

Evaluation of Wetting Behaviour of Nonwoven Fabrics by Different Test Methods

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(MMT),
Test methods

Abstract: Nonwoven fabrics are used in a wide range of consumer and industrial products. Depending on the application, high-performance products can be obtained through raw material selection, web-forming and bonding methods, and advanced finishing processes, ensuring cost-effective, flexible, and quickly produced products. One of the common qualifications sought out for most nonwoven products is wetting and liquid transfer properties. Depending on the end-use area, this property significantly affects the comfort, functionality, and quick reusability properties of the product. Besides, several methods are accepted for evaluating the wetting and/or water-transfer properties of fabrics. Some of these methods require specialised testing devices, while others are easier to apply and more available. By considering these facts, the purpose of this study was to comparatively investigate the wetting/liquid transfer and drying properties of a wide range of nonwoven fabrics, addressing different technical areas. The motivation of the work arose from the need to determine the differences and relationships among wetting measurement methods for nonwoven fabrics. For this purpose, 13 nonwoven fabrics were tested by the moisture management test (MMT), drop absorption test, drop spread test, contact angle test, and vertical wicking tests. Correlation analysis between different test methods highlighted that drop test results were in very good agreement with contact angle results, but due to the high level of absorbency of the selected samples, MMT and vertical wicking results performed better numerical distinguishability. In addition, the drop spread test provided visual data on the longer-term wetting properties of the samples, in contrast to the drop absorption and contact angle results.

Dokusuz Yüzey Kumaşların İslanma Özelliklerinin Farklı Test Metotlarına Göre Değerlendirilmesi

Anahtar Kelimeler

Dokusuz yüzey kumaşlar,
İslanma,
Kuruma,
Nem yönetimi testi (MMT),
Test metotları

Öz: Dokusuz yüzey kumaşlar çeşitli tüketim ürünleri ve endüstriyel ürünlerde kullanım alanı bulmaktadır. Uygulamaya bağlı olarak; hammadde seçimi, tülbent oluşturma ve bağlama yöntemleri ve gelişmiş terbiye işlemleri yoluyla yüksek performanslı ürünler elde edilerek uygun maliyetli, esnek ve hızlı üretim sağlanabilir. Çoğu dokusuz yüzey üründe aranan ortak niteliklerden biri ıslanma ve sıvı transfer özelliğidir. Bu özellik, son kullanım alanına bağlı olarak ürünün konforunu, işlevselliğini ve hızlı tekrar kullanım özelliklerini önemli ölçüde etkiler. Kumaşların ıslanma ve/veya sıvı transfer özelliklerini değerlendirmek için kabul görmüş çeşitli yöntemler bulunmaktadır. Bu yöntemlerden bazıları özel test cihazları gerektirirken, bazıları ise daha kolay uygulanabilir ve daha erişilebilirdir. Bu çalışmanın amacı; farklı teknik alanlarda kullanıma uygun çeşitli dokusuz yüzey kumaşların ıslanma/sıvı transferi ve kuruma özelliklerini karşılaştırmalı olarak incelemektir. Bu çalışmanın motivasyonu, dokusuz yüzeyler için ıslanma ölçüm yöntemleri arasındaki farklılık ve ilişkilerin belirlenmesi ihtiyacından doğmuştur. Bu amaçla, 13 farklı kumaş tedarik edilmiş ve nem yönetimi (MMT), damla, yayılma, temas açısı ve dikey emicilik testleri ile test edilmiştir. Farklı test yöntemleri arasındaki korelasyon analizi; damla testi sonuçlarının temas açısı sonuçlarıyla çok iyi uyum gösterdiğini, ancak seçilen numunelerin yüksek emicilik seviyesi nedeniyle MMT ve dikey emicilik sonuçlarının daha ayırt edici olduğunu ortaya koymuştur. Ayrıca, damla yayılma testi, numunelerin damla ve temas açısı testi sonuçlarına kıyasla daha uzun süreli ıslanma özelliğine dair görsel veriler sağlamıştır.

1. Introduction

Nonwoven fabrics are fibrous web or sheet structures that are not knitted or woven, but are produced via entangling textile fibres together, using various methods [1]. Thanks to their tuneable properties, which depend on diverse production methods and raw materials, they can be applied across a wide range of end-use areas, including disposable or durable clothing, medical and hygiene textiles, automobile textiles, geotextiles, home textiles, industrial textiles, and packaging [1-4].

To be applied to a particular end-use area, the nonwoven fabrics should possess different levels of technical and/or aesthetic properties such as weight, thickness, water absorbency/repellency, permeability (air, water, and water vapour), mechanical properties (tensile, tear, and bursting strengths, compressibility, bending rigidity, drapeability, etc.), visual appeal, etc. For example, to be used in durable apparel, a nonwoven fabric should possess higher strength, lower bending rigidity, better breathability, higher drape, better hand, and higher visual appeal when compared to a nonwoven cleaning cloth. Besides, there are some shared properties that are required highly in nonwoven materials for particular application areas. One of these properties is wetting. Wetting is related to the behaviour of the textile structure while it's in contact with water or another pre-determined liquid [5]. Wetting can be defined as the displacement of the fiber-air interface by a fiber-liquid interface, and it is closely related to wicking (liquid flow in textiles driven by capillary forces) [6, 7]. In terms of the individual fiber units, wetting is mainly determined by the surface tension of the fiber, that is an indicator of the surface energy. The fiber gets wet when its surface energy is high enough to overcome the free surface energy of the liquid [6]. Wetting is essential for many nonwoven fabric application areas such as apparel, hygiene textiles, geotextiles, medical textiles, cleaning cloths, and wet wipes [6, 8]. In these areas, wetting directly affects the main functional properties or the comfort of the end-use product via liquid moisture management [6].

Wetting behaviour of textiles can be determined via different testing methods, such as drop (absorption, drop penetration), contact angle, vertical wicking, drop spreading, and moisture management tests [6, 9-11]. In the drop test, a quantitative measurement is performed based on the measurement of the time the drop is fully absorbed by the textile fabric [10]. The wicking term is used for the spontaneous flow of the liquid within the capillary spaces of the textile structure, accompanied by a simultaneous diffusion of the liquid into the interior of the fibers or a film on the fibers [12]. Wicking property is measured in both the vertical wicking test and the spreading test, but using different methodologies. The contact angle between the textile surface and the liquid is obtained as a consequence of wetting, which reveals a hydrophilic

structure for 0-90° and a hydrophobic structure for 90-180° [12]. The lower the contact angle, the more hydrophilic the surface. On the other hand, the moisture management term is generally used to describe the controlled movement of water vapour and liquid water through the textile substrate [13], and its "liquid" moisture transport component is evaluated using a series of wetting-related parameters with the moisture management tester (MMT) [6, 14].

As for woven and knitted fabrics, different wetting test methods were employed alone or in combination for the evaluation of nonwoven fabrics, in the literature. For example, Zaman et al (2022) evaluated the wettability of woven and nonwoven geotextiles by contact angle measurements [15]. Similarly, contact angle measurements were employed to evaluate the wetting behaviour of nonwoven samples in other studies [16-19]. Konopka and Pourdeyhimi (2002) developed an improved test method to investigate the in-plane liquid movement by visualising spreading [20]. In a similar work by Çelik et al. (2020), the spreading area of the artificial blood on the airlaid nonwoven fabrics was determined using an image-processing approach [21]. Atasagun and Kara (2022) used MMT to evaluate the wetting characteristics of double-layer sanitary napkin upper layers [22]. Similarly, MMT was used in other nonwoven studies [17, 23, 24]. Cheema et al. (2018) conducted wicking and absorption tests to evaluate the comfort properties of nonwoven apparel fabrics [25]. Dubrovski and Brezocnik (2016) studied the relation between the porosity and vertical wicking properties of nonwoven samples [26].

In our previous studies, many properties of various nonwoven fabrics across several end-use areas were examined and discussed. For example, the physical, morphological, mechanical, and permeability properties of hydroentangled nonwoven samples made up of bicomponent microfilaments were evaluated in detail to assess their suitability for durable apparel [27]. In a different study, the ultrasonic weldability of the same fabrics was studied extensively via 60 different types of ultrasonic welding applications with 12 parameters [28]. In another study, three different nonwoven samples (light-, medium-, and heavy-weight) were stitched with varying sewing parameters to demonstrate their sewability [29]. In our latest study, objective circular and linear contact methods were compared and supported by subjective roughness/hand tests to determine the surface properties of 9 nonwoven samples for next-generation durable apparel [30]. Additionally, the authors examined the frictional and moisture management properties of two-layered upper layers of sanitary napkins [22] and the time- and wetness-dependent bending and compressibility properties of sanitary napkin layers [31].

By considering the extensive knowledge and practical experience in testing broad nonwoven materials

across different areas, this study gathered samples for four different application areas where liquid moisture transfer is of great importance. The application areas were selected as wound dressings, cleaning cloths, apparel, and hygienic pads. Both determining the liquid moisture management properties of several nonwoven samples and comparing different test methods by correlation analysis were in focus. The motivation question and the novelty of the work arose from the need to determine the differences and relationships among wetting measurement methods for nonwoven fabrics. In addition, the drying behaviour, which is important for many application areas and related to the moisture transfer properties of fabrics [32], was under investigation.

2. Material and Method

2.1 Materials

The materials of this study consisted of 13 nonwoven fabrics produced for different end-use areas. The samples covered a wide range of unit mass, from 20 to 190 g/m², according to the suppliers' data. The codes, application areas, contents, and production methods of nonwoven samples are given in Table 1. Nonwoven samples of the study were produced to be used especially for four different areas, namely; wound dressings, apparel, cleaning cloths, and hygienic pads. Samples were made up of bamboo, Tencel, polypropylene, bicomponent polyester: polyamide fibers, and wood pulp with and without superabsorbent polymer (SAP), that suited and specialized for the end-use area purposes. With the same goal, they were produced via different methods and machinery.

2.2 Methods

2.2.1 Wetting properties

The main focus of the study was to evaluate the wetting properties of nonwoven samples via different testing methods. For this purpose, five different testing methods were utilised, namely moisture management test (MMT), contact angle measurement, drop (absorption) test, vertical wetting (wicking) test and drop spread test. In addition, six different parameters were tested within the MMT method. The details of the wetting tests are as follows.

The moisture management properties of samples were determined with an SDL Atlas Moisture Management Tester (MMT) according to the AATCC 195-2009 standard [14]. Wetting time, absorption, maximum wetted radius, and spreading speed were measured for both the top and bottom surfaces. In addition, accumulative one-way transport (AOTI) and overall moisture management capacity (OMMC) values were yielded from the tests.

The drop test (absorbency test) was used to determine the water absorbency (wettability) of fabrics. In this study, the drop test was performed according to AATCC 79-2014 [33]. Samples with 20x20 cm dimensions were prepared, and one drop of pure water was allowed to fall onto the taut fabric from a distance of 1 cm using a burette with 15-25 drops/ml. The time in seconds was recorded when the drop on the fabric lost any light reflection and changed to a dull and wet spot. If the time was longer than 120s, it was recorded as >120s.

Table 1. Sample properties, corresponding end-use areas, and sample codes

No	End-use area	Sample code	Content	Production method	Unit mass* (g/m ²)
1	Wound dressing	Y1	Bamboo	Spunlace	40
2		Y2	Tencel	Spunlace	40
3	Apparel	G1	Bicomponent PET:PA	Bicomponent hydroentangled	110
4		G2	Bicomponent PET:PA	Bicomponent hydroentangled	138
5		G3	Bicomponent PET:PA	Bicomponent hydroentangled	165
6	Cleaning cloth	T1	PP	Meltblown	45
7		T2	PP	Meltblown	70
8		T3	PP	Meltblown	80
9	Hygienic pad layers	H1	PP (top sheet)	Spunbond thermally bonded	20
10		H2	PP (top sheet)	Spunbond thermally bonded	30
11		H3	Cellulose (Wood pulp) (ADL**)	Latex-bonded airlaid	60
12		H4	Cellulose (Wood pulp) (ADL)	Latex-bonded airlaid	70
13		H5	Wood pulp + Latex + SAP (absorbent layer)	Latex-bonded airlaid	190

*Suppliers' data ** Acquisition distribution layer

Spreading test was performed to evaluate the speed of water transfer, via spreading area [32, 34] For this purpose, 0.2 ml of pure water was allowed to drop on the sample surfaces by using a glass pipette. The distance between the pipette tip and the sample surface was kept 1 cm. After dripping the drop on the samples, the sample surfaces were recorded by a camera for the following 120 seconds. The records were further evaluated, and the area and the speed of the spreading were compared based on visual assessment.

Vertical wicking rate of the samples was determined according to the ISO 9073-6:2025 standard [35]. Five 25x3 cm sized samples were prepared in both machine and cross directions for all sample types. A 1.4 g weighed clip was attached to the narrow bottom end of the samples to maintain a vertical position and ensure equal contact with the liquid for all samples. Samples were marked at a 1.5 cm distance on the bottom edges to be immersed in the test solution. Each sample was immersed in a 10 g/L potassium chromate (K_2CrO_4) solution, ensuring only the lower end was in contact. Timing was started when the liquid level was at 0 cm on the ruler. The capillary rise (vertical wicking height) of the liquid within the fabric was recorded in cm at 10 different time points: 30, 60, 90, 120, 150, 180, 210, 240, 270, and 300 seconds. The K_2CrO_4 was added to the test solution to ensure correct readings for the vertical wicking heights. K_2CrO_4 was selected because synthetic fibers did not show affinity to this inorganic salt [36, 37].

Contact angle is another test to evaluate the surface hydrophilicity/hydrophobicity. In this study, contact angle measurements were performed using a OneAttention contact angle measurement device, which operates based on optical imaging and analysing the shape of the liquid drop. During the test, fabric samples were placed evenly and tautly on the device platform, and one drop of pure water was applied to the surface of each sample. The device automatically calculated and recorded the contact angle value in 10 seconds after the water drop was deposited on the fabric surface. The resulting contact angle values were evaluated according to 6th seconds' values to assess the fabrics' hydrophilic (wetting) or hydrophobic (non-wetting) surface characteristics.

All wetting tests were repeated 5 times for each sample type.

2.2.2. Drying properties

To determine the drying properties, 5x5 cm samples were cut and conditioned. 0.5 ml of pure water was added to a plastic sample container, and the 5x5 sample was placed on the water and became wet. Then the wetted fabric sample was weighed with the container. This was called the beginning weight (w_b). The weight of the wet sample with the container was

weighed again after 30, 60, 90, 120, and 180 minutes (w_i). The drying percentages were calculated using the weight changes according to Equation 1. The resulting weight changes indicated the amount of water evaporation over time and provided quantitative information about the drying characteristics of each fabric. 5 repetitions were performed for each type of sample.

$$DP(i)\% = \frac{w_b - w_i}{0.5} * 100 \quad (1)$$

(DP(i) %= drying percentage at the i^{th} minute, w_b =beginning weight, w_i = weight at the i^{th} minute)

2.2.3. Physical properties

Unit mass (BS EN 29073-1) [38] and thickness (TS 7128 EN ISO 5084 [39], James Heal RxB Cloth Thickness Tester) of samples were determined as the physical properties of the samples. The thickness of the samples was determined under a 5 gf/cm² test pressure. Each test was repeated five times for each sample type.

All wetting, drying, and physical tests were performed under standard atmosphere conditions (20 ± 2 °C, $65 \pm 5\%$ relative humidity) after conditioning the samples for at least 24 h.

Statistical analysis was performed to examine the relationships among different wetting test results. For this purpose, SPSS 30 Package Programme was utilised to perform Pearson's correlation analysis at a 0.05 significance level.

3. Results

3.1. Physical Properties

The unit mass and thickness results of the samples are given in Table 2. The unit mass of the samples was diverse, varying between 20 and 216 g/m², and changed according to their end-use areas. This variation was intentionally chosen to gather different samples together while comparing different test methods. The thicknesses of the samples were also consistent with the unit mass values, ranging from 0.23 to 1.26 mm. The top sheet samples H1 and H2 were the thinnest samples, while the absorbent layer H5 was the thickest.

Table 2. Unit mass and thickness results of samples

No	End-use area	Sample code	Unit mass (g/m ²)		Thickness (mm)	
			Mean	St. Dev.	Mean	St. Dev.
			1	Wound dressing	Y1	44.0
2	Y2	45.1	1.5		0.42	0.04
3	Apparel	G1	109.1	3.7	0.55	0.05
4		G2	137.2	4.8	0.57	0.02
5		G3	152.0	4.6	0.57	0.03
6	Cleaning cloth	T1	48.5	2.1	0.43	0.01
7		T2	72.9	2.0	0.60	0.05
8		T3	82.4	3.4	0.64	0.03
9	Hygienic pad layers	H1	20.2	0.5	0.23	0.03
10		H2	30.4	0.5	0.28	0.04
11		H3	61.6	3.1	0.66	0.05
12		H4	75.2	1.8	1.13	0.02
13		H5	216.6	5.7	1.26	0.06

3.2 Wetting properties

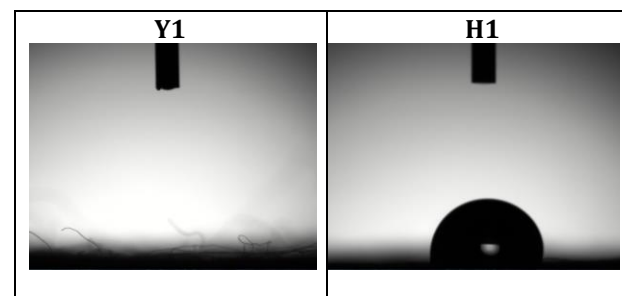
The drop test and contact angle measurement results of the samples are presented in Table 3. Shorter times indicate better absorbency of the samples for the drop test [33]. **The drop test** results showed that the spunlace fabrics for wound dressings (Y1, Y2), the bicomponent microfiber fabrics for clothing (G1, G3), and the meltblown polypropylene fabrics for cleaning cloths (T1-T3) and some of the hygienic pad layers (H4, H5) all absorbed water immediately upon contact and yielded 0 s absorption time. Similarly, G2 and H3 samples exhibited very short absorption times (11 and 2.5 s, respectively). Only the spunbond polypropylene fabrics coded H1 and H2 gave absorption times longer than 120 s. The water droplet did not spread on these fabrics and retained its shape for a long time. This is thought to be due to the hydrophobic nature of the PP raw material and the insufficient application of hydrophilic treatment for these samples [40]. Similar long absorption time result as for H1 and H2 samples was obtained for nonwoven polyester fabric in the literature, although having hydrophilic treatment [11].

The contact angle results were in good agreement with the drop test results. It was observed that the water dripped onto the wound dressing (Y1, Y2), clothing (G1, G2, G3), and cleaning cloth (T1, T2, T3) samples spread completely onto the fabric surface, and was not hold on the sample surfaces as a drop (Figure 1). The contact angle values for these samples were measured as 0° at 6th second, indicating that these surfaces were completely hydrophilic and rapidly absorbed the test liquid. On the other hand, the top-layer samples H1 and H2, in the hygienic pad group, exhibited significantly hydrophobic behaviour with contact angles of 86.20° and 82.55°, respectively. These values indicate that these samples retained the liquid on the surface, absorption was slower, and the

liquid remained on the fabric surface rather than penetrating it. This result is in line with the literature in which the contact angles for untreated PP nonwovens were detected around 120- 140° [40, 41]. This result proves the need for an additional hydrophilic treatment due to the need to transfer the liquid to the lower layers in a pad structure. These results were also in accordance with the absorption test results (Pearson's correlation coefficient: 0.977). The contact angle was measured as 0° in samples H3, H4, and H5, demonstrating that these hygienic pad layers tend to rapidly absorb liquid as expected. Overall, for both of these two test methods, the absorbency and hydrophilicity of all samples except H1 and H2 were assessed as very high. Although having the same raw material (PP), cleaning cloth samples (T1-T3) exhibited superior absorption times (0 s) and contact angle results (0°) compared to H1 and H2 competitors. The difference of these results may be sourced from the fabric production technologies (melt-blowing and spunbonding), fabric unit masses, fiber fineness and the finishes applied to fabrics.

Table 3. Drop test and contact angle measurement results of the samples

No	End-use area	Sample code	Drop Test Absorption time (s) (St. Dev.)	Contact angle at 6 th second (°) (St. Dev.)
1	Wound dressing	Y1	0	0
2		Y2	0	0
3	Apparel	G1	0	0
4		G2	11.0 (3.1)	0
5		G3	0	0
6	Cleaning cloth	T1	0	0
7		T2	0	0
8		T3	0	0
9	Hygienic pad layers	H1	>120	86.2 (13.09)
10		H2	>120	82.55 (21.28)
11		H3	2.5 (1.1)	0
12		H4	0	0
13		H5	0	0

**Figure 1.** Representative contact angle test photographs of samples at the 6th second of the test (Samples Y1 and H1)

The drop spreading test results are exhibited as sample images taken at the beginning of the test and 30, 60, 90, and 120 s later, as a function of time (Figure 2). Figure 2 shows that the nature of the samples' spreading behaviour was different. In general, the spreading area of the clothing fabrics was the highest. Especially, the G1 sample achieved the highest spreading diameter during the entire test period, starting from the beginning of the test. At 120 seconds, the liquid spread over a relatively large area. This demonstrates that G1, with its high absorbency and spreading capacity, exhibits effective moisture management performance. The clothing fabrics G2 and G3 also exhibited high spreading areas at 120 s. In accordance with the absorption test, the G2 sample did not rapidly absorb the water in the beginning; however, within 30 seconds, the reflectivity of the drop was lost completely, and the drop was absorbed by the sample and distributed to the surface.

Wound dressing fabrics (Y1-Y2) also showed considerable spreading, which might assist in maintaining surface dryness. While clothing fabrics (G1, G2) were highly effective at moisture management due to their high absorbency and spreading properties, cleaning cloths (T1-T3) focused on absorbing the liquid. Therefore, the observation that the water did not spread along the cleaning cloth samples during the test period was deemed adequate for their intended end use.

The spreading behaviour of water on hygienic pad layers was also interesting. When water was dripped onto the H1 and H2 samples, it was not rapidly absorbed by the fabrics, consistent with the contact angle and absorption test results. Within 30 seconds, the drop was absorbed by H1 and began spreading on the fabric. However, sample H2 showed almost no liquid spreading. The droplet shape remained intact throughout the entire time interval, in parallel with absorbency and contact angle results. As for cleaning cloth samples, contrary to expectations, the H3 and H4 samples used as the ADL layer in hygienic pads did not show any spreading after absorbency. In sample H5 (absorbent layer), the droplet appearance was quite faint, and spreading could not be observed. Normally, the absorbent layer ensures rapid absorption of liquid, trapping it within the interior of the pad; therefore, the horizontal spreading of liquid in this layer is undesirable. The spreading test results are in line with this expectation. According to the spreading images, the spreading area was altered to an elliptical shape for some samples, which may be due to the more dominant anisotropic structure of these samples [20].

Vertical wicking measures the rate at which water is transported into the sample by capillary action [35]. The vertical wicking heights of the tested samples in both machine (MD) and cross (CD) directions are given in Figure 3. In the machine direction, generally higher capillary rise values were obtained. This was in line with the literature [11, 42]. Y1, G1, and T1 samples

demonstrated higher liquid rises from the beginning of the test. These fabrics reached capillary wicking heights of 9.9 cm, 10.4 cm, and 9.0 cm, respectively, at 300 seconds. This indicates that these fabrics have higher capillarity, facilitating liquid transmission [9]. In contrast, capillary rise was almost non-existent in samples H1 and H2. Liquid rise remained at 0 cm for these fabrics. This suggests that these structures were resistant to liquid permeation and could be assessed as liquid repellent. This result was in accordance with other wetting tests. In tests conducted in the cross-machine direction, generally lower capillary rise values were observed. Compared with the machine-direction values for the same fabric groups, it is clear that the directional effect plays a significant role in liquid transmission. On the other hand, low capillary wicking performance was observed in some fabrics, such as H3, H4, and Y2, indicating that their liquid transmission capacity or capillarity was limited. There were strong negative correlations between the vertical wicking results (both in MD and CD) and drop/contact angle results (Corr. coefficients were between -0.7 and -0.8).

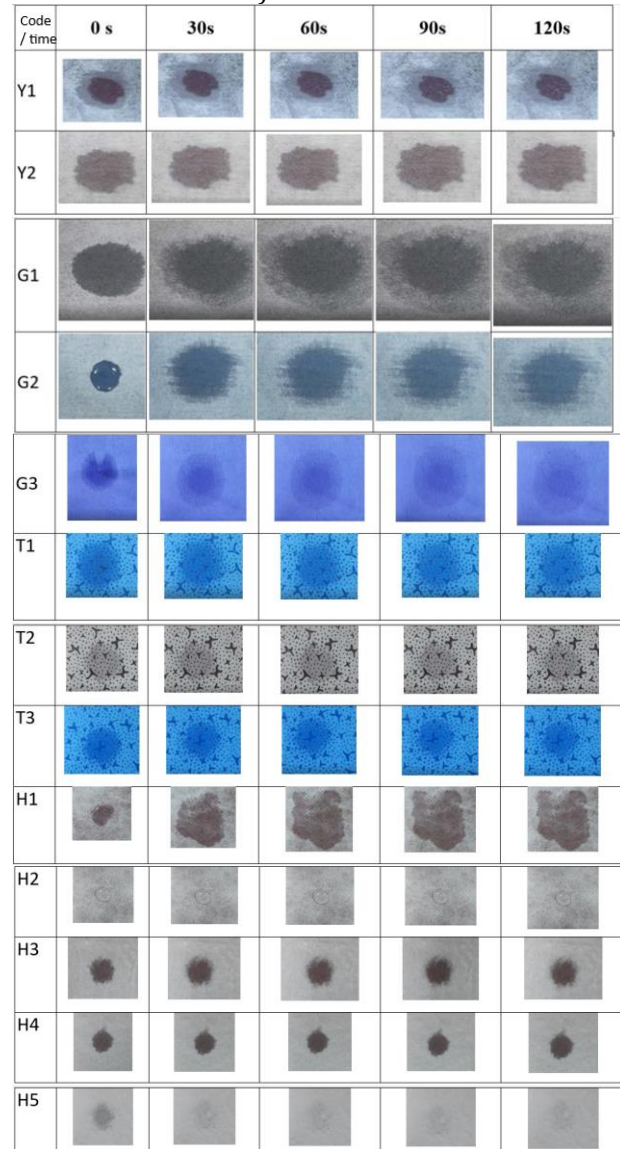


Figure 2. Spreading test results depending on time

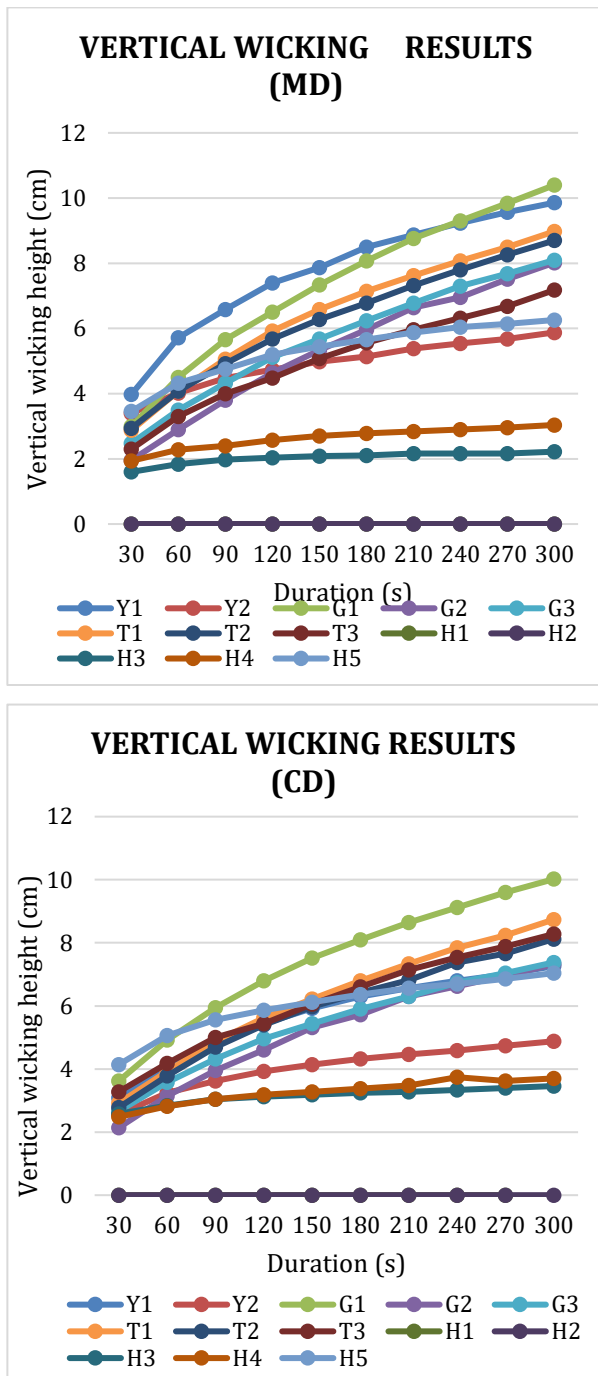


Figure 3. Vertical wicking results of samples

3.3 Moisture Management Test Results

Moisture management test results of samples were evaluated under six test parameters, namely: Wetting time (top and bottom surfaces), absorption (top and bottom surfaces), maximum wetted radius (top and bottom surfaces), spreading speed (top and bottom surfaces), accumulative one-way transport index (AOTI), and overall moisture management capacity (OMMC). The numeric results were evaluated as wetting qualifications according to the grading system in Appendix A. The relations between the MMT parameters and the other wetting tests were examined via correlation analysis.

Wetting time corresponds to the time period in which the sample surfaces start to get wet [22, 43]. The top and bottom surface wetting time results are given in Figure 4.a. Samples Y1 and T1 wetted in less than 3 seconds and were considered as very fast-wetting samples. Similarly, samples G1, T2, T3, H3, and H4 wetted from the top surface in 3-5 seconds, qualifying them as fast-wetting samples. Most of the other samples wetted in the 5-19 seconds range and were considered as medium-fast wetting samples. Only samples Y2 and H1 wetted for 20 seconds or more, qualifying them as slow-wetting samples. Positive weak correlations were detected between the top surface wetting time and drop and contact angle results (corr. coef.: 0.353 and 0.378, respectively). A relationship was reported between the drop test and MMT wetting time results in Kaplan et al [24]. Supporting this inference, a weak correlation was exhibited statistically between these two test outputs in the current study. Very weak negative correlations were found between the top surface wetting time and vertical wicking results (corr. coef.: -0.280 to -0.301). The bottom surface wetting times of the samples were generally similar to the top surface wetting times, but the Tencel sample Y2 wetted faster on the bottom surface than on the top surface. A similar result was observed for the H1 sample as well. Unlike all other samples, the H2 pad layer fabric wetted much more slowly (100 seconds) on the lower surface. This is thought to be due to the water droplet remaining on the fabric surface without being absorbed during analysis in samples H1 and H2. This demonstrates the hydrophobic nature of these two samples and is consistent with the results of previous contact angle and droplet tests. The correlation coefficients were higher for the bottom surface wetting time and drop/contact angle test results, as 0.661 and 0.596, respectively (positive moderate correlation), similar to the stronger negative correlations with the vertical wetting results (corr. coef.: -0.492 to -0.525).

The absorption test results are given in Figure 4.b. Almost all of the samples exhibited moderate or fast absorption (30-49 and 50-100 %/sec). Generally, the absorption rates on the bottom surfaces were slightly higher. Only the H2 sample showed a high absorption rate at the top surface but a very slow rate at the bottom surface (1%/sec). This is thought to be due to the test liquid's inability to penetrate the fabric's bottom surface because of its hydrophobic structure. Only the top surface absorption results exhibited a positive low correlation with the drop and contact angle test results (corr. coef.: 0.390 and 0.432, respectively).

The maximum wetted radius values of samples are given in Figure 4.c. The highest radii were generally observed in wound dressing fabrics and cleaning cloth fabrics. In general, the maximum wetting radii on the top and bottom surfaces of the fabrics were similar.

The hydrophobic samples H1 and H2 also had low top and bottom surface wetting radii. These samples did not get wet according to the scale. In general, all of the wound dressing, clothing, and cleaning cloth fabrics exhibited very high maximum wetting radii. While the highest spreading after 2 minutes was found in the clothing fabrics in the drop spreading test (Figure 2), this was not confirmed by the maximum wetting radii in the MMT. This may be due to the wetting liquid properties [6]. Nevertheless, negative moderate or strong correlations were detected between the top and bottom surface wet radii and the drop/contact angle tests (corr. coef. were between -0.668 and -0.743). In addition, positive moderate to strong correlations were detected between the top/bottom surface wet radii and the vertical wicking results (corr. coef. were between 0.651 and 0.753).

Spreading speed results for samples are given in Figure 4.d. According to the results, the test liquid spread very rapidly on the wound dressings and cleaning cloths, corresponding to the very fast category (>4 mm/s). Samples H1 and H2 of the hygienic pad layers exhibited very slow water

spreading. This is considered to be required for the top layers, so that the bodily liquids would be transferred into the adjacent inner layers quickly. Samples H3 and H4 exhibited medium-fast spreading. Slow or medium spreading was observed in H5, the absorbent layer. A low spreading rate is considered normal because the liquid is absorbed by the superabsorbent polymers in this layer. Samples H3 and H4 exhibited higher spreading speeds on both the top and bottom surfaces than the other pad layers. However, because this layer must rapidly spread absorbed body fluid across the surface, its diffusion rate may be further improved. Sample G1 exhibited fast/very fast spreading, while G3 exhibited fast spreading, and G2 exhibited slow spreading on both surfaces. As shown in Figure 4.c and d, the maximum wetted radii and spreading speeds were in line for the samples [44]. Top and bottom surface spreading speeds were in negative weak correlations with the drop and contact angle test results (corr. coef. were between -0.425 and -0.489) while positive low to moderate correlations were observed for vertical wicking results in both directions (corr. coef.: 0.428 to 0.573).

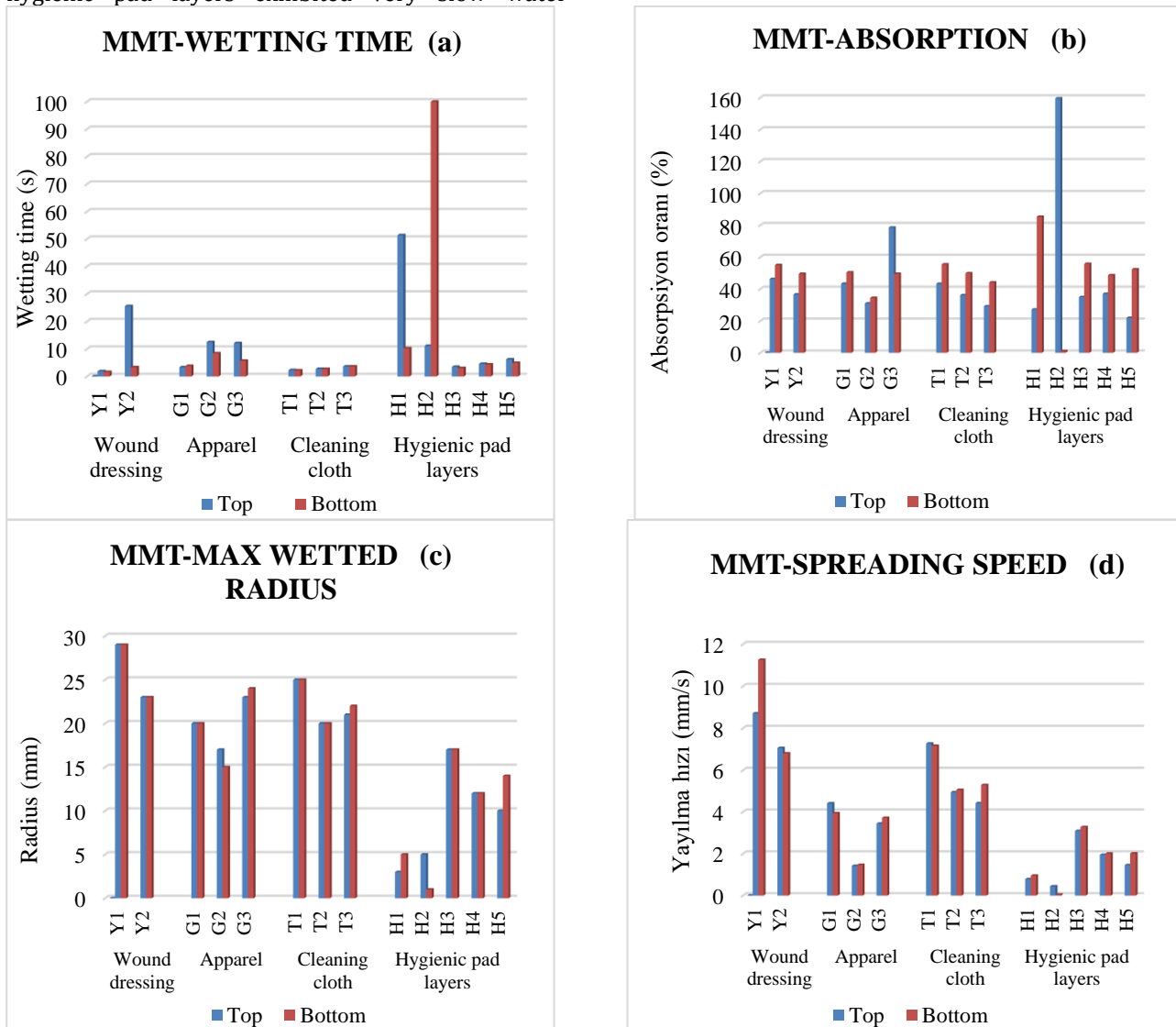


Figure 4. MMT test results

The AOTI and OMMC results of the samples are given in Table 4. **AOTI** shows the one-way liquid transport capacity from the top to the bottom surface of the material [22, 43]. According to the results, the most successful one-way transport values were observed in H1 and H5 pad layers. While most of the garment and cleaning cloth fabrics exhibited very good AOTI performance, the wound dressing samples exhibited good conductance performance. In this respect, although the sanitary pad layers generally performed very well, a negative AOTI value was observed in the top layer fabric, coded H2. As observed in all other wetting tests, the water droplet remained on the top surface and was not transferred to the inner side of the sample. This was considered a negative feature for the pad's top layer. The AOTI results showed a negative weak correlation with only the drop test result (corr. coef.: -0.247) among all other wetting test results. The OMMC results showed that all samples had good or very good overall moisture management capacity. Only the hydrophobic H2 sample exhibited very poor liquid management performance. The OMMC results exhibited negative moderate correlations with drop and contact angle test results (corr. coef.: -0.4484 and -0.449, respectively) while showing positive moderate correlations with vertical wicking results in machine and cross-directions (0.404 and 0.434, respectively).

Table 4. The AOTI and OMMC values of the samples

No	End-use area	Sample code	One-Way Transport Index (%)		OMMC Index	
			Mean	St. Dev.	Mean	St. Dev.
1	Wound dressing	Y1	197	21	0.6	0.0
2		Y2	194	33	0.6	0.2
3	Apparel	G1	293	28	0.7	0.1
4		G2	180	158	0.4	0.2
5		G3	202	25	0.6	0.1
6	Cleaning cloth	T1	225	9	0.7	0.0
7		T2	303	50	0.8	0.1
8		T3	246	120	0.7	0.2
9	Hygienic pad layers	H1	807	235	0.7	0.1
10		H2	-741	34	0.0	0.0
11		H3	358	55	0.8	0.0
12		H4	166	36	0.4	0.0
13		H5	534	24	0.7	0.0

3.4 Drying properties

Drying test results are tabulated in Appendix B and visualised in Figure 5. Drying rates were measured at specified time intervals (30, 60, 90, 120, and 180 minutes). The highest drying rates were obtained from apparel fabrics in general, with a level higher than 87%. In 180 minutes, the G1 and G2 samples got almost totally dry. As the weight of the apparel fabrics

increased, drying speed decreased. A similar inference was made for viscose nonwoven fabrics in the literature [45]. The apparel fabrics (G1, G2, G3) were generally noted for their high moisture transport (Figure 2), and the high drying rates are considered to be related to this. Wound dressing samples (Y1, Y2) exhibited moderate drying properties, with sample Y1 demonstrating a higher performance with a drying rate of 90.86%. This suggests that they provide a suitable absorbent surface structure to balance moisture in the wound environment. The cleaning cloth samples (T1, T2, T3) exhibited balanced and functional performance with drying rates exceeding 90%; T2 reaching the highest rate at 94.11%. This feature is important for quickly preparing the cleaning cloths for reuse. Significant differences were observed between the samples H1–H5, which were evaluated as hygienic pad layers. Sample H1 achieved the highest drying rate among all the samples, with 99.99%. This sample is the thinnest and lightest in weight. In contrast, samples H2–H5 exhibited lower drying rates, indicating that the liquid was retained in the structure for a longer period of time and that evaporation occurred more slowly. H3, H4, and H5 samples dried to most 46% after 180 min of wetting. Drying would be important if the sanitary napkins were intended to be reused [46]; however, due to the usage of disposable sanitary napkin layers, low drying rates were not considered a deficiency.

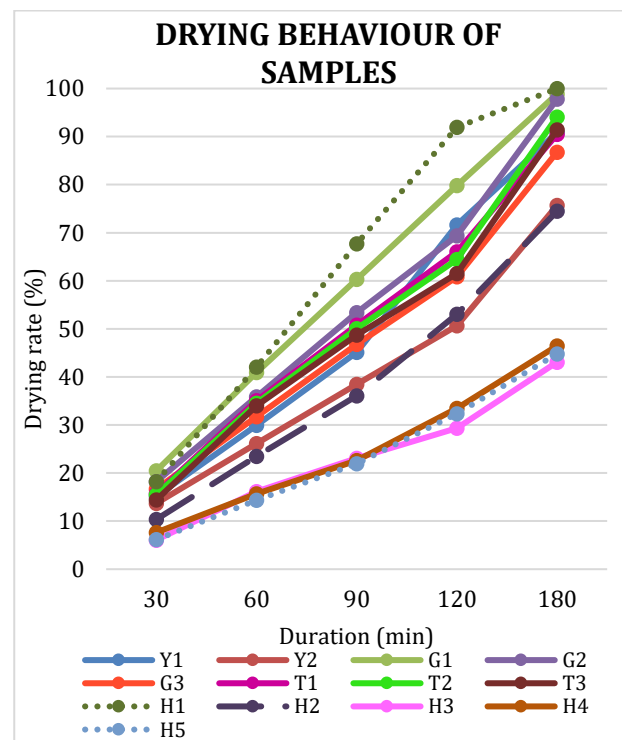


Figure 5. Drying behaviour of the samples

4. Discussion and Conclusion

In this study, a comparison work was performed on the evaluation of wetting properties of nonwoven fabrics via different test methods. For this purpose, 13

nonwoven samples from four different application areas with a wide unit mass (20-216 g/m²) and production method range were selected. The basic criterion of the sample detection was the high wetting/liquid moisture transfer requirements for the targeted end-use areas. As an additional experiment, the drying behaviour of the samples was determined.

According to the evaluations, although the results in the drop test would be affected by the observer, its results were in very good agreement with the objective contact angle measurement results. Most of the samples with a 0° contact angle also yielded 0 seconds or very small values for water absorption in the drop test. In addition, despite the fact that the vertical wicking rates were determined separately for machine and cross directions, they also showed a strong correlation with drop and contact angle test results, but this time negatively. This was related to the different evaluation approaches for these methods: The increasing numbers in drop and contact angle tests indicated lower qualification of wetting, while increasing values in the vertical wicking test proved better wetting qualification.

On the other hand, the drop spreading test reflected relatively longer time dependent liquid transfer behaviour of the samples. Because most samples absorbed water quickly in the drop test and yielded 0° contact angles, it was difficult to distinguish the samples from the test results. It was mentioned in the literature that contact angles could be useful for comparative measurements on hydrophobic samples, and also, the sessile droplet will penetrate the porous hydrophilic substrates, typically in seconds, effectively prohibiting the measurement [10, 47]. Differently, the spreading behaviour could be used to group samples in more details. The leading results were obtained for apparel fabrics, which were found very useful to spread and evaporate the sweat apart from the human body. Interestingly, the hygienic pad layers did not spread the drops in general but absorbed them immediately in the inner parts, covering a smaller area. It was clearly understood that time-dependent planar spreading of water on samples was tuned for the targeted application areas.

MMT results were evaluated under 6 parameters. The top and bottom surface wetting times correlated with all drop test (positive correlation), contact angle (positive correlation), and vertical wicking (negative correlation) test results. The correlations with the bottom surface wetting times were stronger. However, as the drop test was considered to be closely related to wetting time, the correlation coefficients were obtained smaller than expected. Similarly, the MMT absorption test results exhibited low correlation with the drop and contact angle results.

The maximum wetted radius values showed negative moderate-to-strong correlations with the drop and

contact angle test results and moderate-to-strong correlations with the vertical wicking test. The harmony between the maximum wetted radii and vertical wicking results was considered appropriate as both tests handled spreading-related wicking behaviour. However, the visual appearance obtained from the spreading test was not entirely consistent with the top-surface maximum wetted radius results. A related property, spreading speed, also exhibited correlations with drop, contact angle, and vertical wicking test results, but with lower strength compared to that of maximum wetted radii. On the other hand, the AOTI that shows the one-way liquid transport capacity from the top to the bottom surface only showed a weak correlation with the drop test, which indicates that the other testing methods cannot be used to explain the one-way transport behaviour of samples. The drying behaviour of samples was also investigated within the study, introducing a testing method to evaluate the time-dependent drying of fabric samples.

The study was limited by the samples preferred in this study. In further work, the study may be enhanced by adding less absorbent samples for other application areas such as automotive and packaging. In addition, in the future studies, the direct effects of raw materials and nonwoven fabric production technologies on the wetting properties can be evaluated using systematically produced sample sets in which the other technological parameters such as fiber fineness, fabric unit mass etc. will be kept constant.

Acknowledgments

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Declaration of Ethical Code

In this study, we undertake that all the rules required to be followed within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" are complied with, and that none of the actions stated under the heading "Actions Against Scientific Research and Publication Ethics" are not carried out.

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Appendices

Appendix A. AATCC 195-MMT Evaluation Table

Index	Surface	Grade				
		1	2	3	4	5
Wetting time (s)	Top	≥120 No wetting	20-119 Slow	5-19 Medium	3-5 Fast	<3 Very fast
	Bottom	≥120 No wetting	20-119 Slow	5-19 Medium	3-5 Fast	<3 Very fast
Absorption (%/s)	Top	0-9 Very slow	10-29 Slow	30-49 Medium	50-100 Fast	>100 Very fast
	Bottom	0-9 Very slow	10-29 Slow	30-49 Medium	50-100 Fast	>100 Very fast
Maximum wetted radius (mm)	Top	0-7 No wetting	8-12 Small	13-17 Medium	18-22 Large	>22 Very large
	Bottom	0-7 No wetting	8-12 Small	13-17 Medium	18-22 Large	>22 Very large
Spreading Speed (mm/s)	Top	0.0-0.9 Very slow	1.0-1.9 Slow	2.0-2.9 Medium	3.0-4.0 Fast	>4 Very fast
	Bottom	0.0-0.9 Very slow	1.0-1.9 Slow	2.0-2.9 Medium	3.0-4.0 Fast	>4 Very fast
AOTI (%)		<-50 Poor	-50-99 Fair	100-199 Good	200-400 Very good	>400 Excellent
		0.0-0.19 Poor	0.2-0.39 Fair	0.4-0.59 Good	0.6-0.8 Very good	>0.8 Excellent

Appendix B. Drying behaviour of the samples

No	End-use area	Code	Drying percentage (%)									
			30 min		60 min		90 min		120 min		180 min	
			Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
1	Wound dressing	Y1	15.16	0.96	29.97	2.17	45.16	3.22	71.62	5.98	90.86	4.43
2		Y2	13.71	0.81	26.12	1.80	38.48	2.54	50.67	3.13	75.70	4.98
3	Apparel	G1	20.47	3.58	40.94	7.34	60.32	11.09	79.85	14.80	98.87	6.12
4		G2	18.23	1.91	35.89	3.08	53.37	4.70	69.41	5.64	97.80	2.81
5		G3	16.68	2.59	31.76	4.90	46.79	7.18	60.84	9.64	86.79	12.80
6	Cleaning cloth	T1	15.75	2.00	35.10	2.88	50.79	3.84	66.06	5.20	90.47	7.22
7		T2	15.48	1.90	34.55	4.54	50.05	6.48	64.44	8.17	94.11	5.73
8		T3	14.40	2.66	33.99	6.56	48.71	9.44	61.53	11.47	91.40	8.16
9	Hygienic pad layers	H1	18.23	1.91	42.05	4.14	67.70	4.81	91.96	7.69	99.99	0.12
10		H2	10.35	7.37	23.45	9.21	36.05	12.40	53.03	12.15	74.47	13.86
11		H3	6.07	1.08	16.17	1.23	23.08	1.17	29.34	1.53	43.08	2.27
12		H4	7.63	1.20	15.69	2.35	22.63	3.26	33.47	4.06	46.47	5.41
13		H5	6.15	0.68	14.37	1.45	21.93	1.02	32.32	3.40	44.81	4.56