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Influence of ply number and unit weight on the quality characteristics of cellulose-based hygienic products

Abstract

In this study, properties expected of toilet paper such as wet and dry strength, absorbency, water-holding capacity, softness, and water resistance, were measured in accordance with international standards. The samples examined in this study are commercially available products made from cellulose. The products were examined in two separate categories: toilet paper and paper towels. The samples were produced in 2- and 3-ply versions, and the effect of the number of plies on the aforementioned properties was investigated. Additionally, 2-ply samples were produced in three different weights as light, medium, and heavy during manufacturing to determine the relationship between performance and weight. Test results were analyzed using graphs, and the statistical significance of the results was demonstrated using the SPSS software package. The results indicate that unit weight has a significant effect on performance; however, the number of layers yielded different results for each test and was not a determining factor. Since there are few detailed and systematic studies on hygienic papers in the literature, the primary motivation for this study is to serve as a foundation for future research.

Keywords: hygienic papers, paper quality, paper production

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Introduction

Hygiene paper is a material produced industrially, with cellulose as its primary raw material. Before hygiene paper was invented, people used other methods to clean themselves. The earliest written record regarding toilet paper dates back to the 7th century AD. No written records were found from that time until the 14th century. A written source from the 14th century mentions soft, square-cut fabrics produced for the Ming Dynasty. The toilet paper we use today—a gray-colored core tube wrapped in perforated paper—emerged in the 19th century following Seth Wheeler's patent.[1]

Since hygiene papers are primarily used by people for personal hygiene, they fall under the category of products that come into contact with the human body. To achieve sufficient whiteness during the production process, bleaching agents and certain chemicals are used in these papers. These chemicals and bleaching agents must be used in the lowest possible quantities. The lower the levels of chemicals and bleaching agents used in a paper product, the less harmful it is to human health and the environment. In addition, some consumers in this market prefer scented hygiene papers. To produce these scented products, the manufacturer applies perfumed chemicals directly to the paper products or to the gray cardboard tube—known as the core tube—located in the center of the roll of hygiene paper. These chemicals must not irritate human skin or have carcinogenic effects. The durability of hygiene papers must vary depending on the product type. Napkins may have the lowest durability due to their intended use. Toilet paper and paper towels are produced in different strengths to meet varying durability requirements. Durability is a property imparted to the paper during the processing of the raw materials. Papers with sufficient durability may be altered during the converting process when patterns are applied to the paper. The paper is passed through steel-made patterned rollers and plastic-made flat rollers in the converting machine to apply patterns specific to each company. These patterns help the company take a step toward branding, while simultaneously causing the paper to bulge at certain points and collapse at others to create a textured surface, ensuring it remains puffed up when wound onto the core tube. This process instantly compresses the paper against the protrusions on the steel rollers. As the paper is compressed, it undergoes structural damage that is imperceptible to the naked eye but detectable by testing equipment. This structural damage alters the paper's strength properties.

The hygiene paper market has made these papers available to consumers in multi-ply formats. As the number of plies increases, the amount of paper per square meter within the product will increase. The increased paper content will result in greater absorbency and help produce a more durable product. On a global scale, considering toilet paper, paper towels, and napkins, the average person consumes approximately 4.4 kg of paper per year. If we calculate each toilet paper roll as 78 grams, 4.4 kg of paper means a person consumes roughly 56.5 rolls of toilet paper per year. This volume is the primary reason the paper production industry is one of the fastest-growing sectors.[1]

The rapid growth of the world's population has brought about various socio-economic and environmental challenges, even as it has improved living conditions. In this context, the use of recyclable resources has become increasingly important to meet growing needs in a sustainable manner (Özbakır Umut et al., 2015). However, hygiene papers contain various chemicals such as adhesives, dyes, and bleaches during production and recycling processes, and these substances can have adverse effects on human health and the environment even at low concentrations (Satar, E. İ.).

Cellulose, the primary raw material of hygiene papers, cannot be used in an infinite cycle due to the physical and chemical degradation of the fiber structure during recycling processes. The decrease in fiber length and strength, the reduction in water-holding capacity, and the weakening of structural properties necessitate the use of more chemicals at each recycling stage and ultimately lead to the raw material becoming unusable. Nevertheless, paper recycling contributes to reducing environmental pollution and deforestation by offering advantages in terms of cost, energy, and water consumption.[2]

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In the literature, factors affecting the performance of hygiene papers have been examined within the framework of multidimensional parameters such as fiber type, production and converting techniques, layer structure, drying methods, chemical additives, and product design.

Vieira et al.,[3] examined 5-ply toilet papers made from the same raw materials but with different embossing patterns. The study found that products with 3 deco + 2 micro embossing exhibited higher mechanical strength, while those with 2 deco + 3 micro embossing demonstrated better performance in terms of water absorption capacity. Vieira et al.,[1] investigated the effects of perforations in hygiene papers on mechanical behavior and demonstrated that increasing the distance between cuts homogenizes stress distribution, thereby influencing tear behavior. de Oliveira Mendes et al.,[4] examined the effects of converting conditions on product softness and surface properties and determined that embossing patterns affect tactile quality in different ways. Kullander.,[5] examined the effects of fiber type and dewatering methods on the final product and demonstrated that vacuum dewatering better preserves fiber structure, whereas mechanical dewatering damages fiber walls and negatively affects water-holding capacity. Tutuş et al.,[6] examined the physical and optical properties of hygiene papers in Turkey and demonstrated that parameters such as basis weight, density, absorbency, and strength affect product performance in various ways. Wang et al.,[7] determined that drying technologies have a significant effect, particularly on softness, and that product price is primarily related to volume, unit weight, and softness. Banavath et al.,[8] examined the effect of refining on fiber properties and demonstrated that as refining increases, specific surface area, water-holding capacity, and fiber bonding potential also increase. De Assis et al.,[9] examined the effects of machine technologies and fiber types on hygiene paper properties; they found that air-drying methods produce softer and more voluminous products, while wet pressing yields denser products but with lower softness and absorbency. Hubbe et al.,[10] examined the changes occurring in cellulose fibers during the recycling process and noted that recycled fibers can be reused with appropriate processing. Bouchard and Douek.,[11] investigated the effect of recycling on chemical properties and stated that only limited changes occurred. Zwilling et al. (2021) noted that the hygiene paper market has a significant economic volume and maintains its growth potential. Wang et al.,[12] examined the relationship between human perception and instrument measurements and demonstrated that the Emtec TSA device provides reliable results in softness measurements. Keşmer investigated the effect of long and short fibers on hygiene paper performance and determined that long fibers increase strength, while short fibers support performance when used in appropriate combinations. Hezer.,[2] conducted research aimed at reducing dust formation in paper production and demonstrated that the design of the refiner blade, combined with chemical binders, can significantly reduce dust generation. Elmas and Ozturk.,[13] examined the disintegration properties of toilet paper and determined that there is a relationship between physical properties and sewer blockages. Jain et al.,[14] examined the disintegration performance of toilet paper and identified product combinations with optimal softness, strength, and disintegration time. Kweon et al.,[15] reviewed test methods for usage performance and identified absorbency and wet strength as key parameters. Häggman and Ranbro.,[16] examined dispenser designs for high-traffic areas and developed solutions that optimize product consumption. Jain et al.,[17] examined the effect of additives in tissue paper production and demonstrated that strength-enhancing chemicals improve production efficiency. Overall, the literature indicates that the performance of hygiene papers is shaped by the interaction of numerous variables.[18]

Aim of the study is to check the effect of unit weight and ply number on the quality of toilet paper and paper towel. According to the test results it is tried to find out the optimum ply number and weight to produce these products for sustainability.

Experimental study

Twenty rolls of toilet paper were produced at a commercial facility for use in the study. Production was carried out with light, medium, and heavy grammages, and 2- and 3-ply configurations. Tests for grammage, thickness, dry tensile strength, wet tensile strength, tear strength, water absorption capacity, absorption time, and whiteness were conducted on the obtained samples according to the standards presented in Table 1.

Table 1 Standards used in the study

Unit weight	ISO 536 /	Determines the mass per unit area (g/m²); a fundamental parameter affecting cost, strength, and overall quality
Thickness	ISO 534	Measures paper thickness and bulk; closely related to softness and perceived volume
Dry tensile strength (MD & CD)	ISO 1924-2 /	Determines tensile strength and elongation under constant rate of elongation; key mechanical property
Wet strength	ISO 12625-5	Measures strength after exposure to water; critical for tissue products
Elongation	ISO 1924-2	Indicates the extensibility of the material before rupture
Softness	ISO 12625-4	Evaluates surface softness of tissue products (instrument-based measurement)
Dispersion in water	ISO 12625-17	Assesses the ability of the product to disperse in water after use
Whiteness	ISO 2470	Determines optical properties related to product appearance

Results

The effect of unit weight on toilet paper performance characteristics

The toilet paper samples are varied according to the unit weight and grouped as light weight, (30-35 g/m²) moderate weight (40-45 g/m²) and high weight (more than 45g/m²). Widthwise and lengthwise strength of the samples are presented in Figure 1.

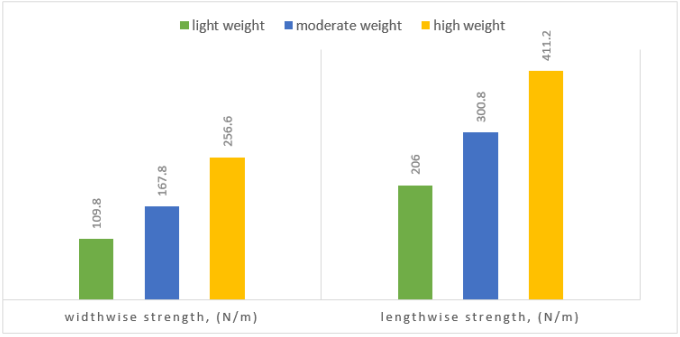

Figure 1 Strength of the samples.

As shown in the figure by raising the unit weight the strength of the samples raises both directions. Lengthwise strength of the samples

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are about two times of widthwise strength of the samples. This is an important result because the force is applied to the papers with this direction.

Elongation and also wet widthwise strength test are applied to the samples and the results are given in Figure 2.

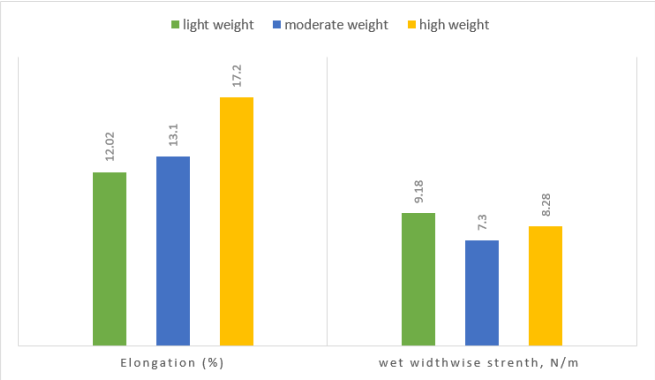

Figure 2 Elongation and wet widthwise strength of samples.

Elongation of the samples were also affected by the raised unit weight. The elongation of light weight and moderate weight samples were closer each other but for high weight samples this value was quite high so it was concluded that this value 45g/m^2 was important to obtain elongation. Widthwise strength of samples decreased by the effect of wetting significantly. Interesting result was about the effect of unit weight on this strength. It is clear that wetting was more important than unit weight variation.

According to the Figure 3, softness of the moderate weight samples are the most and by increasing the unit weight softness decreased. Softness is very important selection criteria for toilet paper. Dispersion in water is another important criterion because many users left the paper to the toilet water after using. Therefore, the time dispersed in water should be low to prevent the toilet from clogging. The light weight samples were convenient according to this property. Whiteness was not affected by unit weight.

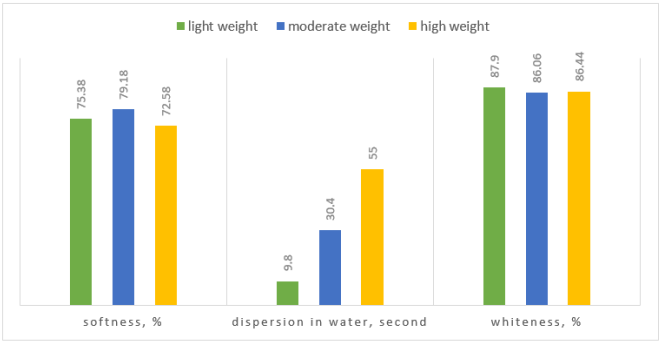

Figure 3 Softness, dispersion in water and whiteness of samples.

The effects of differences in the unit weight of toilet paper on performance were analyzed using one-way ANOVA with a statistical software package and given in Table 2.

According to the ANOVA results, which were conducted to determine whether there were significant differences between groups in terms of the variables examined in this study, statistically significant differences were found in some characteristics.

First, there is a highly significant difference between groups in terms of the unit weight variable ($F = 254.703$, $p < 0.001$). This indicates that the applied treatment or group factor has a strong effect on unit weight. Similarly, statistically significant differences were also found between groups in the variables widthwise strength ($F = 11.439$, $p = 0.002$), lengthwise strength ($F = 22.407$, $p < 0.001$), and elongation ($F = 8.534$, $p = 0.005$). These findings demonstrate that the relevant mechanical properties are significantly influenced by the group factor.

Table 2 One-way ANOVA test results of samples on the effects of differences in the unit weight

S. no	Sum of squares	Df	Mean square	F	Sig.
Unit weight	303,436	2	151,718	254,703	,000
Thickness	,006	2	,003	3,339	,070
Widthwise strength	54,666,133	2	27,333,067	11,439	,002
Lengthwise strength	105,470,400	2	52,735,200	22,407	,000
Elongation	74,681	2	37,341	8,534	,005
Wet widthwise strength	8,841	2	4,421	1,832	,202
Softness	109,733	2	54,867	2,083	,167
Dispersion in water	5,120,933	2	2,560,467	34,064	,000
Whiteness	9,436	2	4,718	1,898	,192

Additionally, the dispersion in water property is another variable showing significant differences ($F = 34.064$, $p < 0.001$). This result indicates that the group effect is significant, particularly regarding the material's interaction with water.

In contrast, the result obtained for the thickness variable ($F = 3.339$, $p = 0.070$) is above the threshold for statistical significance, indicating that there is no significant difference between the groups. However, since this value indicates borderline significance, it may be advisable to re-evaluate it with a larger sample size. Similarly, no statistically significant differences were found between the groups for the variables wet widthwise strength ($p = 0.202$), softness ($p = 0.167$), and whiteness ($p = 0.192$).

The effect of ply count on toilet paper performance characteristics

In this part of the study the unit weight was made constant but this weight was obtained by two and three plies. It was tried to find out the effect of ply on the performances of the papers. Applying a ply is an extra process and ıf the desired value was obtained by two-ply instead of three this sample should be selected because of lower cost. The strength of the samples were tested and the results were presented in Figure 4.

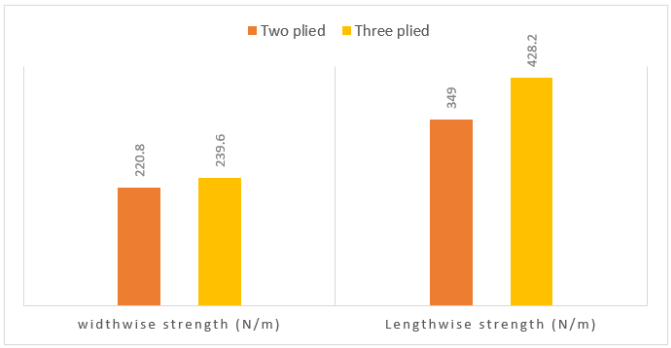

Figure 4 Strength of the samples.

It is clear that plying increased the strength for both directions and lengthwise strength value was two times of widthwise strength. The

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elongation and wet widthwise strength of the samples were shown in Figure 5.

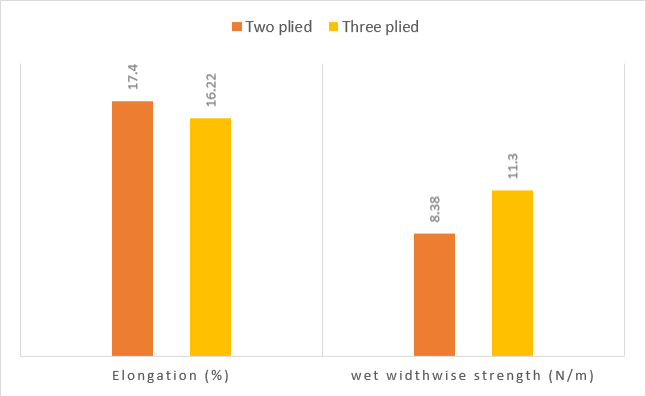

Figure 5 Elongation and wet widthwise strength of samples.

By the effect of ply the elongation of the samples decreased as predicted. The ply caused an increase in wet widthwise strength of the samples.

The effect of ply on softness, dispersion in water and whiteness of the samples were given in Figure 6.

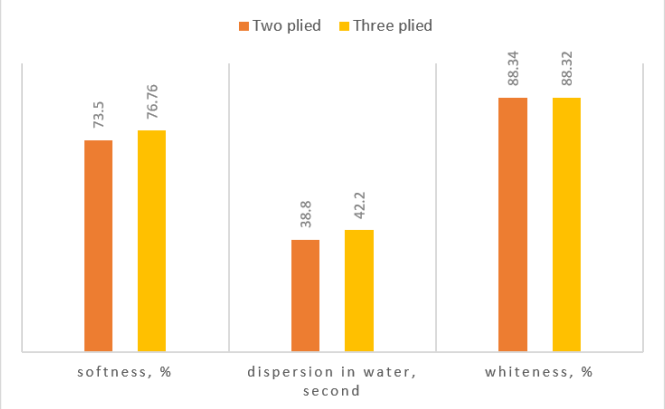

Figure 6 Softness, dispersion in water and whiteness of samples.

Figure 6 showed that softness of the samples raised a little by the effect of ply but the dispersion time was also raised. Dispersion time is more important than the softness. Whiteness was not affected by ply.

The effects of differences in the ply number of toilet paper on performance were analyzed using one-way ANOVA with a statistical software package and given in Table 3.

Table 3 One-way ANOVA test results of samples on the effects of differences in the ply number

S.no	Sum of squares	df	Mean square	F	Sig.
Unit weight	,013	1	,013	9,696	,014
Thickness	883,600	1	883,600	,134	,724
Widthwise strength	15,681,600	1	15,681,600	7,219	,028
Lengthwise strength	3,481	1	3,481	,805	,396
Elongation	21,316	1	21,316	8,315	,020
Wet widthwise strength	26,569	1	26,569	,735	,416
Softness	28,900	1	28,900	,747	,413
Dispersion in water	,001	1	,001	,004	,954
Whiteness	2,500	1	2,500	.	.

According to the results of the analysis of variance, significant differences between groups emerge selectively with respect to the variables examined.

First, a statistically significant difference was found between groups with respect to the unit weight variable ($F = 9.696$, $p = 0.014$). This result indicates that the relevant factor has a significant effect on unit weight. Similarly, significant differences were also identified in the variables widthwise strength ($F = 7.219$, $p = 0.028$) and elongation ($F = 8.315$, $p = 0.020$). These findings reveal that certain mechanical properties are particularly sensitive to the applied treatment or group variable.

In contrast, no significant difference was found between groups regarding the thickness variable ($F = 0.134$, $p = 0.724$). Similarly, for lengthwise strength ($p = 0.396$), wet widthwise strength ($p = 0.416$), softness ($p = 0.413$), and dispersion in water ($p = 0.954$). This suggests that these properties were not influenced by the group factor or that the effect could not be statistically demonstrated. The fact that the F and significance (Sig.) values for the "Whiteness" variable were not reported indicates that variance could not be calculated in the analysis or that the dataset may exhibit a constant value (i.e., no variance). Therefore, no statistical interpretation can be made for this variable.

In conclusion, the analysis findings indicate that the group factor has significant effects, particularly on unit weight, transverse strength, and elongation; however, it has no significant effect on other physical and mechanical properties. Since two groups are involved, the direction of the difference in the variables found to be significant can be interpreted by directly comparing the group means; however, examining the mean values is recommended for a more detailed evaluation.

Conclusion

Toilet paper is manufactured with consumer preferences in mind. The key characteristics expected of toilet paper can be summarized as sufficient mechanical strength (dry strength and controlled wet strength), high softness, good absorbency, appropriate basis weight and thickness, and rapid disintegration in water. There is a trade-off among these characteristics; for example, as strength increases, softness or dispersibility may decrease. Therefore, the goal during the product development process is to achieve optimal performance.

The ANOVA results obtained in this study indicate that the performance criteria of toilet paper are affected to varying degrees depending on the group/factor variable. In particular, the presence of statistically significant differences in the parameters of basis weight, transverse strength, and elongation demonstrates that the applied process plays a decisive role in the mechanical performance of the paper. This suggests that changes in fiber structure, bonding degree, or production conditions directly affect the material's strength properties.

In contrast, no significant differences were observed in properties such as thickness, tensile strength, wet strength, softness, and water dispersibility. This finding indicates that the relevant parameters were either unaffected by the process used or that the variation was at a level that could not be statistically detected. The absence of differences in critical user experience characteristics, particularly softness and water solubility, may indicate that the products offer functionally similar performance.

Considering the trade-off relationships highlighted in the literature, the fact that the observed increase in mechanical strength did not result in a significant change in softness or dispersibility suggests that the production parameters used in the study provided a balanced

optimization. However, the absence of a significant difference in water dispersibility may necessitate more detailed analyses, particularly regarding environmental and post-use performance.

In conclusion, based on the findings, it can be stated that the applied factor improves certain mechanical properties of toilet paper but has a limited effect on user-oriented properties. For future studies, it is recommended to compare group averages and apply multiple comparison tests, particularly for variables showing significant differences.

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Conflicts of interest

The author declares no conflict of interest.

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