Determination of In-use Properties of Paper Towels

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For a hygiene paper such as tissue and towel, strength, softness, and absorbency are known as attributes that a user is looking for. It is proposed here that purchasing decisions are likely to be influenced by in-use experiences, which may be quite different from the physical properties measured with current standardized tests. There have been continuous efforts on developing physical test methods to replace subjective in-use tests because the benefits of the former are too significant to be overlooked. This paper considered some in-use test methods for paper towel products that can be carried out by panel members quickly in the course of sensory panel testing. In addition, laboratory tests were developed in an attempt to quantify such input. The sensory panel testing showed that (wet) strength and absorbency were the key contributions to the performance of paper towels. Softness did not show any significant contribution to it. Wet strength showed a high correlation with absorbency. The (wet) ball burst strength had the highest correlation with the in-use strength. Although both the tensile strength and the ball burst strength had a high correlation with preference, the ball burst tester is preferred because more reproducible and simpler to operate.

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INTRODUCTION

Paper towels, toilet tissue, and facial tissue are classified as hygiene paper products. Literature on these products is relatively scarce because they are usually treated as a trade-secret and protected as intellectual property. Nevertheless, it is generally accepted that strength, softness, and absorbency are the three key in-use attributes that consumers seek. Very few systematic studies exist in this area (Ramasubramanian 2002; Ko *et al*. 2018). Among the hygiene paper products, there is especially very little literature available on paper towel products.

It is important to realize that these in-use attributes may be quite different from the properties to be determined by physical measurement (Ko *et al*. 2017). It is highly desirable to develop physical test methods to replace subjective in-use attribute tests because the benefits would be too significant to be overlooked.

In developing a hygiene paper such as toilet tissue, facial tissue, and paper towel, it is necessary to obtain in-use properties that a user is looking for. Strength, absorbency, and softness (or hand-feel) are considered the key attributes for a hygiene paper although the degree of their importance may depend on the products.

It is critically important to realize that the in-use properties can be entirely different (or, even move in the opposite direction) from the physical properties because a product may be disposed well before it reaches an equilibrium (or maximum) stage. It is also important to realize that the in-use properties are dynamic, not static, requiring "contact testing" which induces structural changes. Therefore, both the subjective in-use properties and physical properties will depend on "testing conditions". This indicates that the physical test methods should be based on the subjective in-use properties that may be obtained from subjective tests (Ko and Park 2016; Ko *et al*. 2018; Lee *et al*. 2024).

Although very challenging, it is desirable to develop physical test methods to replace the subjective tests due to their outstanding benefits such as 1) cost effectiveness (*i.e.*, much cheaper than subjective testing), 2) time effectiveness (faster to complete the testing), 3) uses for quality and process control, and 4) guidance and direction to developing and improving product (Ko and Park 2016). The main object of this paper is to develop a set of test methods that can be used quickly by members of a panel to evaluate in in-use strength, softness, and absorbency to be used for predicting the corresponding in-use properties and ultimately replacing the subjective attributes of testing. A sensory panel, with application of a rating method, was used to obtain the in-use properties of commercial paper towel products. Their physical properties of strength, softness, and absorbency were also determined.

EXPERIMENTAL

Paper Towel Samples

Seven paper towel samples (sample codes: A, B, C, D, E, F, G) were tested for their in-use properties. Table 1 shows a list of the samples with physical properties.

Table 1. Physical Properties of the Seven Commercial Paper Towel Samples

Sample code	Sheet size (mm)		Basis weight (g/m^2)	Thickness (mm)	Density (g/cm^3)
	Width	Length			
A	149	279	53.7	0.29	0.19
B	139	279	52.2	0.30	0.17
C	114	221	41.1	0.15	0.27
D	116	223	37.4	0.16	0.24
E	114	235	43.2	0.18	0.24
F	114	227	40.3	0.15	0.27
G	120	223	40.0	0.16	0.24

Note: The number of plies in all samples was 2.

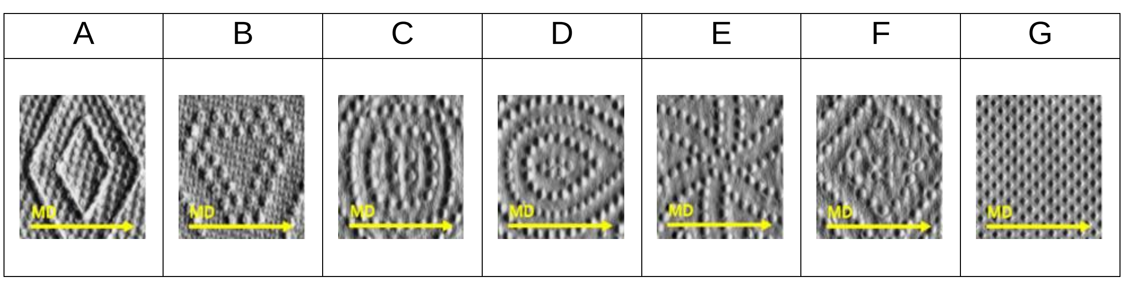

Fig. 1. Optical photographs of the paper towel samples

Optical photographs of the samples were captured using the Optitopo surface deviation (OSD, L&W, Sweden) apparatus. Because all products consisted of two plies, there was no discernible pattern variation in the optical images between the top and bottom layers of each sample. Consequently, only the top layer of each sample was utilized for assessing surface roughness and friction. Figure 1 depicts the top layers of the seven paper towel samples, with arrows indicating the machine direction (MD). It shows that all samples were embossed. Their surface textures were quite different, suggesting that the surface properties should depend on the embossing patterns.

Determination of the In-use Properties

The rating method by the sensory panel testing was used (Kim 1992; Ko *et al.* 2015). A total of 25 panelists participated, and each panelist was instructed to rate on a scale bar from 1(least) to 99(most) for each sample. The samples were prepared as follows: sample length, 220 mm; sample width, 110 mm; and wiping material, ketchup (1 g). The specific questions and instructions for testing in-use properties were as follows:

1. ***Softness:*** Feel the sample surface and rate it on a “scale bar” from 1 to 99.
2. ***Water absorbency:*** Drop 4 mL of water into each sample and rate it on from 1 to 99 on the following “scale bar”.
3. ***Wiping:*** Wet the sample with 4 mL of water, wipe off any ketchup on the test plate, and rate it on from 1 to 99 on the following “scale bar”.
4. ***Wet strength:*** Tear a sample soaked with 6 mL of water and rate wet strength on from 1 to 99 on the following “scale bar”.
5. ***Preference:*** Please rate overall preference for each paper towel rate it on from 1 to 99 on the following “scale bar”.

Physical Measurements

To test the physical properties of the paper towels, humidity control treatment was performed for more than 48 h under standard atmospheric conditions of temperature 23 ± 1 °C and relative humidity 50 ± 2% according to ISO 187 (1990).

Tensile Testing

A tensile tester from MTS, Eden Prairie, Minneapolis, USA (Criterion® Model 41) was used. The testing conditions are as follows according to ISO 12625-4 (2022): sample length, 150 mm; sample width, 50 mm; load cell, 50 N; span length, 75 mm; and strain rate, 12.5%/min. For each sample, 10 measurements were taken in the machine direction (MD) and cross-machine direction (CD). The geometric mean (GM) was also calculated by Eq. 1.

$$GM = \sqrt{(MD \times CD)} \quad (1)$$

Wet Tensile Testing – Wet Sponge Method

A wet sponge method was developed to measure wet tensile strength. In this method, after the sample was soaked with the wet sponge (size: 35cm x 25cm; thickness: 1 cm; density: 15 kg/m^3; material: polyurethane; Jeongan Sponge Co., Ltd., Korea) for 5 seconds, the excess water was removed from the sample by gently rolling the couch roll on the sample, as shown in Fig. 2. The wet tensile testing of the sample was carried out the same way as the dry tensile testing.

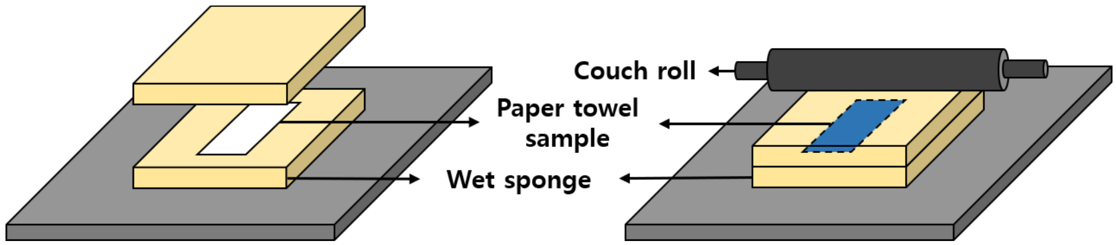

Fig. 2. Diagram of the wet sample production process using the sponge method

Absorbency Test – Amount of Retention

To measure water absorbency, the wet tensile test absorbency of each sample was measured using the wet sponge method. This method measures the water content after removing water above saturation during the process of gently rolling the couch roll. The formula is shown in Eq. 2.

$$\text{Absorbency (g/g)} = \text{(Wet weight-Dry weight)/Dry weight} \quad (2)$$

Ball Burst Testing

A ball burst tester from Universal Testing Machine (UTM), Shimadzu, Japan (Model AGX-V) was used. The test used a steel ball that has a 16 mm diameter, and during a ball burst test, the ball is pushed vertically against the sample until it bursts and the force-displacement values are recorded. The testing conditions are as follows according to ISO 12625-9 (2015): sample length and width, 80 mm; load cell, 20 N; and speed shall, 125 mm/min. For each sample, 10 measurements were taken. It is to be noted that there is no MD and CD for the ball burst testing.

Wet Ball Burst Testing

Wet ball burst test was performed according to ISO 12625-11 (2019). The measurement was made within 3 to 4 seconds after dropping 5 mL of water on the area where the ball touches the sample. Figure 3 shows the wet ball burst testing method. 10 measurements were made for each sample. Testing conditions for wet ball burst testing were the same as the dry ball burst testing.

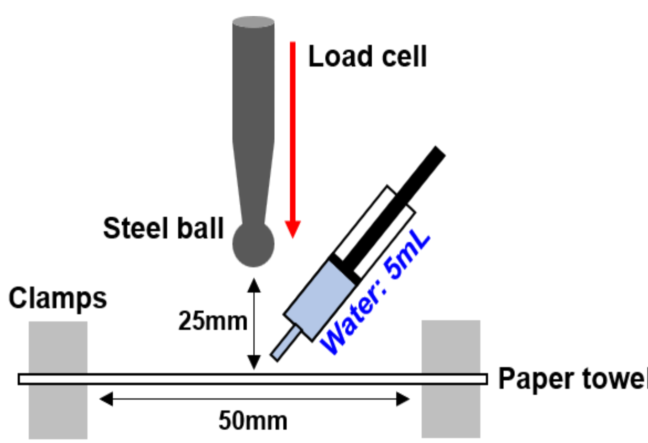

Fig. 3. The wet ball burst testing diagram

Surface Roughness and friction Testing

Two ISO standard methods of using a stylus-type contact profilometry have been established (ISO 12625-18, ISO 24118-1). A Kawabata surface tester (Model: KES-SESRU, Kato Tech, Kyoto, Japan) was used to measure the surface roughness and friction of the paper towel samples simultaneously on the same scan lines (Kato Tech 2018a, b).

Figure 4 shows the configuration of the surface tester and geometry of the U-tube type stylus. Notably, it is the sample, not the stylus, that moves in the scan direction. This is intended to minimize the direct contact of the stylus with the sample surface. In this way, the damage of the sample can be minimized, in contrast to the conventional surface tester where the stylus moves along the sample surface (Park 2017; Ko *et al*. 2018; Moon 2021; Lee *et al*. 2023, 2024).

The testing conditions were as follows according to ISO 12625-18 (2022): scan speed, 1.0 mm/s; contact force, 5 gf; data acquisition rate, 10 Hz (or 10 point/s); and sample scan length, 20 mm. For each sample, 10 measurements were taken in the machine direction (MD) and cross-machine direction (CD).

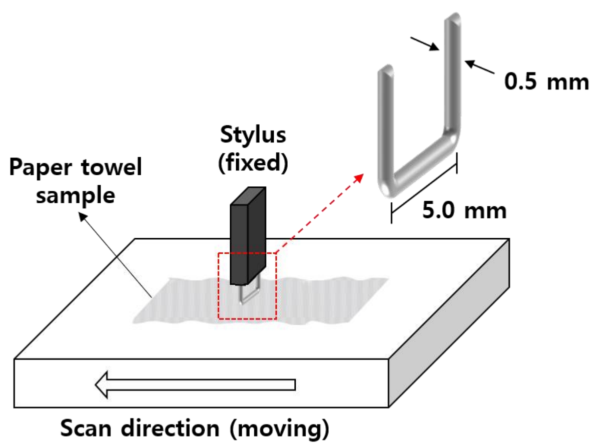

Fig. 4. Configuration of the surface tester and geometry of U-tube type stylus

Surface Roughness Determination

A profilometry generates a roughness profile of roughness *vs.* scan length as illustrated in Fig. 5 for the paper towel sample (code A) in the machine direction (MD). The distance between the two adjacent points is defined as the separation distance and is determined as follows (Park *et al*. 2021),

$$X = \frac{v}{dar} \tag{3}$$

where X is the separation distance (mm), v is the scan speed (mm/s), and dar is the data acquisition rate (Hz (or points/s)). The separation distance may be referred to as the resolution, with shorter separation distance indicating higher resolution. In Eq. 3, it is to be noted that the separation distance is determined by the scan speed and the data acquisition rate, independent of the size of the stylus. This is quite unexpected because it is conventionally accepted that a finer stylus should be necessary to obtain a finer resolution. As a numerical illustration, at v=1 mm/s, X becomes 100-micron, 10 micron, 1 micron at dar=10 Hz, 100 Hz and 1000 Hz, respectively. In the conventional method, a stylus of 1 micron size was used to obtain the resolution of 1 micron, whereas a dar of 1000 Hz is required, independent of the size of the stylus in the present method.

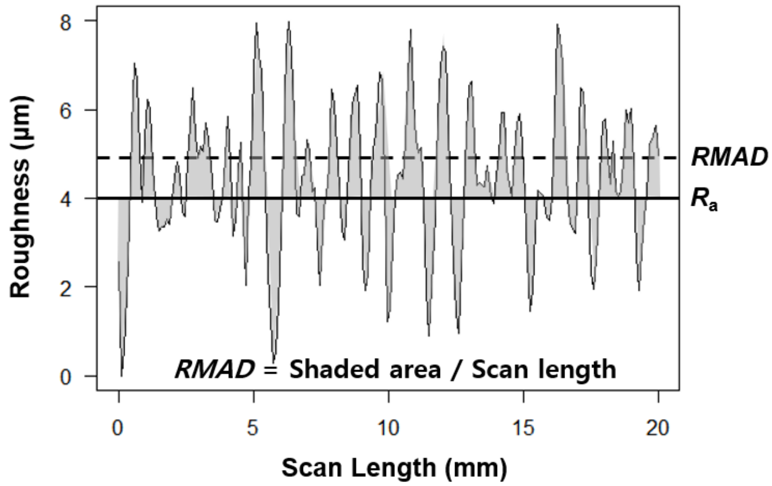

Fig. 5. A surface roughness profile of the paper towel sample (code A)

Roughness Parameters

Roughness average (R_a) and the mean absolute deviation from R_a (*RMAD*) were calculated from Fig. 5 using Eqs. 4 through 7 (Park *et al*. 2021; Moon 2022; Lee *et al*. 2023; Lee *et al*. 2024),

$$RMAD = \frac{1}{N}\sum_{1}^{N}|R_i - R_a| \quad (4)$$

$$R_a = \frac{1}{N}\sum_{1}^{N} R_i \quad (5)$$

$$N = \frac{dar}{v} \quad (6)$$

$$d = \frac{1}{N} \quad (7)$$

where *RMAD* is the mean absolute deviation from the R_a, R_i is the roughness (µm) at scanning point i, R_a is the roughness average (µm), *N* is the number of data points in the scan length, and *d* is the separation distance between two adjacent points (mm). The ISO 24118-1 (2023) standard introduced a new surface parameter of *M* which has the same meaning as *RMAD*. In Fig. 5, R_a and *RMAD* are shown by the solid line and broken line, respectively. *RMAD* is the shaded area divided by the scan length. Eq. 4 indicates that R_a is treated as a constant in calculating *RMAD*.

Surface Friction Determination

Figure 6 shows a friction profile of the same paper towel sample (code A), which was obtained simultaneously with Fig. 5. As mentioned above, this tester allows the determination of both the surface roughness and friction on the same scan lines simultaneously, which is ideal for examining the relationship between the surface roughness and friction parameters. In Fig. 6, *FMAD* is the shaded area divided by the scan length. The distance between $\bar{\mu}$ and *FMAD* remains same regardless of the position of $\bar{\mu}$. This indicates that $\bar{\mu}$ is treated as a constant for determining *FMAD*.

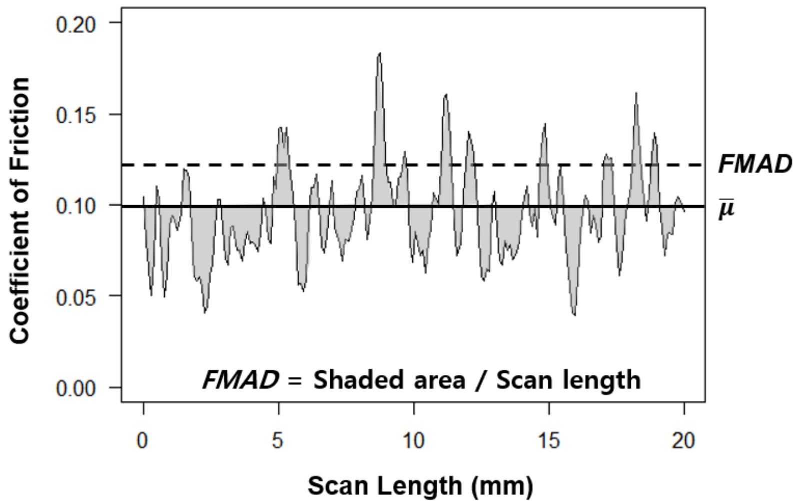

Fig. 6. The surface friction profiles of the paper towel sample (code A). μ¯ and FMAD were shown by the solid and broken line, respectively.

Friction Parameters

The average coefficient of friction ($\bar{\mu}$) and the mean absolute deviation from $\bar{\mu}$ (*FMAD*) were calculated according to Eqs. 8 and 9, respectively,

$$FMAD = \frac{1}{N}\sum_{1}^{N}|\mu_i - \bar{\mu}| \tag{8}$$

$$\bar{\mu} = \frac{1}{N}\sum_{1}^{N}\mu_i \tag{9}$$

where *FMAD* is the mean absolute deviation from the average *COF*, μ_i is the COF at point *I*, and $\bar{\mu}$ is the average *COF*. In Fig. 6, $\bar{\mu}$ and *FMAD* are shown by the solid line and broken line, respectively. *FMAD* is the shaded area divided by the scan length. Eq. 8 indicates that $\bar{\mu}$ is treated as a constant in calculating *FMAD*. ISO Standard (12625-18, 2023) introduced a new friction parameter, *M* which has the same meaning as *FMAD* (Park *et al*. 2021; Moon 2022; Lee *et al*. 2023; Lee *et al*. 2024).

RESULTS AND DISCUSSION

Subjective Testing – Rating

Each panelist was asked to rate the seven coded samples from 1 for Poor to 99 for Excellent. Table 2 shows the subjective rating test results for each product. Table 3 shows the correlation analysis. According to Table 3, the preference showed a very high correlation with absorbency (*r*=0.95), and wet strength (*r*=0.94) followed by wiping (*r*=0.87). The preference showed a very poor correlation with softness (*r*=0.25). This finding is in contrast with bathroom tissue and facial tissue whose softness plays an important contribution to the preference (Ko *et al*. 2015, 2017, 2018; Lee *et al*. 2024). The table also shows high correlations among the absorbency, wiping, and wet strength. For example, the wet strength had a correlation with absorbency (*r*=0.85), with wiping (*r*=0.80); such high correlations among them may indicate that decoupling the performance into each functional attribute should be difficult, if not impossible. A future study might consider a larger number of specimens to address this issue.

Table 2. The Subjective Rating Test Results of the Samples

Attribute	Preference	Softness	Absorbency	Wiping	Wet Strength
A	81	52	78	80	84
B	72	42	70	70	63
C	59	55	55	59	59
D	55	49	49	53	54
E	58	70	58	53	57
F	53	52	57	58	43
G	45	27	49	58	43

Table 3. Correlation Analysis of the Subjective Attributes Testing Results

Attribute	Preference	Softness	Absorbency	Wiping	Wet Strength
Preference	1.00				
Softness	0.25	1.00			
Absorbency	0.95	0.18	1.00		
Wiping	0.87	0.17	0.92	1.00	
Wet strength	0.94	0.29	0.85	0.80	1.00

Tensile Properties

Table 4 summarizes the dry tensile properties of the seven paper towel samples. The geometric mean (GM) was calculated as the square root of product of the MD and CD values. Table 5 summarizes the wet tensile properties of seven paper towel samples. The geometric mean (GM) was calculated as the square root of the product of the MD and CD values. The wet of dry ratio of each sample was calculated by Eq. 10.

$$W/D\ (\%) = (\text{Wet tensile strength}/\text{Dry tensile strength}) \times 100 \quad (10)$$

ISO 12625-5 (2024) defines Eq. 10 as the wet tensile strength retention (%). According to ISO 12625-5, *W/D* (%) is referred to wet tensile strength retention (%) as shown in Table 5. Sample B had the highest wet tensile strength retention, while G had the lowest wet tensile strength retention. Generally, a high wet tensile strength retention is preferred for a paper towel because it provides a good wet strength while providing better handfeel (*i.e.*, softness). A high wet tensile strength retention may be achieved by increasing the wet strength, or lowering the dry strength, or both.

Table 4. Dry Tensile Properties of the Samples

Sample	Dry Tensile Strength (N/m)			Elongation at Break (%)		
	MD	CD	GM	MD	CD	GM
A	556.2 ± 38	320.5 ± 27	421.6 ± 23	45.0 ± 2	24.1 ± 1	32.9 ± 1
B	426.2 ± 11	408.3 ± 16	417.0 ± 9	70.4 ± 2	33.7 ± 1	48.7 ± 1
C	470.0 ± 21	232.1 ± 7	331.1 ± 12	75.1 ± 4	16.5 ± 2	35.2 ± 2
D	359.4 ± 12	195.1 ± 6	264.8 ± 6	115.4 ± 3	18.8 ± 2	46.6 ± 2
E	582.3 ± 39	155.1 ± 9	300.3 ± 13	111.8 ± 3	22.9 ± 2	50.5 ± 2
F	470.1 ± 22	243.5 ± 9	336.3 ± 12	83.2 ± 3	13.9 ± 1	33.9 ± 1
G	463.2 ± 12	288.3 ± 12	365.3 ± 8	117.5 ± 4	26.7 ±2	55.9 ± 2

Table 5. Wet Tensile Properties of the Samples

Sample	Wet Tensile Strength (N/m)			Elongation at Break (%)			Wet tensile strength retention (%)
	MD	CD	GM	MD	CD	GM	GM
A	131.3 ± 6	80.2 ± 4	102.6 ± 3	53.3 ± 1	36.8 ± 3	44.2 ± 2	24.3
B	127.1 ± 4	112.5 ± 6	119.1 ± 4	85.2 ± 5	53.0 ± 4	67.0 ± 2	28.6
C	88.5 ± 6	45.6 ± 4	63.5 ± 4	57.2 ± 3	24.4 ± 2	37.4 ± 1	19.2
D	56.7 ± 18	53.6 ± 2	67.8 ± 6	68.0 ± 6	27.7 ± 2	43.4 ± 3	25.6
E	120.5 ± 21	39.2 ± 3	68.4 ± 6	52.6 ± 4	30.8 ± 2	40.0 ± 4	22.8
F	101.7 ± 12	50.1 ± 4	71.2 ± 5	61.3 ± 5	20.7 ± 2	35.5 ± 2	21.2
G	66.7 ± 12	45.6 ± 2	55.0 ± 6	98.6 ± 8	36.1 ± 4	59.5 ± 5	15.1

Water Absorbency Capacity

Table 6 summarizes the water absorbency capacity of seven paper towel samples.

Table 6. Water Absorbency Capacity of the Samples

Sample	Absorbency Capacity	
	(g/sheet)	(g/g)
A	12.98 ± 0.39	5.82 ± 0.17
B	12.10 ± 0.26	5.87 ± 0.14
C	4.48 ± 0.15	4.24 ± 0.13
D	4.33 ± 0.14	4.44 ± 0.16
E	4.85 ± 0.17	4.16 ± 0.15
F	4.31 ± 0.27	4.12 ± 0.26
G	4.12 ± 0.20	3.82 ± 0.19

Ball Burst Properties

Table 7 summarizes the ball burst strength properties. The wet of dry ratio (*W/D*, or wet burst retention) of each sample was calculated according to ISO 12625-11 (2019),

$$W/D\ (\%) = (\text{Wet burst strength}/\text{Dry burst strength}) \times 100 \qquad (11)$$

Sample B had the highest wet burst retention, and sample G had the lowest wet burst retention, which was consistent with the tensile testing results.

Table 7. Ball Burst Properties of the Samples

Sample	Dry (N/m)	Wet (N/m)	Wet burst retention (%)
A	199.5 ± 22.1	66.4 ± 9.7	33.3
B	183.0 ± 20.3	76.7 ± 4.9	41.9
C	96.1 ± 11.2	27.5 ± 6.3	28.7
D	73.0 ± 8.8	21.1 ± 5.1	28.9
E	66.0 ± 9.2	22.5 ± 5.3	34.1
F	86.0 ± 5.7	21.1 ± 4.7	24.5
G	110.3 ± 8.8	21.4 ± 4.0	19.4

Surface Roughness

Table 8 summarizes the surface roughness properties of seven paper towel samples. R_a and *RMAD* were calculated according to Eqs. 4 and 5, respectively. Both the MD- and CD- values were determined. As shown in Table 2, commercial paper towels are usually embossed; inevitably, the roughness profile depends on the pattern and degree of the embossing. This has caused the problem of determining the surface roughness for the embossed samples (Hollmark and Ampulski 2004). Thus, R_a provides higher values than *RMAD*, because in the latter, the embossing effect has been treated as constant. Secondly, R_a depends on the testing conditions. In contrast, the variations coming from the test conditions are also treated as constant in calculating *RMAD*. Consequently, *RMAD* generates lower values and less coefficient of variation (COV) than R_a. The surface roughness depends on the embossing pattern on the surface (Hollmark and Ampulski 2004). To illustrate this point, the two scan lines of the sample (code E), as shown in Fig. 7 and Table 9.

Table 8. R_a and *RMAD* of the Samples

Sample	R_a		*RMAD*	
	Mean (μm)	COV (%)	Mean (μm)	COV (%)
A	4.9	23.0	1.3	18.2
B	5.5	22.3	1.4	13.0
C	7.9	21.2	1.8	14.1
D	5.1	15.3	1.4	12.6
E	7.5	29.3	1.7	14.1
F	9.3	22.3	1.9	15.1
G	5.1	14.7	1.5	12.0

Note: All values are geometric means.

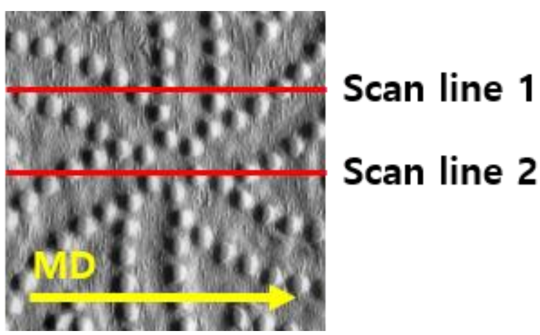

Fig. 7. Scan lines for embossing impact analysis (sample E)

Table 9. R_a and *RMAD* of the Scan Lines

Scan line	R_a		*RMAD*	
	Mean (μm)	COV (%)	Mean (μm)	COV (%)
1	8.4	19.3	2.1	13.1
2	7.5	23.3	1.9	11.2
Avg.	8.0	21.3	2.0	12.2

The results show that both R_a and *RMAD* may depend on the scan line selected, though its dependence was much less with *RMAD*. In addition, the R_a and its COV were much larger than the *RMAD* and its COV. This demonstrates that the effects of the embossing on the surface roughness characterization should be minimized by determining the *RMAD*. It is remarkable that *RMAD* may practically eliminate the effects of embossing.

It may be readily understandable that it can eliminate other effects such as creping, patterning and calendaring.

Surface Friction Properties

Table 10 summarizes the surface friction properties of seven paper towel samples. $\bar{\mu}$ and *FMAD* were calculated according to Eqs. 8 and 9, respectively. Both the MD- and CD- values were determined. Table 10 shows the geometric mean (GM) values. The $\bar{\mu}$ and *FMAD* show similar behavior observed between R_a and *RMAD*. That is, *FMAD* was lower and less variable than $\bar{\mu}$.

Table 10. $\bar{\mu}$ and *FMAD* of the Samples (GM Values)

Sample	$\bar{\mu}$		*FMAD*	
	Mean	COV (%)	Mean	COV (%)
A	0.36	30.7	0.12	18.8
B	0.28	23.6	0.10	20.4
C	0.42	24.2	0.13	13.3
D	0.36	30.1	0.11	23.8
E	0.37	28.6	0.13	26.1
F	0.48	28.5	0.15	24.9
G	0.31	19.4	0.08	16.3

In-use Properties *vs*. Physical Properties

Table 11 shows a correlation matrix among the subjective attributes and the physical properties.

Softness attributes vs. surface roughness and friction

In Table 11, the *FMAD* (*r*=0.78) had the highest correlation with the softness attribute. It was much higher than the *RMAD* (*r*=0.40). This finding is consistent with the findings from bathroom tissue and facial tissue (Ko *et al*. 2017; Lee *et al*. 2024).

Wet strength attributes vs. wet tensile and wet ball burst

Table 11 shows that the wet strength attribute had the highest correlation with the wet ball burst strength (*r*=0.74), followed by the wet tensile (*r*=0.68). Additionally, as a result of correlation analysis between wet tensile strength and wet ball burst strength, *r*=0.96 (regression eq.: y = 1.15x – 0.13) was found, indicating a high correlation between the two physical properties.

Table 11. Correlation Analysis of Subjective Attributes and Physical Properties

Attribute / Physical	Preference	Softness	Wet strength	Absorbency	Wiping
RMAD	0.51	0.40	0.59	0.43	0.58
FMAD	0.07	0.78	0.02	0.08	0.16
Wet ball burst	0.88	0.13	0.74	0.89	0.89
Wet tensile	0.87	0.01	0.68	0.88	0.80
Absorbency capacity	0.94	0.01	0.82	0.90	0.87

Tensile Strength *vs*. Ball Burst Strength (The Ram-Ko Theory)

Ramasubramanian and Ko (1989) applied finite element analysis to find a relationship between tensile strength and ball burst strength. They found that the relationship between the two may be given as follows,

$$Ball\ burst\ index\ (N/m) = CD\ strain\ X\ GMT \quad (12)$$

where *GMT* is the geometric mean tensile (N/m). Equation 12 is referred to as the Ram-Ko theory. The CD strain (not MD, or GM) strain is used because the finite element analysis shows that the weaker strain between the MD and CD determines the ball burst strength. If the MD strain is weaker than the CD strain, the CD strain should be replaced by the MD strain. Table 12 summarizes the ball burst strength properties and the calculated values according to the Ram-Ko theory for the seven paper towel samples.

Table 12. The Ball Burst Strength vs the Calculated Ball Burst Strength According to Ram-Ko Theory

Sample	Dry (N/m)	Wet (N/m)	Wet burst retention (%)	Ram-Ko Theory		
				Dry (N/m)	Wet (N/m)	Wet burst retention (%)
A	199.5	66.4	33.3	101.6	37.8	37.2
B	183.0	76.7	41.9	140.5	63.1	44.9
C	96.1	27.5	28.7	54.6	15.5	28.4
D	73.0	21.1	28.9	49.8	18.8	37.7
E	66.0	22.5	34.1	68.8	21.1	30.6
F	86.0	21.1	24.5	46.8	14.7	31.5
G	110.3	21.4	19.4	97.5	19.9	20.4

Figure 8 shows a plot of the ball burst value against the predicted ball burst value according to Ram-Ko theory based on the values in Table 12. The analysis results suggest that the two values are highly correlated. This validates the Ram-Ko theory of calculating the ball burst strength from the tensile strength. More importantly, the ball burst strength alone may be sufficient to predict the subjective wet strength attribute while it is much simpler and easier than tensile testing.

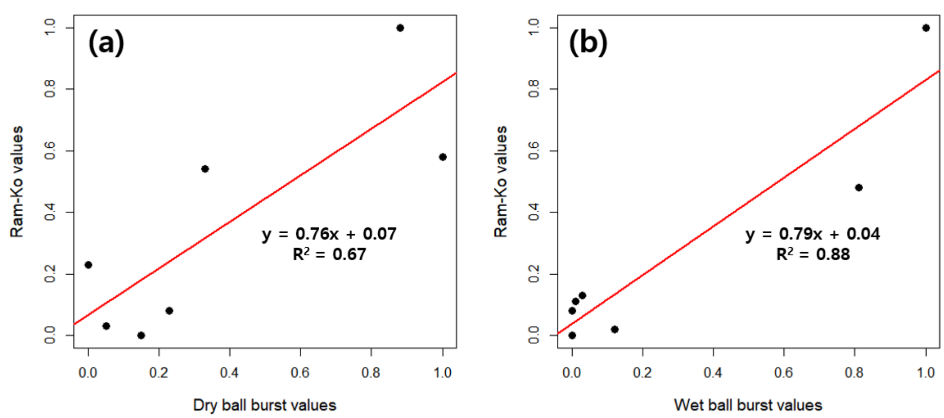

Fig. 8. Ram-Ko value vs. Ball burst value (a: dry; b: wet)

Wet Tensile Strength and Burst Retention

Table 13 shows that the *W/D* tensile strength and burst ratio of the seven commercial paper towels ranged from 15.1 to 28.6 and 19.4 to 41.9, respectively. For a hygiene paper, a higher wet strength retention is usually preferable. One way of achieving this may be achieved by lowing the dry strength while maintaining the same wet strength.

Table 13. The *W/D* Ratio of the Seven Commercial Paper Towel Samples

Code	Wet Tensile Strength Retention (%)	Wet Burst Retention (%)
A	24.3	33.3
B	28.6	41.9
C	19.2	28.7
D	25.6	28.9
E	22.8	34.1
F	21.2	24.5
G	15.1	19.4

CONCLUSIONS

1. A sensory panel testing using a ranking method was used to determine in-use properties of seven types of commercial paper towel products. The testing showed that the absorbency attribute and the wet-strength attribute were the main contributors to the preference, whereas the softness contributed the least.
2. A surface profilometry technique was successfully applied to determine the surface roughness and friction of the paper towels. As a new surface parameter, *RMAD* (roughness mean absolute deviation) was introduced. While R_a (roughness average) may depend on the operating conditions, *RMAD* is practically independent of testing conditions, providing more reliable and less variable values. Unlike R_a, *RMAD* showed that it should be practically independent of converting processes such as creping, embossing, and printing. These problems had significantly limited the use of R_a as the surface roughness parameter. As ISO standards have introduced *RMAD* and *FMAD* (friction mean absolute deviation), these two may become the critical surface parameters in the future.
3. The wet ball burst testing showed the highest correlation with the in-use wet strength. The wet ball burst testing should be preferable to the wet tensile testing because it does not require determination of both the MD and CD. This method should also be much simpler and more reliable than wet tensile testing.
4. The validation of the Ram-Ko theory is expected to ultimately minimize the use of tensile testing methods for determining in-use strength attributes.

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