The profile was treated with a second order digital elliptic filter with data below 13 Hz and above 82 Hz removed, 0.5 B of ripple in the pass band and 40 B of attenuation in the stop band. For each tissue profile, the arithmetic mean roughness, R_a (μm) and the root mean square roughness, R_q (μm) were computed using Eqs. 3 and 4, respectively:



5. Facial tissue surface profiles with filtering treatment: (A) The softness of the sample was 40; (B) The softness score was 71.

$$R_a = \frac{1}{l_m}\int_0^{l_m} |z(x)| dx \qquad (3)$$

$$R_q = \sqrt{\frac{1}{l_m}\int_0^{l_m} z^2(x) dx} \qquad (4)$$

Where L_m is the scanned distance, μm, $Z(x)$ is the adjusted z direction amplitude (deviation from the least-square fit mean line of data).

The R_a and R_q values of the tissue samples were used to correlate with the tissue softness. **Figures 3 and 4** give the power function correlation results. **Figures 5A and 5B** show the filtered profiles of two tissue samples. The profile of the sample with a softness score of 40 had larger height differences between the peaks and valleys than did the other sample with a softness score of 71. The feature differences between tissue profiles were reflected in the quantities, such as R_a and R_q. Within the range of R_a and R_q, the tissue softness score decreased with the increase of surface roughness values (Fig. 4).

The static coefficient of friction, μ, is defined as the ratio of the frictional force, f, to the normal force, N, asserted to the tissue sample by the measuring arm:

$$\mu = \frac{f}{N} \qquad (5)$$

The static coefficient of friction was irrelevant to the softness score, probably for two reasons. First, the normal force applied by Amontons I was 700 grams-force (about 6.865 N). The applied pressure by the sled on the tissue sample was about 2.66 kPa. This pressure might not be the optimum pressure to measure the coefficient of friction. Second, the measurement of static friction coefficient could not reflect the relative displacement between the finger and the sample that usually occurs in the customer evaluation process. In fact, this study agreed with a previous study where the static aspects of mechanical stimulus could not be related with the tactile sensations [20].

The concept of critical slope could also be used to explain the results. Critical slope is the minimum rate of displacement that would produce a neural response. Studies have shown the critical slope of smooth monkey skin ranged from 0.08 mm/s to 3.5 mm/s [21]. As the displacement rate decreased toward the critical slope, the displacement thresholds increased exponentially. The dynamic coefficient of friction might be more relevant in the softness prediction.

Traditionally, the tissue industry relies on the Handle-O-Meter to quantify softness. The Handle-O-Meter measures the combined effects of flexibility and surface friction of sheeted materials. Tests are quickly accomplished by placing the test sample over a slot that extends across the instrument platform. The slot opening is adjustable to easily accommodate a variety of materials. A penetrator beam then pivots on a cam, engages the sample and forces it in to the slot. The resistance encountered by the penetrator beam as it moves into the slot is measured. Stiff materials offer greater resistance to the motion of the beam as it moves into the slot. Rough materials also

Properties	B (Corr. #)	K (Corr. #)	$R^2_{(adj)}$,%	F (Stat. #)	P (Stat. #)
B_0 (0.687 kPa)	2.20	0.424	13.9	3.09	0.104
B_1 (1.168 kPa)	2.21	0.429	14.9	3.27	0.096
B_2 (1.648 kPa)	2.24	0.428	14.1	3.13	0.102
B_3 (2.129 kPa)	2.31	0.414	12.5	2.85	0.117
B_4 (2.610 kPa)	2.32	0.415	11.8	2.74	0.124
B_5 (3.091kPa)	2.38	0.405	10.4	2.51	0.139
B_6 (3.571kPa)	2.54	0.370	7.7	2.09	0.174
B_f (50.0 kPa)	2.76	0.342	3.9	1.53	0.24
B_0/B_f (0.687 kPa)	3.05	1.98	24.6	5.23	0.041
B_1/B_f (1.168 kPa)	3.01	2.41	35.7	8.21	0.014
B_2/B_f (1.648 kPa)	3.17	2.30	29.8	6.51	0.025
B_3/B_f (2.129 kPa)	3.23	2.37	25.9	5.55	0.036
B_4/B_f (2.610 kPa)	3.29	2.39	22.4	4.76	0.050
B_5/B_f (3.091 kPa)	3.15	3.00	23.3	4.95	0.046
B_6/B_f (3.571 kPa)	3.36	2.57	11.3	2.65	0.129

II. The correlation results of tissue softness with bulk and compressibility factors.

exert resistance as they are dragged over the edge of the slot.

We investigated the correlation significance of Handle-O-Meter values in both MD and CD in this study. Generally, tissue with higher flexibility or a coarser surface usually yields higher values. The ratios of MD to CD Handle-O-Meter values (H_{MD}/H_{CD}) and their combined average were also evaluated. The CD Handle-O-Meter values were more sensitive (with the adjusted R^2 of 46.1 and P value <0.05) to the softness than those at the machine direction.

Next, compressibilities of the tissue samples were determined. The correlation results in **Table II** show that tissue thickness values measured at all pressures except at 1.168 kPa failed to contribute to tissue softness in a significant way. The tissue thickness measured at 1.168 kPa is the most statistically significant as it has the lowest P-value. The thickness values measured at higher pressures were less relevant to tissue softness (i.e. decreasing correlation coefficients and P values). The compressibility is defined in Eq. 6, and describes thickness changes versus thickness measurement pressures:

$$Compressibility = \frac{T_i}{T_f} \qquad (6)$$

Where T_i is the thickness value measured at P_i, T_f is the thickness measured at 50 kPa.

High compressibility value indicates high tissue deformability, or tissue cushion. Table II seems to suggest that 1.168 kPa is the more relevant pressure for facial tissue bulk and compressibility measurement as a predictor of softness value. Under normal use, the pressure on a paper towel to wipe water is about 1.380 kPa. Facial tissue was handled at a pressure of no more than 3.447 kPa [6]. We based the selection of bulk measurement pressure for this study on tissue application conditions, while the pressures used in a previous study were out of the range [22]. The poor correlation of tissue softness with compressibility is probably because measurement pressure was unreasonable high. When the loading pressure is 50 kPa, the thickness differences between samples are reflecting the basis weight.

We also measured the thermal conductivity of the tissue samples. A heat capacitor of 32°C was put in contact with one side of the tissue. The condition for the other side of the tissue was treated as being thermally insulated. We used Eq. 7 to calculate the thermal flux at time t:

$$q = \frac{24k}{a}\sum_{n=1}^{\infty}\exp\left[-\frac{(2n-1)^2\pi^2}{4a^2}kt\right] \qquad (7)$$

For each sample, we calculated the thermal flux q at 0.2 s, 1 s, 1.5 s, 2 s, 3 s, 5 s, and 10 s using Eq. 7. The thermal flux at times greater than 10 s is not of practical use, and was not considered here. The correlation using the power relationship was determined. High thermal flux would correspond to the feeling of low tissue temperature or "coolness," and vice versa. The thermal flux was considered because the thermal condition of the panelist's hands and the tissue samples is believed to contribute to the overall perceived softness. The adjusted R^2 at all time intervals were less than 8.4%, the F values were less that 2.20, and the P values were >0.05, indicating that tissue softness is statistically independent of the thermal flux.

The above section presented the correlation results of individual tissue physical property with softness value, and discussed the effects of individual tissue property on softness. Multivariable regression techniques were used to construct empirical softness models with improved prediction capability. With two predictors (i.e., E_{avg} and CM), the accuracy of the model was greatly improved, and its adjusted correlation coefficient was 91.4%. By incorporating surface arithmetic roughness R_a, the adjusted coefficient of correlation further increased to 99.5%. The model's correlation was not significantly improved by adding the fourth predictor, CD Handle-O-Meter stiffness, H_{CD}.

The 2-predictor softness model takes the form shown in Eq. 8:

$$S = 354.25\left(\frac{CM}{E_{avg}^{0.706}}\right)^{0.463} \qquad (8)$$

The softness model predicted by three predictors, i.e., CM, E_{avg} and R_a, in Eq. 9:

$$S = 1164.4\left(\frac{CM}{R_a^{1.220}E_{avg}^{0.793}}\right)^{0.387} \qquad (9)$$

Figure 6 compares the softness values predicted by the 3-parameter models with the tissue softness scores given by the panelist. As mentioned before, we developed this model to predict the softness of conventional facial tissue. To test the model's validity, we selected five creped facial tissue samples that were not included in the model development and measured their physical properties. **Figure 7** shows the high degree of correlation between the softness scores by the model and those by the panelist, with an adjusted R^2 of 96%.

The model does not show strong predictive power with respect to through-air-drying (TAD) technology tissues, and rightly so, because the model was developed using tissue samples made by creping technology. Tissues made by through-air-drying technology have higher bulk and water absorbency, and lower strength, because the sheet is not significantly pressed [23].

Even if the same subjective softness scores were obtained from separate tissue samples made with these different technologies, that does not mean that the measured physical properties would be the same. We can conclude from Fig. 7 that for the TAD, the measured tensile index is greater, and/or the measured elastic modulus is lower, and/or the measured arithmetic mean roughness is greater. Generally speaking, at the same breaking elongation, tissue with low Young's modulus also has low tensile strength. TAD tissues are lower in strength compared to creped tissues; consequently, the measured elastic modulus is less. In previous studies, TAD tissue samples fail to fit into the relationship between bending stiffness or flexural rigidity and softness [8].

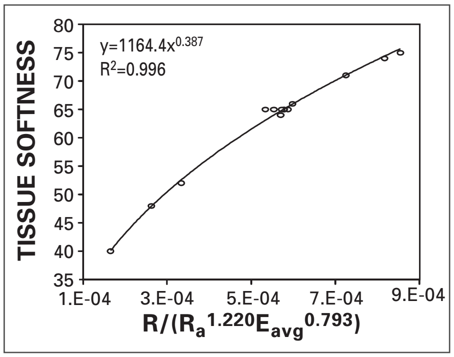
CONCLUSIONS

We have investigated the physical properties that contribute to human tactile sensation of conventional facial tissue extensively in this study. Our model attempts to correlate mechanical properties and surface properties. Tensile index at MD, elastic modulus (MD), the mean elastic modulus, and the CD Handle-O-Meter values had significant statistical correlation with tissue softness. Static coefficient of friction and thermal flux had no significant correlation with softness. We have developed a softness model based on the CD-to-MD tensile index ratio, arithmetic surface roughness, and the mean elastic modulus. This model can predict the softness of creped facial tissue with high accuracy. It does not predict softness scores for TAD samples well. More work is needed to further clarify the mechanistic meaning of *tissue softness*.

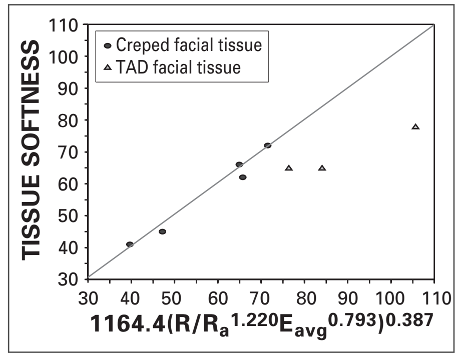
The facial tissue softness model, coupled with enabling technologies, such as acoustical and optical techniques [16, 22], opens the possibility of developing on-line softness monitoring capabilities. **TJ**

ACKNOWLEDGEMENT

The authors thank Julie Yoh for her support, Dennis Gunderson for tissue friction coefficient measurement, Bill Anderson for showing us how to apply profilometry to tissue samples, J. C. Chun for the expertise on digital signal processing, and Akpojotor Shemi for his assistance in revising the manuscript.



6. Comparison of tissue softness by the panelist and by the 3-parameter softness model.



7. Predictive power of the softness model; creped facial tissue samples were represented by ○, and the through-air-dried tissue samples were represented by △.

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Received: July 18, 2001
Accepted: November 25, 2003

This paper is also published on TAPPI's web site <www.tappi.org> and summarized in the April *Solutions! for People, Processes and Paper* magazine (Vol. 87 No. 4).

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