Studies on the Moisture Management Characteristics of Spunlace Nonwoven Fabric

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Abstract

Liquid moisture transfer, sweat absorbency and sweat drying in clothing have a significant influence on the wearer’s perception. Moisture management is one of the key performance criteria in determining the comfort level of fabric. It is thus important to study the moisture management characteristics of spunlace nonwoven fabric to investigate the possibility of its use in apparel. In the present study, spunlace nonwoven fabrics were produced by varying waterjet pressure, delivery speed, web mass and web composition. The effect of different parameters on various properties of the moisture management tester was studied using a response surface methodology with backward elimination. The statistical analysis showed that web composition affected all parameters of the moisture management tester. Waterjet pressure and web mass do not have a significant effect on wetting time (top), absorption rate (bottom) and one-way transport capability. The effect of delivery speed was not found to be significant. The overall moisture management coefficient of all nonwoven fabrics studied was found to be very good. An increase in web mass resulted in a decrease in the overall moisture management coefficient value of nonwoven fabric, which can be halted by using higher waterjet pressure and through the proper selection of web composition. Nonwoven fabric with either 100% viscose or 50% polyester/50% viscose blended composition, with higher waterjet pressure and higher web mass, was found to be suitable for the apparel industry.

Keywords: moisture, overall moisture management coefficient, waterjet pressure, web mass

Izvleček

Prenos in absorpcija znoja ter sušenje znoja pomembno vplivajo na občutek nošenja oblačil. Odziv oblačil na vlago je eden ključnih dejavnikov vrednotenja udobnosti tekstilnega materiala. Zato je za oceno primernosti vlaknovin, utrjenih z zračnim curkom, za oblačila pomembno proučiti njihovo odzivanje na vlago. V tej študiji so bile izdelane vlaknovine, utrjene z različnimi pritiski vodnega curka, različnimi hitrostmi izdelave, z različnimi ploščinskimi masami in surovinsko sestavo. Z uporabo metodologije odzivnih površin in povratne eliminacije so bili proučeni različni vplivni parametri vlaknovin na izmerjene lastnosti prenosa vlage. Statistična analiza je pokazala, da surovinska sestava vpliva na vse parametre prenosa vlage. Tlak vodnega curka in ploščinska masa vlaknovine nista pomembno vplivala na njen čas omotčenja (zgornje strani), hitrost absorbicije (na spodnji strani) in sposobnost odvajanja vlage. Tudi hitrost izdelave vlaknovine ni imela pomembnega vpliva. Ugotovljeno je bilo, da je bil skupni koeficient odzivanja na vlago pri vseh vlaknovinah zelo dober. Povečanje ploščinske mase je vplivalo na znižanje skupnega koeficienta odzivanja vlaknovine na vlago, kar pa je mogoče preprečiti z uporabo višjega pritiska vodnega curka in z ustreznim izbirom surovinske sestave vlaknovine. Ugotovljeno je bilo, da so vlaknovine iz 100-odstotnih viskoznih vlaken ali iz mešanice 50 % poliester/50 % viskoza ob uporabi višjega pritiska vodnega curka in večje ploščinske mase primerno za izdelavo oblačil.

Ključne besede: vlaga, skupni koeficient prenosa vlage, tlak vodnega curka, ploščinska masa

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1 Introduction

Moisture regulation is one of the key performance parameters in today’s apparel industry. The microclimate between the skin and clothing should be thermally stable via moisture management, [1] and has a significant effect on the thermo-physiological comfort of the human body [2]. Moisture vapour transfer and liquid moisture transfer (sweat absorbency and sweat drying) in clothing plays an important role in the wearer’s perception. Moisture management fabric should transfer sweat in vapour moisture form when the body is motionless and should allow liquid moisture to be drawn off to the outer surface to evaporate when the body is working [3]. The multidimensional moisture transport property of a fabric is generally referred to as moisture management characteristics [4]. Fibre-liquid interaction affects the moisture management of fabric [5]. Fibre-liquid interaction phenomena depend on the surface tension and pore diameter/porosity of a fabric [6–7]. Because the transfer of heat and moisture through fabric is vital for designing clothing for specific uses, [8] many theoretical and experimental studies have been conducted to understand the moisture transport phenomena for both woven and knitted structures. Very few studies, [9–12] however, have discussed the moisture transport characteristics of nonwoven fabrics. Nonwoven fabrics are engineered fabrics that today are used almost everywhere. Spunlace nonwoven fabric is the most promising technology for the production of fabric used extensively in the apparel industry, on account of its good handling and tensile properties. Its structure also offers good structural integrity and is comparable to other nonwoven products. Spunlacing (hydroentanglement) is a mechanical type of bonding that uses high-speed jets of water to strike a web, so that fibres knot about one another [13]. The physical characteristics of hydroentangled nonwoven fabrics, such as softness, flexible handling, high drape and bulk, conformability and high strength without binders and good delamination resistance, make it unique among all other types of nonwoven fabrics. Applications of this fabric include bacteria-proof clothing, wet wipes and as interlining fabric [14]. Recent research also suggests the application of spunlace nonwoven fabrics in fashion apparel [15–16]. Application in the apparel industry, however, requires the careful study of thermal and moisture transmission characteristics. Limited reports in this regard are available.

Hajiani et al. [17] studied the absorbency behaviour of spunlace nonwoven fabrics produced at varying water jet pressures and different basic fabric weight. Increased jet pressure was reported to increase mass density, while water retention and permeability were reduced. Berkalp [18] studied the air permeability and porosity of spunlace nonwoven fabric, but did not discuss moisture transfer. He stated that the pore structure of nonwoven fabric affects various comfort properties, such as thermal conductivity and air permeability. The pores inside nonwoven fabrics are highly complex in terms of size, shape and capillary geometry [19]. Knowledge of pore size distribution is essential for understanding transport phenomena, particularly in a porous structure such as nonwoven fabric [20]. The absorption and spreading of fluid can be engineered by controlling the pore configurations of the substrate, [11, 21] while studies of the moisture and heat transfer characteristics of light nonwoven fabric have reported that a blend with hydrophobic fibre has a favourable effect on the drying behaviour of fabric. Ahmad et al. developed a hydroentangled fabric using comber noil and reported that waterjet pressure and conveyor speed (delivery speed) affect the moisture management properties of fabric [12]. The moisture transport characteristics of a fabric can be affected by any of the following parameters:

(i) the nature and quantity of each constituent fibre;
(ii) the structural parameters of fabric (which define the fluid flow passage geometry, i.e. pore size and the distribution thereof);
(iii) the mass and thickness of the material; and/or
(iv) structural or surface modification through mechanical or chemical treatment.

An attempt has been made in this study to investigate the effect of different material and process parameters of spunlace nonwoven fabric on the moisture management characteristics thereof.

2 Material and methods

2.1 Materials

Twenty-seven spunlaced nonwoven fabrics were produced from cross-laid carded web by varying water pressure, delivery rate, web composition and web mass, using a Box-Behnken experimental design. Viscose (38 mm, 1.4 dtex) and polyester (38 mm, 1.4 dtex) fibres were used in the study. Two fibres with significantly different moisture absorption characteristics

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Table 1: Factors and the levels thereof for the Box-Behnken design

| Material and process parameters | Level |
|--------------------------------|-------|
| Waterjet pressure [bar] X₁    | –1 0 1 |
| Delivery speed [m/min] X₂    | 50 100 150 |
| Web mass [g] X₃             | 50 100 150 |
| Web composition X₄           | PET a) 50PET/50CV b) CV c) |

a) Hereinafter, the abbreviation PET is used for 100% PET. b) Hereinafter, the abbreviation 50PET/50CV is used for a 50% PET/50% viscose blend. c) Hereinafter, the abbreviation CV is used for 100% viscose.

Table 2: Physical parameters of nonwoven fabric samples [22]

| Sample code | Waterjet pressure [bar] X₁ | Delivery speed [m/min] X₂ | Web mass [g] X₃ | Web composition X₄ | Fabric weight Mean/COV² [g/m²]/[%] | Fabric thickness Mean/COV [mm]/[%] | Mean pore diameter Mean/COV [µm]/[%] |
|-------------|----------------------------|--------------------------|----------------|--------------------|------------------------------------|------------------------------------|-------------------------------------|
| 1           | 50.00                      | 1.00                     | 100.00         | 50PET/50CV         | 98.5/6.23                          | 1.64/8.44                          | 74.3/20/5.84                       |
| 2           | 150.00                     | 1.00                     | 100.00         | 50PET/50CV         | 97.2/5.29                          | 1.00/7.64                          | 43.9/80/8.57                       |
| 3           | 50.00                      | 5.00                     | 100.00         | 50PET/50CV         | 99.1/8.25                          | 1.60/7.94                          | 75.9/00/9.55                       |
| 4           | 150.00                     | 5.00                     | 100.00         | 50PET/50CV         | 147.6/6.87                         | 1.08/6.66                          | 44.8/40/6.5                        |
| 5           | 100.00                     | 3.00                     | 50.00          | PET                | 43.7/6.78                          | 0.94/8.29                          | 95.8/30/7.79                       |
| 6           | 100.00                     | 3.00                     | 150.00         | PET                | 148.2/5.69                         | 1.20/7.13                          | 75.2/70/6.27                       |
| 7           | 100.00                     | 3.00                     | 50.00          | CV                 | 42.8/7.59                          | 0.62/5.29                          | 60.5/00/4.26                       |
| 8           | 100.00                     | 3.00                     | 150.00         | CV                 | 145.7/6.63                         | 1.12/4.92                          | 38.5/00/4.5                        |
| 9           | 100.00                     | 3.00                     | 100.00         | 50PET/50CV         | 96.7/8.91                          | 0.90/8.27                          | 53.5/30/7.22                       |
| 10          | 50.00                      | 3.00                     | 100.00         | PET                | 98.4/7.53                          | 1.28/6.4                           | 98.3/90/6.17                       |
| 11          | 150.00                     | 3.00                     | 100.00         | PET                | 96.2/9.39                          | 1.20/7.88                          | 62.9/20/8.51                       |
| 12          | 50.00                      | 3.00                     | 100.00         | CV                 | 97.8/9.39                          | 0.88/7.21                          | 46.6/85/8.36                       |
| 13          | 150.00                     | 3.00                     | 100.00         | CV                 | 96.3/7.27                          | 0.79/5.89                          | 36.0/63/5.96                       |
| 14          | 100.00                     | 1.00                     | 50.00          | 50PET/50CV         | 48.9/6.31                          | 0.85/8.24                          | 58.7/80/7.47                       |
| 15          | 100.00                     | 5.00                     | 50.00          | 50PET/50CV         | 48.5/5.49                          | 0.89/9.22                          | 49.1/60/6.58                       |
| 16          | 100.00                     | 1.00                     | 150.00         | 50PET/50CV         | 146.4/7.62                         | 1.22/6.91                          | 27.1/60/4.84                       |
| 17          | 100.00                     | 5.00                     | 150.00         | 50PET/50CV         | 147.0/8.57                         | 1.30/5.37                          | 27.9/60/8.43                       |
| 18          | 100.00                     | 3.00                     | 100.00         | 50PET/50CV         | 98.3/9.22                          | 1.10/6.84                          | 50.2/90/7.25                       |
| 19          | 50.00                      | 3.00                     | 50.00          | 50PET/50CV         | 49.1/7.94                          | 1.30/6.57                          | 69.9/60/7.65                       |
| 20          | 150.00                     | 3.00                     | 50.00          | 50PET/50CV         | 48.3/5.47                          | 0.86/8.87                          | 48.1/80/6.88                       |
| 21          | 50.00                      | 3.00                     | 150.00         | 50PET/50CV         | 148.7/8.97                         | 2.64/7.39                          | 69.4/60/7.71                       |
| 22          | 150.00                     | 3.00                     | 150.00         | 50PET/50CV         | 146.9/6.23                         | 1.16/7.10                          | 19.3/40/8.17                       |
| 23          | 100.00                     | 1.00                     | 100.00         | PET                | 98.4/4.59                          | 1.21/9.44                          | 67.1/40/7.27                       |
| 24          | 100.00                     | 5.00                     | 100.00         | PET                | 98.9/4.99                          | 1.32/6.98                          | 65.5/20/6.93                       |
| 25          | 100.00                     | 1.00                     | 100.00         | CV                 | 96.3/7.29                          | 0.73/4.64                          | 50.2/60/5.7                        |
| 26          | 100.00                     | 5.00                     | 100.00         | CV                 | 96.8/7.34                          | 0.84/5.43                          | 28.3/10/5.5                        |
| 27          | 100.00                     | 3.00                     | 100.00         | 50PET/50CV         | 97.8/8.11                          | 0.95/4.26                          | 59.5/70/7.66                       |

a) Hereinafter, the abbreviation COV is used for coefficient of variation.
were chosen to study the transport behaviour of moisture through the structure, in particular when using a blend of the two fibres. The corresponding values of different levels of the above-mentioned factors are presented in Table 1. The fibre/fibre blends were first opened and carded using a stationary flat card. A bimodal fibre orientation in the web was achieved using a cross-lapper. A pilot-scale hydroentangling machine was used to produce fabric as per the required setting based on the Box-Behnken design. The machine was set up with the following values: orifice discharge coefficient = 0.7, orifice diameter = 0.127 mm, number of jets/m = 1600 and pre-wetting pressure = 50 bars. The nozzle type, nozzle geometry and all other parameters were kept same for all samples. Various physical parameters were measured using standard methods for all nonwoven fabrics that were produced according to the Box-Behnken design [22]. Mean fabric weight, mean fabric thickness and mean pore diameter is presented in Table 2.

### 2.2 Methods

The moisture management behaviour of the fabrics was accurately and objectively measured on an SDL-ATLAS M290 moisture management tester according to the AATCC Test Method 195 [23]. A 5 cm x 5 cm fabric specimen was used in the tester. A certain known volume of a predefined test solution was then put on the top surface of the fabric (i.e. the side of the fabric in contact with skin). The saline solution transferred in three directions after being placed on the top surface of the specimen. The aforementioned instrument was integrated with a computer via moisture management software that records changes in resistance due to the solution, which can conduct electricity. Changes in the electrical resistance of specimens were measured and recorded during the test. According to the AATCC Test Method 195–2012 [23], the indices are graded and converted from a value to a grade based on a five-grade scale. Table 3 presents the range of values converted into grades.

**Table 3: Grading of different indices obtained from the moisture management tester [23, 24]**

| Index                          | Grade               |
|-------------------------------|---------------------|
| Wetting time – top [s]        | □ 1 2 3 4 5        |
| ≥120                          | 20−119              |
| No wetting                     | Slow               |
| Medium                        | Fast               |
| Very fast                     |                    |
| Wetting time – bottom [s]     | □ 1 2 3 4 5        |
| ≥120                          | 20−119              |
| No wetting                     | Slow               |
| Medium                        | Fast               |
| Very fast                     |                    |
| Absorption rate – top [%/s]   | □ 1 2 3 4 5        |
| 0–10                          | 10−30               |
| Very Slow                     | Slow               |
| Medium                        | Fast               |
| Very fast                     |                    |
| Absorption rate – bottom [%/s]| □ 1 2 3 4 5        |
| 0–10                          | 10−30               |
| Very Slow                     | Slow               |
| Medium                        | Fast               |
| Very fast                     |                    |
| Max. wetted radius – top [mm] | □ 1 2 3 4 5        |
| 0–7                           | 7−12                |
| No wetting                     | Small              |
| Medium                        | Fast               |
| Very fast                     |                    |
| Max. wetted radius – bottom [mm]| □ 1 2 3 4 5        |
| 0–7                           | 07−12               |
| No wetting                     | Small              |
| Medium                        | Fast               |
| Very fast                     |                    |
| Spreading speed – top [mm/sec]| □ 1 2 3 4 5        |
| 0–1                           | 1−2                 |
| Very Slow                     | Slow               |
| Medium                        | Fast               |
| Very fast                     |                    |
| Spreading speed – bottom [mm/ sec]| □ 1 2 3 4 5        |
| 0–1                           | 1−2                 |
| Very Slow                     | Slow               |
| Medium                        | Fast               |
| Very fast                     |                    |
| One-way transport capability (OWTC)| □ 1 2 3 4 5       |
| −<50                          | −50−100             |
| Very poor                     | Poor               |
| Good                          | Very good          |
| Excellent                     |                    |
| Overall moisture management coefficient (OMMC)| □ 1 2 3 4 5     |
| 0–0.2                         | 0.2−0.4             |
| Very poor                     | Poor               |
| Good                          | Very good          |
| Excellent                     |                    |
Finally, the moisture management tester classified the tested fabric into seven categories according to their properties, as presented in Table 4 [24]. Before conducting the test, all fabric samples were first conditioned in a tropical atmosphere of 27 °C ± 2 °C and 65% ± 2% relative humidity. For each sample of the Box-Behnken design, fifteen samples were tested to minimise the coefficient of variation (%). Minitab 17 software was used for statistical analysis. An analysis of variance was carried out on responses corresponding to the Box-Behnken design, with the aim of examining the effect and contribution of different factors, at a 95% confidence level.

Table 4: Fabric classification based on the results of the moisture management tester [24]

| Sample code | Type Name                        | Properties                                                                 |
|-------------|----------------------------------|-----------------------------------------------------------------------------|
| 1           | Waterproof fabric (WF)           | Very slow absorption, slow spreading, no one-way transport, no penetration |
| 2           | Water-repellent fabric (WRF)     | No wetting, no absorption, no spreading, poor one-way transport without external forces |
| 3           | Slow-absorbing and slow-drying fabric (SA&SDF) | Slow absorption, slow spreading, poor one-way transport |
| 4           | Fast-absorbing and slow-drying fabric (FA&SDF) | Medium to fast wetting, medium to fast absorption, small spreading area, slow spreading, poor one-way transport |
| 5           | Fast-absorbing and quick-drying fabric (FA&QDF) | Medium to fast wetting, medium to fast absorption, large spreading area, fast spreading, poor one-way transport |
| 6           | Water penetration fabric (WPF)   | Small spreading area, Excellent one-way transport                            |
| 7           | Moisture management fabric (MMF) | Medium to fast wetting, medium to fast absorption, large spreading area and fast spreading at bottom surface, good to excellent one-way transport |

3 Results and discussion

Moisture management properties of spunlace non-woven fabrics

Moisture transport through the nonwoven fabrics was experimentally determined using a moisture management tester. The results are presented in Table 5.

Table 5: Mean value of various indices of moisture management tester with cl

| Sample code | Wetting time: Mean [s]/COV [%] | Absorption rate: Mean [%/s]/COV [%] |
|-------------|--------------------------------|-------------------------------------|
|             | Top surface                     | Bottom surface                      | Top surface                      |
| 1           | 3.98/4.8                        | 9.12/9.05                           | 57.59/3.4                        |
| 2           | 4.12/5.1                        | 7.21/4.13                           | 18.61/5.37                       |
| 3           | 4.22/5.36                       | 9.55/6.54                           | 82.33/5.72                       |
| 4           | 4.45/2.54                       | 7.90/3.74                           | 32.8/8.67                        |
| 5           | 9.86/5.33                       | 12.29/8.66                          | 0.0/0.0                          |
| 6           | 10.26/7.25                      | 14.37/6.12                          | 0.0/0.0                          |
| 7           | 1.96/4.4                        | 9.95/5.95                           | 37.14/9.51                       |
| 8           | 2.26/8.02                       | 10.41/5.27                          | 18.87/6.23                       |
| 9           | 4.23/2.76                       | 8.31/2.43                           | 34.72/5.68                       |
| 10          | 10.56/6.22                      | 13.46/4.19                          | 0.0/0.0                          |
| 11          | 10.39/7.24                      | 14.62/6.22                          | 0.0/0.0                          |
| 12          | 2.93/3.11                       | 9.27/2.36                           | 26.74/4.19                       |
| 13          | 2.71/5.39                       | 9.5/2.56                            | 20.48/9.21                       |
| 14          | 4.38/7.29                       | 7.98/5.96                           | 43.06/5.00                       |
| 15          | 3.82/6.62                       | 7.62/7.29                           | 44.01/3.22                       |
| 16          | 4.33/3.99                       | 8.92/3.05                           | 5.36/3.93                        |
| 17          | 3.81/5.34                       | 9.06/6.63                           | 10.43/4.61                       |
| 18          | 3.68/4.05                       | 8.42/3.21                           | 37.05/4.73                       |
| 19          | 3.38/4.28                       | 8.97/4.37                           | 27.68/8.68                       |
| 20          | 3.25/3.90                       | 7.92/2.33                           | 50.148/6.35                      |
| 21          | 3.65/6.11                       | 9.84/3.54                           | 71.7/8.21                        |
| 22          | 3.85/7.93                       | 8.60/9.27                           | 17.74/7.38                       |
| 23          | 9.55/3.94                       | 13.95/2.81                          | 0.0/0.0                          |
| 24          | 8.85/4.95                       | 13.44/1.19                          | 0.0/0.0                          |
| 25          | 1.88/6.74                       | 9.36/4.37                           | 24.88/9.68                       |
| 26          | 1.55/5.02                       | 9.77/6.55                           | 28.72/3.70                       |
| 27          | 4.11/3.32                       | 8.11/3.54                           | 30.52/4.22                       |
3.1 Wetting time

Wetting time is defined as the time in seconds when the slope of total water contents at the top and bottom surfaces becomes greater than tan (15°), the specimen begins to be wetted. Wetting time can be compared with the absorbency drop test specified in AATCC 79. The basic unit of any textile structure is fibre. Generally, the wetting time on the top surface of any fabric is affected by its composition, in addition to the structural arrangement of the fibre it contains. The wetting of the surface is also affected by the interaction between the liquid and the fibre that makes up the fabric. The contact angle between the fibre and the liquid affects the transportation of liquid in both directions, i.e. horizontally and vertically. Hence, a fibre with lower interfacial energy/surface

| Assimilation of type of fabric | Absorption rate: Mean [%/s]/COV [%] | Max. wetted radius: Mean [mm]/COV [%] | Spreading speed: Mean [mm/s]/COV [%] | One-way transport capability: Mean/COV [%] | Overall moisture management coefficient: Mean/COV [%] | Remarks on type of fabric |
|-------------------------------|-------------------------------------|--------------------------------------|--------------------------------------|------------------------------------------|------------------------------------------------|--------------------------|
| Bottom surface                | Top surface                         | Bottom surface                       | Top surface                          | Bottom surface                          | Top surface                          | Bottom surface                          | Overall moisture management coefficient: Mean/COV [%] | Remarks on type of fabric |
| Bottom surface                | Top surface                         | Bottom surface                       | Top surface                          | Bottom surface                          | Top surface                          | Bottom surface                          | Overall moisture management coefficient: Mean/COV [%] | Remarks on type of fabric |
| 121.17/8.7                   | 10.0/0.0                            | 10.0/0.0                             | 0.83/9.2                             | 1.16/9.2                                | 449.25/4.84                          | 0.71/8.88                              | MMF                                           | |
| 69.04/4.97                   | 11.66/8.92                          | 21.66/10.32                          | 2.44/9.14                           | 4.13/8.26                               | 487.34/7.83                          | 0.88/8.49                              | MMF                                           | |
| 146.03/8.57                  | 8.33/3.48                           | 10.0/0.0                             | 0.73/8.6                             | 0.89/3.6                                | 239.94/3.42                          | 0.67/3.12                              | FA&SDF                                        | |
| 58.74/10.05                  | 20.0/0.0                            | 20.0/0.0                             | 3.69/3.18                           | 3.98/3.55                               | 395.74/6.27                          | 0.8/5.83                               | MMF                                           | |
| 246.23/7.35                  | 0.0/0.0                             | 10.0/0.0                             | 0.0/0.0                             | 1.19/9.39                               | 865.06/4.83                          | 0.62/2.97                              | WPF                                           | |
| 398.79/9.51                  | 0.0/0.0                             | 5.0/0.0                              | 0.0/0.0                             | 0.4/1.36                                | 914.05/7.59                          | 0.57/3.94                              | WPF                                           | |
| 73.54/7.37                   | 25.0/0.0                            | 28.33/0.0                            | 5.24/9.19                           | 5.35/5.79                               | 340.88/6.05                          | 0.86/5.22                              | MMF                                           | |
| 46.01/5.38                   | 13.33/2.29                          | 16.66/2.88                           | 1.64/8.22                           | 2.72/5.09                               | 347.44/8.55                          | 0.66/5.52                              | MMF                                           | |
| 95.03/3.33                   | 20/0.7                              | 22.5/3.53                            | 3.66/4.60                           | 3.89/4.23                               | 510.77/5.67                          | 0.93/4.16                              | MMF                                           | |
| 241.21/7.93                  | 0.0/0.0                             | 5.0/0.0                              | 0.0/0.0                             | 0.46/2.8                                | 856.76/2.11                          | 0.65/3.59                              | WPF                                           | |
| 298.67/5.91                  | 0.0/0.0                             | 5.0/0.0                              | 0.0/0.0                             | 0.39/3.9                                | 1081.61/6.89                         | 0.73/3.95                              | WPF                                           | |
| 63.35/5.75                   | 18.33/2.88                          | 18.33/2.88                           | 2.78/3.2                            | 2.72/2.92                               | 406.11/9.11                          | 0.78/7.43                              | MMF                                           | |
| 53.97/8.87                   | 20.0/0.0                            | 20.0/0.0                             | 1.06/7.32                           | 3.13/3.41                               | 385.11/6.86                          | 0.76/4.71                              | MMF                                           | |
| 130.36/4.68                  | 27.5/3.53                           | 27.5/3.53                            | 5.54/7.04                           | 5.63/6.97                               | 471.18/2.89                          | 0.96/4.43                              | MMF                                           | |
| 131.78/5.29                  | 27.5/3.53                           | 22.5/3.62                            | 5.55/3.75                           | 5.14/5.24                               | 546.05/2.99                          | 0.97/3.03                              | MMF                                           | |
| 35.5/5.77                    | 10.0/0.0                            | 18.33/3.14                           | 0.39/6.09                           | 2.19/7.65                               | 245.05/5.21                          | 0.77/4.95                              | MMF                                           | |
| 46.03/7.34                   | 5.0/0.0                             | 20.0/0.0                             | 0.83/4.14                           | 3.16/5.66                               | 502.94/3.71                          | 0.76/6.17                              | MMF                                           | |
| 101.54/5.21                  | 22.5/0.0                            | 22.5/0.0                             | 3.95/3.33                           | 4.39/4.67                               | 564.44/4.96                          | 0.88/3.56                              | MMF                                           | |
| 153.3/9.23                   | 10.0/0.0                            | 10.0/0.0                             | 0.85/7.87                           | 0.9/8.43                                | 278.86/8.65                          | 0.74/7.75                              | MMF                                           | |
| 136.59/6.76                  | 26.66/2.93                          | 26.66/2.93                           | 4.73/5.33                           | 5.13/4.72                               | 393.53/7.29                          | 0.94/5.11                              | MMF                                           | |
| 145.3/4.33                   | 10.0/0.0                            | 10.0/0.0                             | 0.62/6.54                           | 1.43/7.92                               | 336.35/5.61                          | 0.71/6.37                              | FA&SDF                                        | |
| 87.73/6.89                   | 20.0/0.0                            | 20.0/0.0                             | 3.12/6.54                           | 3.44/4.72                               | 429.93/5.04                          | 0.81/2.39                              | MMF                                           | |
| 245.42/5.67                  | 0.0/0.0                             | 5.0/0.0                              | 0.0/0.0                             | 0.67/3.75                               | 526.47/2.58                          | 0.65/3.58                              | WPF                                           | |
| 239.12/5.28                  | 0.0/0.0                             | 5.0/0.0                              | 0.0/0.0                             | 0.43/1.14                               | 910.41/4.95                          | 0.63/5.26                              | WPF                                           | |
| 89.51/5.18                   | 20.0/0.0                            | 20.0/0.0                             | 4.3/5.36                            | 4.19/2.18                               | 284.53/3.19                          | 0.79/3.31                              | MMF                                           | |
| 61.66/4.05                   | 20.0/0.0                            | 20.0/0.0                             | 3.48/8.80                           | 3.54/5.70                               | 398.57/6.21                          | 0.85/6.86                              | MMF                                           | |
| 112.32/6.11                  | 20.0/0.0                            | 20.0/0.0                             | 3.29/5.29                           | 3.41/4.90                               | 580.97/2.53                          | 0.91/3.89                              | MMF                                           | |
tension should support wetting. The fibre-liquid molecular attraction on the surface of fibrous assemblies dictates the flow of moisture through a textile fabric. The surface tension and dimensional parameters of pores in porous media are the main parameters that affect this fibre-liquid interaction [2, 6].

A statistical analysis of variance (ANOVA) using a backward elimination technique showed that the web composition has a significant effect on the wetting time on the top surface, while the effect of waterjet pressure, web mass and delivery speed was found to be insignificant at a 95% confidence interval (Table 6). The response surface equation in coded units for the mean top wetting time is given in equation (1) with a $R^2$ value of 0.9755.

Top wetting time  $= 3.951 - 3.848X_4 + 2.114X_4^2$  \hspace{1cm} (1)

The effect of web composition on mean wetting time is shown in Figure 1 using equation 1. It is evident from Figure 1 that the experimental data for top wetting time is fitted to a second order polynomial equation. It is also evident from Figure 1 that and increase in CV content reduces mean wetting time. The surface tension of PET is higher than that of CV for water, while the mean pore diameter of PET nonwoven fabric is higher than that of CV nonwoven fabric. A higher surface tension and higher pore diameter impede the wetting of fabric surface. Hence, the wetting time on the top surface of PET nonwoven fabric is significantly higher than that of CV fabric and 50PET/50CV blended nonwoven fabric (Figure 1).

Table 6: ANOVA for mean top wetting time

| Source     | Degree of freedom | Sum of square | Mean square | F value | P value | Percentage contribution [%] |
|------------|------------------|--------------|-------------|---------|---------|-----------------------------|
| Model      | 2                | 207.4        | 103.7       | 478.1   | 0.000   | 97.55                       |
| X4         | 1                | 177.6        | 177.6       | 818.9   | 0.000   | 83.55                       |
| X4*X4      | 1                | 29.8         | 29.8        | 137.3   | 0.000   | 14.01                       |
| Error      | 24               | 5.20         | 0.217       | 2.45    |         | 2.45                        |
| Lack of fit| 22               | 5.0          | 0.22        | 2.74    | 0.302   | 2.37                        |
| Pure error | 2                | 0.2          | 0.1         |         | 0.08    |                             |
| Total      | 26               | 212.6        |             |         |         | 100                         |

The wetting time on the bottom surface was expected to be affected by the ability of the structure to transport liquid. The pore diameter is used to affect wicking in any textile structure. The pore diameter of spunlace nonwoven fabric depends on waterjet pressure, web weight and web composition. Hence, the wetting time on the bottom surface should be affected by a change in these parameters. The results (Table 5) indicate the wetting time of the bottom surfaces is generally higher than the top surfaces for all fabrics.
The statistical analysis of variance (ANOVA) for the mean wetting time on the bottom surface is presented in Table 7. It is evident from Table 7 that the web composition has a significant effect on the wetting time on the bottom surface, while the effect of waterjet pressure and web mass are also significant, although their percentage contribution is very small. Delivery speed is found to be insignificant at a 95% confidence interval. The response surface equation in coded units for the mean bottom wetting time is given in equation 2 with a $R^2$ value of 0.9464.

$$\text{Bottom wetting time} = 8.502 - 0.372X_1 + 0.539X_3 - 1.989X_4 + 3.197X_4^2$$  \hspace{1cm} (2)

Figure 2: Bottom wetting time depending on waterjet pressure, web mass and web composition
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nonwoven fabrics. This is due to the presence of CV fibre, which helps in the quick absorption of liquid/moisture, while PET fibre supports the wicking of liquid. Hence, the wetting time on the bottom surface is lower in 50PET/50CV blend. Table 7 shows that the percentage contribution of web composition is 90%.

It is also evident from Figure 2 that an increase in web mass increases the mean wetting time on the bottom surface. An increase in web mass results in a higher number of water absorbing sites at a molecular level, which delays the wicking phenomenon, despite a lower pore diameter. The mean wetting time on the bottom surface also depends on waterjet pressure, as shown in Table 7. It is evident from Figure 2 that an increase in waterjet pressure decreases mean wetting time on the bottom surface. An increase in waterjet pressure leads to a decrease in the mean pore diameter and thickness of fabric, [22] which supports the wicking phenomena. Hence, a higher wicking rate reduces the wetting time on the bottom surface. After the conversion of wetting time values into grades (Table 3), it is evident that nonwoven fabric made of PET, 50PET/50CV and CV exhibits slow (grade 2), medium (grade 3) and fast (grade 4) wetting behaviour on the top surface, and medium (grade 3), medium (grade 3) and fast (grade 4) wetting behaviour on the bottom surface, respectively.

3.2 Absorption rate
The absorption of liquid by a textile substrate indicates the degree of transfer of liquid on its surface. The absorption of liquid by a fabric depends on the type of fibre, fabric structure and openness in the structure. The absorption rate on the top surface of all spunlace nonwoven fabric samples is presented in Table 5. An ANOVA of the mean absorption rate is presented in Table 8. It is evident from Table 8 that the effect of delivery speed is not significant, while waterjet pressure, web mass and web composition have a significant effect on the mean absorption rate on the top surface. The response surface equation in coded units for mean bottom wetting time is given in equation 3 with a $R^2$ value of 0.7320.

$$\text{Top absorption rate} = 37.58 - 10.52X_1 - 6.49X_3 + 13.07X_4 - 24.51X_4^2 - 19.11X_1X_3$$  \hfill (3)

The effect of waterjet pressure, web mass and web composition on the mean absorption rate on the top surface is shown in Figure 3 using equation 3. It is evident from Figure 3 that an increase in waterjet pressure decreases the mean absorption rate on the top surface. This is due to a decrease in fabric thickness, which results in the compactness of the structure at a higher waterjet pressure [22]. Waterjet pressure is a significant parameter for the mean absorption rate on the top surface, as its percentage contribution is more than 10%.

### Table 8: ANOVA for the top absorption rate

| Source          | Degree of freedom | Sum of square | Mean square | F value | P value | Percentage contribution [%] |
|-----------------|-------------------|---------------|-------------|---------|---------|-----------------------------|
| Model           | 5                 | 9351.2        | 1870.24     | 11.47   | 0.000   | 73.20                       |
| Linear          | 3                 | 3884.3        | 1294.78     | 7.94    | 0.001   | 30.41                       |
| X1              | 1                 | 1328.5        | 1328.5      | 8.15    | 0.009   | 10.40                       |
| X3              | 1                 | 506.2         | 506.2       | 3.10    | 0.093   | 3.96                        |
| X4              | 1                 | 2049.6        | 2049.6      | 12.57   | 0.002   | 16.04                       |
| Square          | 1                 | 4006.5        | 4006.5      | 24.57   | 0.000   | 31.36                       |
| X4*X4           | 1                 | 4006.5        | 4006.5      | 24.57   | 0.000   | 31.36                       |
| 2-way interaction | 1              | 1460.3        | 1460.3      | 8.96    | 0.007   | 11.43                       |
| X1*X3           | 1                 | 1460.3        | 1460.3      | 8.96    | 0.007   | 11.43                       |
| Error           | 21                | 3423.8        | 3423.8      | 26.80   |         |                              |
| Lack of fit     | 19                | 3401.9        | 4.20        | 14.48   | 0.059   | 26.63                       |
| Pure error      | 2                 | 21.9          | 10.96       |         | 0.17    |                              |
| Total           | 26                | 12775.0       |             |         |         | 100                         |
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The mean absorption rate (%) on the top surface for CV nonwoven fabric is higher than that of PET nonwoven fabric due to the presence of a higher number of hydrophilic sites in the CV nonwoven fabric. The mean absorption rate (%) is higher in 50PET/50CV blended nonwoven fabric than in CV nonwoven fabric (Figure 3). CV nonwoven fabric has good absorbency due to its hydrophilic CV fibre. However, it forms a strong bond with the absorbing group of fibre molecules due to its high affinity to water when water molecules in the capillary flow reach a smaller diameter. This impedes the capillary flow along the channel formed by the fibre surface, leading to a decrease in the mean absorption rate. In the 50PET/50CV blend, the PET fibre helps in the wicking of moisture/water being absorbed by CV fibre, resulting in a higher mean absorption rate.

The effect of web mass on the mean absorption rate is also shown in Figure 3. It is evident that the mean absorption rate for 50 g/m² is higher than that for 150 g/m². This difference in the mean absorption rate was statistically significant. Nonwoven fabric at a lower web mass demonstrates a higher absorption rate because a fabric with a lower mass is more porous (high pore diameter), which helps in the absorption of moisture at faster rate, while at higher web mass, a compact structure with a smaller pore diameter results in a lower absorption rate.

The interaction effect of web mass and waterjet pressure on the top surface is shown in Figure 4. It is evident from Figure 4 that at a low web mass, an increase in waterjet pressure increases the mean absorption rate due to a more open structure. The openness of the structure becomes...
more prominent at a high waterjet pressure and low web mass due to the grouping of fibres. Similarly, a higher web mass and low waterjet pressure result in an increase in the mean absorption rate due to the reduced binding of fibres. A higher web mass and high waterjet pressure lead to a compacted structure, resulting in a decrease in the mean absorption rate. The mean absorption rate on the bottom surface plays an important role in the moisture management behaviour of any textile structure. A textile structure with a higher bottom surface absorption rate helps to transfer the moisture in the environment, which is wicked through the structure. The mean absorption rate on the bottom surface of spunlace nonwoven fabric samples are presented in Table 5. An ANOVA of the mean absorption rate on the bottom surface is presented in Table 9.

It is evident from Table 9 that only web composition has a significant effect on the mean absorption rate on the bottom surface. The response surface equation in coded units for the mean bottom wetting time is given in equation 4 with a $R^2$ value of 0.8002.

$$\text{Bottom absorption rate} = 104.7 - 106.8X_4 - 66.8X_4^2$$ (4)

The effect of web composition on the mean absorption rate on the bottom surface is shown in Figure 5 using equation 4. It is evident from Figure 5 that PET nonwoven fabric demonstrates a significantly higher bottom absorption rate than CV nonwoven fabric. An increase in the CV content in a nonwoven structure leads to an increase in the absorption rate on the top surface. Due to its high affinity to water molecules, however, the CV nonwoven fabric results in the formation of a strong bond between those molecules, which inhibits the capillary flow across the structure, causing a decrease in the absorption rate on the bottom surface.

After the conversion of absorption values into grades (Table 3), PET nonwoven fabric demonstrates a slow absorption rate (grade 2) on the top surface and a very fast absorption rate on the bottom surface (grade 5), while CV nonwoven fabric demonstrates a medium/fast absorption rate (grade 3/4) on the top surface and a medium/slow absorption rate on the bottom surface (grade 3/2). The 50PET/50CV blend exhibited an optimum absorption rate on both
the top and bottom surfaces, considering the presence of moisture in the structure.

3.3 Wetted radius
The value of the wetted radius demonstrates the extent of water spread on a textile structure. The wetted radius is directly related to the drying behaviour of a fabric. The value of the wetted radius should be affected by the web composition and web mass of a textile structure. The values of the top surface wetted radius are presented in Table 5. An ANOVA of the mean wetted radius (mm) on the top surface is presented in Table 10. It is evident that, apart from the delivery speed, all other factors have a significant effect on the mean value of the wetted radius on the top surface.

The response surface equation in coded units for the mean top wetted radius is given in equation 5 with a $R^2$ value of 0.8002.

$$\text{Top wetted radius} = 16.61 + 3.47X_1 - 4.86X_3 + 9.72X_4 - 6.89X_4^2 \quad (5)$$

Table 10: ANOVA for the top wetted radius

| Source     | Degree of freedom | Sum of square | Mean square | F value | P value | Percentage contribution [%] |
|------------|-------------------|---------------|-------------|---------|---------|-----------------------------|
| Model      | 4                 | 1878.62       | 469.65      | 22.28   | 0.000   | 80.20                       |
| Linear     | 3                 | 1562.29       | 520.76      | 24.71   | 0.000   | 66.70                       |
| $X_1$      | 1                 | 144.63        | 144.63      | 6.86    | 0.016   | 6.17                        |
| $X_3$      | 1                 | 283.53        | 283.53      | 13.45   | 0.001   | 12.10                       |
| $X_4$      | 1                 | 1134.13       | 1134.13     | 53.81   | 0.000   | 48.42                       |
| Square     | 1                 | 316.33        | 316.33      | 15.01   | 0.001   | 13.50                       |
| $X_4^2$    | 1                 | 316.33        | 316.33      | 15.01   | 0.001   | 13.50                       |
| Error      | 22                | 463.73        | 21.08       |         |         |                             |
| Lack of fit| 20                | 459.56        | 22.98       | 11.03   | 0.086   | 19.62                       |
| Pure error | 2                 | 4.17          | 2.08        |         |         | 0.18                        |
| Total      | 26                | 2342.34       |             |         |         | 100                         |

Figure 6: Top wetted radius depending on waterjet pressure, web mass and web composition
The effect of significant factors on the mean top wetted radius is shown in Figure 6 using equation 5. It is evident from Figure 6 that an increase in CV content results in an increase in the mean wetted radius on the top surface. When a liquid droplet is introduced on the surface, absorption by the CV component presumably begins before the start of wicking. This facilitates the spreading of moisture. Hence, the mean wetted radius on the top surface increases. The percentage contribution of web composition to the mean wetted radius on the top surface is around 61.92%.

The effect of web mass on the mean wetted radius on the top surface is shown in Figure 6. It can be concluded that an increase in web mass results in a decrease in the mean wetted radius. This is due to an increase in the number of absorption sites as web mass increases. The percentage contribution of web mass to the mean wetted radius (top surface) is around 12%.

The effect of waterjet pressure on the mean wetted radius on the top surface is shown in Figure 6. It is evident that an increase in waterjet pressure results in an increase in the mean wetted radius on the top surface. Waterjet pressure leads to a more compact structure that better supports the spreading of moisture compared with wicking and/or absorption. The percentage contribution of waterjet pressure to the mean wetted radius (top surface) is around 6%.

The mean wetted radius on the bottom surface demonstrates how well moisture dissipates to the outer environment. The higher the mean bottom wetted radius, the better the moisture dissipation to the environment. The value of the bottom surface wetted radius is presented in Table 5. An ANOVA is also presented in Table 11. It is evident that, besides delivery speed, all other factors have a significant effect on the mean value of the bottom wetted radius. The response surface equation in coded units for mean bottom wetted radius is given in equation 6 with an $R^2$ value of 0.8728.

$$\text{Ton wetted radius} = 20.971 + 4.166X_1 - 4.12X_1^2 - 2.917X_3 + 7.36X_4 - 6.41X_4^2$$  \hspace{1cm} (6)

The effect of significant factors on the mean top wetted radius is shown in Figure 7 using equation 6. It is evident from Figure 7 that PET nonwoven fabric has a smaller wetted radius on the bottom surface than CV nonwoven fabric. This is the result of higher moisture wicking than absorbency in PET nonwoven fabric, while an increase in the CV content results in an increase in the mean wetted radius on the bottom surface. This is due to the hydrophilic nature of CV fibre. Absorption by CV fabric appears to be predominant, while the bottom wetting radius increases as the quantity of CV fibre is increased. The percentage contribution of web composition to the mean wetted radius on the bottom surface is around 60%.

The effect of waterjet pressure on the mean bottom wetted radius is shown in Figure 7. It is evident that

| Source          | Degree of freedom | Sum of square | Mean square | F value | P value | Percentage contribution [%] |
|-----------------|-------------------|---------------|-------------|---------|---------|-----------------------------|
| Model           | 5                 | 1276.57       | 255.31      | 28.81   | 0.000   | 87.28                       |
| Linear          | 3                 | 960.37        | 320.12      | 36.13   | 0.000   | 65.66                       |
| X1              | 1                 | 208.25        | 208.25      | 23.50   | 0.000   | 14.24                       |
| X3              | 1                 | 102.08        | 102.08      | 11.52   | 0.003   | 6.98                        |
| X4              | 1                 | 650.04        | 650.03      | 73.36   | 0.000   | 44.44                       |
| Square          | 2                 | 316.20        | 158.10      | 17.84   | 0.000   | 21.62                       |
| X1*X1           | 1                 | 53.54         | 53.54       | 12.23   | 0.002   | 3.66                        |
| X4*X4           | 1                 | 262.66        | 262.66      | 29.64   | 0.000   | 17.96                       |
| Error           | 21                | 186.07        | 8.86        |         |         | 12.72                       |
| Lack of fit     | 19                | 181.90        | 9.57        | 4.60    | 0.194   | 12.44                       |
| Pure error      | 2                 | 4.17          | 2.08        |         |         | 0.28                        |
| Total           | 26                | 1462.64       |             |         |         | 100                         |

Table 11: ANOVA for the bottom wetted radius
an increase in waterjet pressure results in an increase in the mean wetted radius on the bottom surface. When waterjet pressure is increased, the structure consolidates and the pore size is reduced with a reduction in fabric thickness. The lower diameter of capillary flow facilitates wicking. Hence, moisture transmission from the top surface is faster. This wicked moisture is diffused faster than additional wicking [25] due to the compactness of the structure. This leads to an increase in the bottom wetted radius. The percentage contribution of waterjet pressure to the mean wetted radius (top surface) is around 17%.

The effect of web mass on the mean bottom wetted radius is shown in Figure 7. It is evident that an increase in the web mass results in a decrease in the mean bottom wetted radius. An increase in the number of absorption sites through an increase in web mass leads to a reduction in the openness of the structure, which in turn results in an increase in the mean wetted radius. The percentage contribution of web mass to the mean wetted radius (top surface) is around 6%.

After the conversion of wetted radius values into grades (Table 3), PET nonwoven fabric demonstrates a minimum wetted radius (grade 1) on both the top and bottom surfaces. CV nonwoven fabric demonstrates a good wetted radius (grade 4) on both the top and bottom surfaces, while the 50PET/50CV blend exhibits the best wetted radius on both the top surface and bottom surface.

### 3.4 Spreading speed

The spreading speed of moisture/liquid on a textile substrate indicates the degree of moisture dispersion in a fabric. The spreading speed of moisture/liquid in a fabric depends on the type of fibre, fabric structure and openness of the structure (pore size). The spreading speed of moisture on the top surface of all spunlace nonwoven fabric samples is presented in Table 5. An ANOVA of the mean wetted radius (mm) on the top surface is presented in Table 12. The response surface equation in coded units for the mean spreading speed on the top surface is given in equation 7 with a $R^2$ value of 0.7238.

$$\text{Top spreading speed} = 3.245 + 0.769X_1 - 1.057X_1^2 - 1.276X_3 + 1.542X_4 - 1.35X_4^2 \quad (7)$$

The effect of significant factors on the mean spreading speed on the top surface is shown in Figure 8 using equation 7. It is evident from Figure 8 that an increase in CV content results in an increase in the mean spreading speed. This is due to the higher mean wetted radius on the top surface with a higher CV content, while the hygroscopic nature of CV nonwoven fabric leads to a higher top spreading speed. The percentage contribution of web composition to the mean spreading speed on the top surface is around 40%.

Figure 7: Bottom wetted radius depending on waterjet pressure, web mass and web composition
The effect of waterjet pressure on the mean wetted radius on the top surface is shown in Figure 8. It is evident that an increase in waterjet pressure results in an increase in the mean spreading speed on the top surface. The higher spreading speed on the top surface is due to a higher mean wetted radius at a higher waterjet pressure. The percentage contribution of waterjet pressure to the top spreading speed is around 10%.

The effect of web mass on the mean spreading speed on the top surface is shown in Figure 8. It can be concluded that an increase in web mass results in a decrease in the mean wetted radius on the top surface. Hence, there is decrease in the mean top spreading speed. The percentage contribution of web mass to the top spreading speed is around 20%.

The bottom spreading speed is more important in the moisture management of textile fabrics. A higher spread speed results in better moisture management.

### Table 12: ANOVA for the top spreading speed

| Source       | Degree of freedom | Sum of square | Mean square | F value | P value | Percentage contribution [%] |
|--------------|-------------------|---------------|-------------|---------|---------|-----------------------------|
| Model        | 5                 | 70.97         | 14.19       | 11.0    | 0.000   | 72.38                       |
| Linear       | 3                 | 55.15         | 18.38       | 14.25   | 0.000   | 56.25                       |
| X1           | 1                 | 7.10          | 7.10        | 5.50    | 0.029   | 7.24                        |
| X3           | 1                 | 19.53         | 19.53       | 15.14   | 0.001   | 19.92                       |
| X4           | 1                 | 28.52         | 28.52       | 22.11   | 0.000   | 29.09                       |
| Square       | 2                 | 15.81         | 7.90        | 6.13    | 0.008   | 16.13                       |
| X1*X1        | 1                 | 4.13          | 7.15        | 5.55    | 0.028   | 4.21                        |
| X4*X4        | 1                 | 11.68         | 11.68       | 9.06    | 0.007   | 11.91                       |
| Error        | 21                | 27.09         | 1.28        |         |         | 27.62                       |
| Lack of fit  | 19                | 26.89         | 1.41        | 12.92   | 0.074   | 27.40                       |
| Pure error   | 2                 | 0.22          | 0.11        |         |         | 0.22                        |
| Total        | 26                | 98.05         |             |         |         | 100                         |
Results show that the bottom spreading speed should lead to the quick drying of fabrics. The spreading speed of moisture on the bottom surface of all nonwoven fabric samples is presented in Table 5. An ANOVA analysis of the bottom spreading speed is presented in Table 13.

The response surface equation in coded units for the mean spreading speed on the bottom surface is given in equation 8 with a $R^2$ value of 0.8358.

$$\text{Bottom spreading speed} = 3.816 + 1.053X_1 - 1.047X_1^2 - 0.833X_3 + 1.509X_4 - 1.368X_4^2$$  \hspace{1cm} (8)

The effect of significant factors on the mean spreading speed on the bottom surface is shown in Figure 9 using equation 8. It is evident from Figure 9 that an increase in CV content results in an increase in the mean bottom spreading speed, although a smaller bottom wetted radius was recorded. This is due to the higher moisture absorbency of CV nonwoven fabric compared to PET nonwoven fabric, which induces a higher absorption speed with a high spreading speed on the top surface. The higher spreading speed on the top surface and a low wetting time on

![Figure 9: Bottom spreading speed depending on waterjet pressure, web mass and web composition](image)

| Source          | Degree of freedom | Sum of square \(\text{Mean square} \) | \(F\) value | \(P\) value | Percentage contribution [%] |
|-----------------|-------------------|----------------------------------------|-------------|-------------|-----------------------------|
| Model           | 5                 | 64.93 \(12.98\)                        | 21.39       | 0.000       | 83.59                       |
| Linear          | 3                 | 48.97 \(16.32\)                       | 26.88       | 0.000       | 63.04                       |
| \(X_1\)         | 1                 | 13.31 \(13.31\)                       | 21.93       | 0.000       | 17.14                       |
| \(X_3\)         | 1                 | 8.33 \(8.32\)                         | 13.71       | 0.001       | 10.72                       |
| \(X_4\)         | 1                 | 27.33 \(27.33\)                       | 45.01       | 0.000       | 35.18                       |
| Square          | 2                 | 15.96 \(15.96\)                       | 13.14       | 0.000       | 20.55                       |
| \(X_1*X_1\)     | 1                 | 7.01 \(7.01\)                         | 11.55       | 0.003       | 5.13                        |
| \(X_4*X_4\)     | 1                 | 11.98 \(11.97\)                       | 19.72       | 0.000       | 15.42                       |
| Error           | 21                | 12.75 \(0.60\)                        |             |             |                             |
| Lack of fit     | 19                | 12.27 \(0.64\)                       | 2.69        | 0.306       | 15.80                       |
| Pure error      | 2                 | 0.48 \(0.24\)                        |             |             | 0.62                        |
| Total           | 26                | 77.68 \(100\)                        |             |             |                             |

Table 13: ANOVA for the bottom spreading speed
the bottom surface results in a higher spreading speed on the bottom surface. The percentage contribution of web composition to the mean spreading speed on the bottom surface is around 50%.

The effect of waterjet pressure on the mean bottom spreading speed is shown in Figure 9. The mean bottom spreading speed was found to increase with an increase in waterjet pressure. It was previously found that increased waterjet pressure results in an increase in the mean bottom wetted radius (section 3.3). Hence, there is an increase in the mean bottom spreading speed. The percentage contribution of waterjet pressure to the mean bottom spreading speed is around 22%.

The effect of web mass on the mean spreading speed on the top surface is shown in Figure 9. It can be concluded that an increase in web mass results in a decrease in the mean wetted radius on the bottom surface. Hence, there is a decrease in the mean spreading speed. The percentage contribution of web mass to the mean bottom spreading speed is around 10%.

After the conversion of the mean spreading speed into grades (Table 3), PET nonwoven fabric demonstrates a very slow spreading speed (grade 1/2) on the top and bottom surfaces. CV nonwoven fabric demonstrates a fast spreading speed (grade 4) on the top and bottom surfaces, while the 50PET/50CV blend also exhibits a medium to fast spreading speed (grade 2/3) on both the top and bottom surfaces.

3.5 One-way transport capability

One-way transport capability is the difference between the amount of liquid moisture content on the top and bottom surfaces of a specimen with respect to time. A positive OWTC value means a higher amount of moisture is transferred from the inner surface to the outer surface of a garment. The one-way transport capability of all fabrics is presented in Table 5. An ANOVA analysis of the mean OWTC is presented in Table 14. It is evident that only web composition has a significant effect on the OWTC of spunlace nonwoven fabric. The response surface equation in coded units for the mean OWTC is given in equation 9 with a $R^2$ value of 0.7325.

$$\text{OWTC} = 428.6 - 249.3X_4 - 181.2X_4^2$$

(9)

The effect of web composition on the mean OWTC is shown in Figure 10 using equation 9. It is evident from Figure 10 that OWTC is higher for PET fabrics

| Source       | Degree of freedom | Sum of square | Mean square | F value | P value | Percentage contribution [%] |
|--------------|-------------------|---------------|-------------|---------|---------|----------------------------|
| Model        | 2                 | 964755        | 482377      | 32.86   | 0.000   | 73.25                      |
| Linear       | 1                 | 745884        | 745884      | 50.82   | 0.000   | 56.63                      |
| X4           | 1                 | 745884        | 745884      | 50.82   | 0.000   | 56.63                      |
| Square       | 1                 | 218870        | 218870      | 14.91   | 0.001   | 16.62                      |
| X4*X4        | 1                 | 218870        | 218870      | 14.91   | 0.001   | 16.62                      |
| Error        | 24                | 352278        | 14678       |         | 0.081   | 26.75                      |
| Lack of fit  | 22                | 349584        | 15890       | 11.80   |         | 26.54                      |
| Pure error   | 2                 | 2694          | 1347        |         | 0.20    |                            |
| Total        | 26                | 1317033       |             |         |         | 100                        |
than for CV-based nonwoven fabrics. This can be attributed to the hydrophobic nature of PET, which results in the reduced absorption of liquid, and a smaller wetted radius and spreading speed on the top surface. Hence, the PET nonwoven fabric supports the wicking phenomenon, despite a higher pore diameter, resulting in a higher OWTC.

All nonwoven structures demonstrate a fair to very good one-way transport index/capability on the grading scale (Table 3). PET nonwoven fabric demonstrates a very good to excellent one-way transport index, while CV nonwoven fabric and 50PET/50CV blended nonwoven fabric demonstrate good one-way transport behaviour.

3.6 Overall moisture management coefficient

The overall moisture management coefficient is an index of the overall capability of a fabric to transport liquid moisture in multiple directions. A higher OMMC value indicates that a fabric can handle moisture better. The OMMC of all fabrics is presented in Table 5, with the classification of fabric type based on Table 4. An ANOVA of the mean OMMC is presented in Table 15. It is evident that, apart from delivery speed, all other factors have a significant effect on overall moisture management. The response surface equation in coded units for the mean OMMC is given in equation 10 with a $R^2$ value of 0.7701.

$$OMMC = 0.8239 + 0.055X_1 - 0.0675X_3 + 0.0708X_4 - 0.1168X_4^2$$

The effect of significant factors on the mean OMMC is shown in Figure 11 using equation 10. It is evident from Figure 11 that the overall moisture management coefficient (OMMC) is higher for CV-based fabrics than for PET-based nonwoven fabrics. This is because the smaller pore diameter of CV nonwoven fabric exhibits a smaller wetting time (top and bottom surfaces) with a higher spreading speed and higher wetted radius. These factors together contribute to the absorption, transportation and dispersion of moisture in the structure. Although PET-based nonwoven fabric also demonstrates at good OMMC value due to better one-way transport capability, which helps moisture move through a fabric, its lack of moisture dispersion capacity in the structure leads to the accumulation of moisture in one place. 50PET/50CV blended nonwoven fabric demonstrates a very good transport capability in the presence of PET fibres and better moisture absorption and dispersion due to CV fibres. Hence, the 50PET/50CV blended nonwoven fabric is better than the CV and PET nonwoven fabrics in terms of overall moisture management (Figure 11).

It is evident from Figure 11 that the overall moisture management coefficient (OMMC) decreases with an increase in web mass. A higher wetting time and smaller wetted radius hinder moisture absorption and dispersion. The effect of web mass is negative on the mean OMMC value. Nevertheless, all fabrics exhibited a very good to excellent OMMC value.

Table 15: ANOVA for the OMMC of spunlace nonwoven fabric

| Source    | Degree of freedom | Sum of square | Mean square | F value | P value | Percentage contribution [%] |
|-----------|-------------------|---------------|-------------|---------|---------|-----------------------------|
| Model     | 5                 | 0.265         | 0.053       | 13.98   | 0.000   | 76.90                       |
| Linear    | 3                 | 0.155         | 0.052       | 13.71   | 0.000   | 45.25                       |
| X1        | 1                 | 0.036         | 0.036       | 9.62    | 0.000   | 10.58                       |
| X3        | 1                 | 0.059         | 0.059       | 15.58   | 0.001   | 17.13                       |
| X4        | 1                 | 0.060         | 0.06        | 15.95   | 0.000   | 17.54                       |
| Square    | 2                 | 0.110         | 0.055       | 14.39   | 0.000   | 31.65                       |
| X1*X1     | 1                 | 0.010         | 0.01        | 4.12    | 0.003   | 1.09                        |
| X4*X4     | 1                 | 0.100         | 0.10        | 27.79   | 0.000   | 30.56                       |
| Error     | 21                | 0.080         | 0.004       |         |         | 23.10                       |
| Lack of fit | 19               | 0.079         | 0.004       | 6.48    | 0.142   | 22.73                       |
| Pure error | 2                 | 0.001         | 0.001       |         |         | 0.37                        |
| Total     | 26                | 0.345         | 0.345       |         |         | 100                         |
It is evident from Figure 11 that OMMC increases with an increase in waterjet pressure. This is because the higher relative frequency of the smaller pore diameter [22] at a higher waterjet pressure helps in the wicking phenomenon. Moreover, a smaller wetting time and higher wetted radius at a higher waterjet pressure help in proper moisture absorption and dispersion.

4 Conclusion

This study encompasses the performance of spunlace nonwoven fabrics for moisture management behaviour. It also explains the effect of different processing parameters on moisture management in spunlace nonwoven fabrics. This experimental study reinforces the fact that web composition is a major factor in determining the comfort of fabric in terms of moisture management. It has a significant effect on all attributes of the moisture management tester. The PET nonwoven fabric was seen as a water penetration fabric due to the hydrophobic nature of PET, which supports liquid/moisture wicking at a minimal absorption rate and spreading speed. The CV nonwoven fabric was found to exhibit excellent moisture management behaviour. The hydrophilic nature of CV fibre facilitates a high rate of absorption with a smaller wetting time, while a higher OWTC due to the smaller pore diameter leads to a higher bottom spreading speed and higher bottom wetted radius, resulting in the moisture management of the fabric. The 50PET/50CV blended nonwoven fabric was also shown to be a moisture management fabric. An analysis of moisture management tester results shows that all nonwoven fabrics demonstrated a good OMMC. The interaction of all parameters had no significant effect on the OMMC. Hence, individual parameters can be easily chosen to achieve the required OMMC. A higher waterjet pressure leads to a higher OMMC due to the higher relative frequency of the smaller pore diameter in nonwoven fabric, which supports the transfer of moisture/liquid. A higher web mass attenuates the OMMC value. This reduction can be overcome, however, by producing fabric with a higher waterjet pressure and through the proper selection of web composition. Hence, nonwoven fabric with either a CV or 50PET/50CV blended composition, using a higher waterjet pressure and higher web mass, may be used to develop apparel with the required moisture management properties.

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