*Fibers and Polymers* 2011, Vol.12, No.1, 57-64 DOI 10.1007/s12221-011-0057-9

# Designing Waterproof Breathable Materials Based on Electrospun Nanofibers and Assessing the Performance Characteristics

**Boram Yoon and Seungsin Lee***

*Department of Clothing and Textiles, Yonsei University, Seoul 120-749, Korea*

(Received September 2, 2010; Revised October 15, 2010; Accepted October 19, 2010)

**Abstract:** To develop waterproof breathable materials for diverse consumer applications, we used electrospinning to fabricate layered fabric systems with varying composite structures. Specifically, we developed layered fabric structures based on electrospun nanofiber webs with different levels of nanofiber web density, as well as different substrates and layer structures, and then examined the breathability and waterproofness of the material. The breathability and waterproofness of the layered fabric systems were compared with those of traditional waterproof breathable fabrics, including densely woven fabric, microporous membrane laminated fabric, and hydrophilic nonporous polyurethane coated fabric. Different breathability and barrier performance levels were achieved by varying the layer structure and substrates in the electrospun nanofiber web layered fabric systems. The uniformity of the nanofiber web and lamination process also affected the barrier and comfort performances. The comparison of waterproofness and breathability performances between the new materials and the traditional waterproof breathable materials revealed that the layered structures based on electrospun nanofiber webs provide a higher level of resistance to water penetration than densely woven fabrics and a higher degree of moisture vapor and air permeability than microporous membrane laminates and coated fabrics, with a proper selection of layer structure, substrate fabric, and lamination process.

**Keywords:** Electrospinning, Nanofiber web, Breathable fabric, Barrier, Waterproofness

## Introduction

Waterproof breathable fabrics have been developed for use in garments to provide protection of the human body from environmental factors, such as rain, wind, and harmful agents, while allowing water vapor to diffuse through. The number of applications for waterproof breathable fabrics continues to increase, ranging from outdoor clothing for leisure and sports to specialized medical and military uses [1,2]. The conditions of application and performance requirements, however, vary widely depending on the end use. Waterproof breathable fabrics used in outdoor sportswear and leisurewear need to provide the wearer with a greater level of comfort while providing weather protection, because consumers are more conscious of the comfort of the garments when wearing such performance apparel. Protective workwear for occupations, such as medical personnel and fire fighters, where resistance to liquid penetration is essential, requires a higher degree of waterproofing. Fabrics used in military applications, such as army combat uniforms, may be exposed to severe weather conditions and, thus, require a greater degree of barrier performance. To meet the diverse range of end uses and consumer needs for different types of activities, it is necessary to develop materials that offer different levels of breathability and waterproofness.

The demand for the development of a wide variety of waterproof breathable fabrics drives researchers to explore new techniques to impart waterproofness and breathability in addition to traditional waterproof breathable fabrics on the market. An electrospinning technique has been applied as one approach to develop a waterproof breathable material. Electrospinning provides an ultrathin membrane-like web of extremely fine fibers with very small pore size, which is attractive for a variety of applications from filtration to tissue scaffolds, sensors, and protective clothing [3-7]. Electrospun nanofiber webs can be engineered with a desired porous structure to impart barrier and comfort performance. The unique combination of high specific surface area, flexibility, light weight, and porous structure with the desired level of openness makes such fibers a preferred material for use in high performance apparel.

Nanofiber technology is being taken from the laboratory for use in a wide variety of scaled-up commercial applications that make use of electrospun nanomaterials [8]. Although several companies have achieved the mass scale production of nanofibers, filters are still the primary commercial use of electrospun fibers.

The potential of using electrospun nanofibrous webs for waterproof breathable materials has been investigated. Kang *et al.* [9] examined the feasibility of electrospinning polyurethane onto substrate fabrics to prepare waterproof breathable fabrics. Lee *et al.* [10,11] investigated the changes in mechanical properties and thermal and water transfer properties of mass-produced nanofiber web after laundering to evaluate the possibility of using nanofibers for outdoor wear. They reported that the mechanical properties of nanofiber web were sufficient for use as cloth in outdoor wear if a lamination process was used in its production and the nanofiber web materials maintained thermal and water transfer properties after repeated laundering.

*Corresponding author: SL158@yonsei.ac.kr

Since nanofiber webs are extremely thin, they typically need a supporting structure for commercial applications [12], and the way in which nanofiber layers are placed into the final composite material may affect the barrier and comfort performance of the material. In order to further examine the commercial applications of electrospun nanofiber webs for waterproof breathable fabric applications, it is necessary to develop electrospun nanofiber materials with varying composite structures and different levels of nanofiber web density and examine how these factors affect the waterproofness and breathability. This information would help the industry better design new waterproof breathable materials based on electrospun nanofibers. Also, it is important to compare this new type of waterproof breathable material with traditional waterproof breathable fabrics on the market in terms of the barrier and comfort performance to assess the possibility of creating a new market position. The introduction of new waterproof breathable materials may provide a range of choice for consumers and lead to a higher degree of segmentation in the market.

This research focuses on the development of waterproof breathable materials that meet diverse end uses and consumer needs for different types of applications, using the electrospinning technique. Layered fabric systems based on electrospun nanofiber webs were developed with different levels of nanofiber web density, as well as different substrates and layer structures. Nanofiber webs produced on a mass-scale, as well as nanofiber webs fabricated with different web density in our lab, were used to build various composite structures. The waterproofness and breathability of layered fabric systems were evaluated and compared with those of typical waterproof breathable fabrics on the market, including densely woven fabric, microporous membrane laminated fabric, and coated fabric.

## Experimental

### Materials

***Lab-scale Nanofiber Web Layered Fabric Systems***

Commercial-grade polyurethane pellets (Pellethane$^{TM}$, 2103-80AE, Dow Chemical Company, USA) were used to fabricate a lab-scale nanofiber web with different levels of nanofiber web density. *N*,*N*-dimethylformamide (DMF) (Junsei Chemical Co., Ltd., Japan) was used as a solvent. Electrospinning solutions were prepared by dissolving the polymer in DMF at the concentration of 13 wt%. A vertical electrospinning setup with a two-axis robot system (NNC-ESP200R2, NanoNC Co., Korea) was used. It consisted of a high voltage power supply capable of 0-30 kV, a syringe pump, a grounded collector, and a multiple nozzle system, in which a computer-aided system controls the nozzle system and the collector so that they run lengthwise and crosswise, respectively, to fabricate uniform nanofiber webs.

Layered fabric systems were fabricated to support the limited mechanical properties of nanofiber webs. A densely woven fabric (Kolon Fashion Material Co., Korea) was used as a substrate for the lab-scale nanofiber web layered fabric systems. The substrate fabric was 100 % polyester and had a thickness of 0.17 mm, a weight of 88.4 g/m$^2$, and a fabric count of 160×150 (W×F)/in. An aerosol adhesive (3M Co., USA) was applied to the substrate to improve the adhesion of the nanofiber web to the substrate layers before the electrospinning process. Polyurethane (PU) nanofibers were electrospun directly onto the substrate under a variety of conditions, including various feed rates, electric voltages, collecting distances and capillary diameters to find optimum spinning conditions for our electrospinning setup. Two kinds of lab-scale nanofiber web layered fabric systems were produced with a web density of 5.6 and 10.2 g/m$^2$, respectively, under optimum spinning conditions.

***Mass-produced Nanofiber Web Layered Fabric Systems***

Three kinds of nanofiber web layered fabric systems were fabricated using a mass-produced electrospun nanofiber web supplied by Finetex Technology Co. The mass-produced nanofiber web was polyurethane with a web density of 5.2 g/m$^2$. The nanofiber webs were laminated on substrate fabrics using a mesh roller and polyurethane adhesive to support the thin nanofiber webs. Three kinds of mass-produced nanofiber web layered fabric systems with different substrates and layer structures were prepared. Two kinds of two-layer construction were fabricated, in which different substrates were used. A densely woven fabric and a regular polyester fabric typically used as a substrate in conventional waterproof breathable laminates were chosen for the substrate, respectively. A three-layer structure was also constructed, in which a regular polyester fabric and a nylon tricot were used as substrate fabrics. A mass-produced nanofiber web was laminated to a regular polyester fabric first, and then a nylon tricot knitted fabric was laminated to the other side of the web, so that the nanofiber web was sandwiched between the two substrate fabrics. The regular polyester fabric had a thickness of 0.15 mm, a weight of 109 g/m$^2$, and a fabric count of 93×93/in. The nylon tricot had a thickness of 0.25 mm, a weight of 69 g/m$^2$, and a fabric count of 42×84/in. The descriptions of the lab-scale nanofiber web layered fabric systems and mass-produced nanofiber web layered fabric systems are presented in Table 1.

***Conventional Waterproof Breathable Fabrics***

For comparisons of breathability and waterproofness, three kinds of typical waterproof breathable fabrics currently in use were selected; a densely woven fabric (Kolon Fashion Material Co., Korea), a microporous polytetrafluoroethylene (PTFE) membrane laminated fabric (Donaldson Co., USA) and a hydrophilic nonporous PU coated fabric (Hwashin Special Textile Filter Co., Korea). Fabric descriptions are given in Table 2.

**Table 1.** Fabric construction and characteristics of nanofiber web layered fabric systems

| Specimen | Sample code | Construction | Nanofiber web density ($g/m^2$) | Substrate | Weight ($g/m^2$) | Thickness (mm) |
|---|---|---|---|---|---|---|
| Lab-scale nanofiber web layered fabric system | L1 | 2-layer | 5.6 | Densely woven 100 % polyester | 91.9 | 0.18 |
| | L2 | 2-layer | 10.2 | Densely woven 100 % polyester | 92.4 | 0.23 |
| Mass-produced nanofiber web layered fabric system | C1 | 2-layer | 5.2 | Densely woven 100 % polyester | 97.9 | 0.17 |
| | C2 | 2-layer | 5.2 | 100 % polyester fabric | 120.0 | 0.21 |
| | C3 | 3-layer | 5.2 | 100 % polyester fabric 100 % nylon tricot | 187.9 | 0.46 |

**Table 2.** Characteristics of conventional waterproof breathable fabrics

| Specimen | Substrate | Weave construction | Weight ($g/m^2$) | Thickness (mm) | Fabric count (warp×filling/inch) |
|---|---|---|---|---|---|
| Densely woven fabric | 100 % polyester | Dobby | 88.4 | 0.17 | 160×150 |
| PU coated fabric | 100 % polyester | Plain | 101.3 | 0.13 | 136×84 |
| PTFE membrane laminated fabric | 100 % polyester | Dobby | 101.9 | 0.20 | 179×119 |

### Fiber Morphology

Morphology of electrospun polyurethane fibers and the layered fabric systems was examined using a field-emission scanning electron microscope (FE-SEM) (Hitachi Model S-4200, Nissei Sangyo, Japan) after sputter-coating with Pt/Pd.

### Pore Size Distribution

Pore size distribution was measured by a Capillary Flow Porometer (Model ACFP-1500-AE, Porous Materials, Inc., USA). Gas flow rates through wet and dry samples versus differential pressure were measured, and pore diameters of through-pores at the most constricted part of the pore were determined.

### Resistance to Water Penetration

Resistance to water penetration of each layered fabric system was measured according to ISO 811:1981, Textile Fabrics - Determination of resistance to water penetration - hydrostatic pressure test, using a hydrostatic pressure tester (FX3000III, Textest Co., Switzerland) for five samples. The water temperature was maintained at 20±2 °C, and the rate of increase of water pressure was set at 60 $cmH_2O$/min. The experiments were conducted in a controlled atmosphere, in which the air temperature was 20±2 °C and the relative humidity was 65±5 %.

### Air Permeability

Air permeability was measured according to ASTM D 737-2004, Standard test method for air permeability of textile fabrics, using a Frazier Air Permeability Tester for ten samples. The testing area was 38 $cm^2$, and the pressure drop used was 125 Pa.

### Water Vapor Transmission

Water vapor transmission rate was measured according to ISO 2528:1995, Sheet materials – Determination of water vapour transmission rate – Gravimetric (dish) method, for three samples. Anhydrous calcium chloride was used as a desiccant, and the experiments were conducted in a controlled atmosphere, in which the air temperature was 38±0.5 °C and the relative humidity was 90±2 %.

## Results and Discussion

### Fiber Morphology

To fabricate lab-scale electrospun nanofiber web layered fabric systems, polyurethane fibers were electrospun under various conditions to find optimum spinning conditions for our electrospinning setup. Figure 1(a) shows electrospun polyurethane fibers obtained from a 13 wt % polyurethane solution with a 26-gauge needle (0.23 mm i.d.) at a feed rate of 0.2 m*l*/h, a voltage of 10 kV, and a collecting distance of 11 cm. Cylindrical fibers with diameters ranging from 300 to 500 nm were obtained. At the optimal condition, polyurethane nanofibers were electrospun directly onto a substrate, a densely woven fabric, to form a lab-scale nanofiber web layered fabric system. Figure 1(c) illustrates the cross-sectional view of a lab-scale nanofiber web layered fabric system with the web density of 5.6 $g/m^2$ (L1). We observed that a thin layer of electrospun nanofiber web was deposited onto the substrate fabric, as indicated by a dotted circle.

The surface morphology of the nanofiber web manufactured

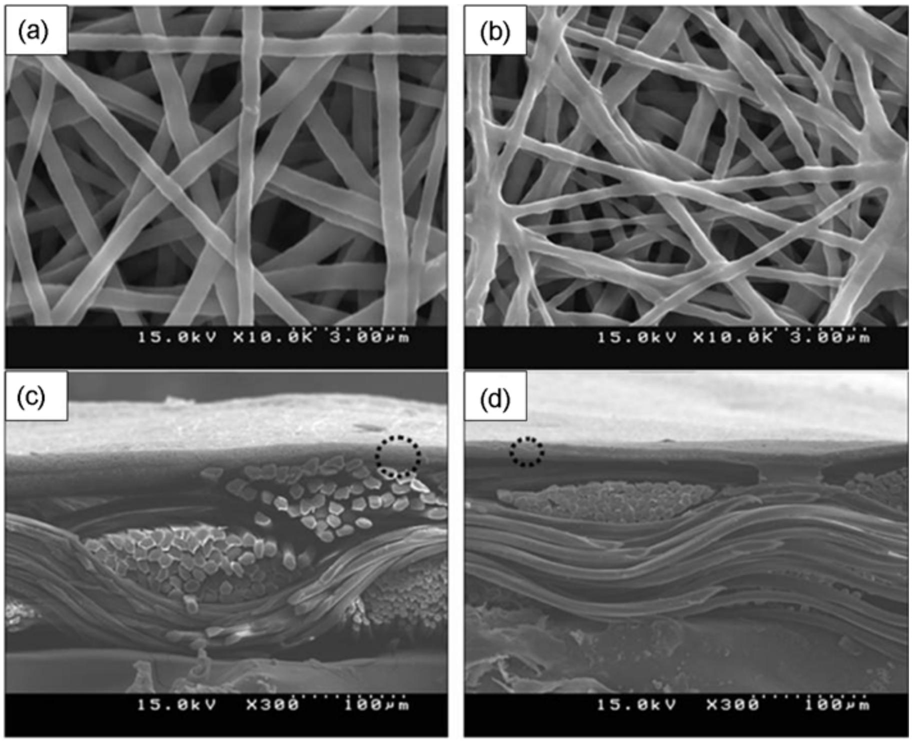


**Figure 1.** SEM micrographs of electrospun polyurethane nanofiber web layered fabric systems; (a) lab-scale nanofiber web, (b) mass-produced nanofiber web, (c) cross-section of a lab-scale nanofiber web layered fabric system with 5.6 g/m$^2$ web density (L1), and (d) cross-section of a mass-produced nanofiber web layered fabric system with 5.2 g/m$^2$ web density (C1).

on a mass scale is shown in Figure 1(b). The diameter of the nanofibers ranged from 300 to 500 nm, which was similar to that of lab-scale nanofibers. The mass-produced nanofiber webs were laminated to substrate fabrics in different composite structure designs. Figure 1(d) presents the cross-sectional view of a mass-produced nanofiber web layered fabric system with a web density of 5.2 g/m$^2$ (C1). As compared with the lab-scale nanofiber web layered fabric system (Figure 1(c)), a much thinner nanofiber web layer with the thickness of around 10 $\mu$m was observed for the mass-produced nanofiber web layered fabric system. This might be due to the laminating process applied to the mass-produced nanofiber web layered fabric systems. The pressure applied to the web and substrate fabric during the laminating process would make the nanofiber web even thinner and compact, and this may affect the barrier and comfort performance of the material.

## Water Vapor Transport

Water vapor transport represents the ability of a material to allow the transfer of moisture vapor through the material. Moisture vapor permeability becomes extremely important in determining thermal comfort, especially in hot environments, because sweat production and evaporation are the major cooling mechanisms for maintaining thermal comfort and

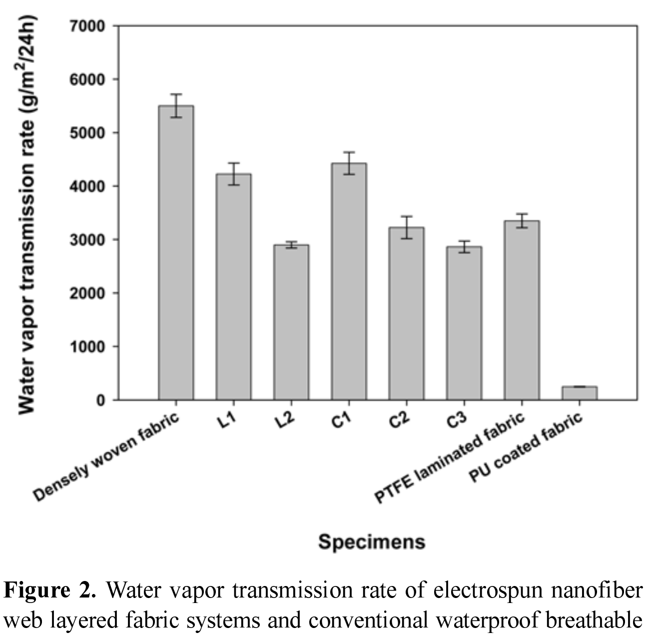


**Figure 2.** Water vapor transmission rate of electrospun nanofiber web layered fabric systems and conventional waterproof breathable fabrics.

avoiding heat stress in such environments.

The water vapor transmission rates of the electrospun nanofiber web layered fabric systems and the conventional waterproof breathable fabrics are presented in Figure 2. Densely woven fabrics exhibited the highest water vapor transmission rate of 5500 g/m$^2$/24 h, as expected. Electrospun nanofiber web layered fabric systems showed water vapor transmission rates in the range between 2899 and 4300 g/m$^2$/24 h, depending on the composite structure design, and these rates were much higher than those for PU coated fabrics. PTFE laminated fabrics showed water vapor transport similar to that of C2, a mass-produced nanofiber web layered fabric systems. PU coated fabric exhibited the lowest water vapor transmission rate, 250 g/m$^2$/24 h, which indicates that it may be thermally uncomfortable if worn for long periods during strenuous activities.

Comparisons of the two lab-scale nanofiber web layered fabric systems, L1 and L2, show the effect of nanofiber web density on water vapor transport of layered structures, considering that the same substrate fabric and layer construction were used in those systems. Layered fabric systems with high web density (L2) had a lower water vapor transmission rate than layered fabric systems with low web density (L1). The type of substrate fabric and the layer structure also had an influence on the water vapor transport of the final composite material. Although the same kind of nanofiber web was used in the mass-produced nanofiber web layered fabric systems (C1, C2, and C3), they exhibited a range of water vapor transmission. The layered structure in which densely woven fabric was used as a substrate (C1) exhibited higher water vapor transport than the one in which the regular polyester fabric was used as a substrate (C2). The three-layer system (C3) gave lower water vapor transport than the two-layer system (C2). Water vapor transport through a textile material has been shown to be governed by various factors, such as pore size, the amount of voids in the material, and thickness [13-15]. Our findings indicate that not only the nanofiber web layer but composite structure design, including layer construction and the structure of substrate fabric, may also contribute to the porosity or pore length of the final composite material, and hence, the water vapor transport performance of the material.

Compared with waterproof breathable fabrics currently in use, electrospun nanofiber web layered fabric systems exhibited water vapor transport in the range between that of densely woven fabric and PU coated fabric. Especially L1 and C1 demonstrated large water vapor transport, which is promising in terms of providing thermal comfort.

### Air Permeability

Air permeability of a fabric represents the breathing or ventilation functions of the material. Generally, fabric air permeability is associated with wearer thermal comfort, especially in hot, humid environments. Figure 3 shows air permeability of the electrospun nanofiber web layered fabric systems and the conventional waterproof breathable fabrics. Densely woven fabrics showed the highest air permeability, whereas the PU coated fabrics gave the lowest, followed by the PTFE laminated fabrics. Electrospun nanofiber web layered fabric systems exhibited air permeability much higher than that of the coated fabrics and laminated fabrics.

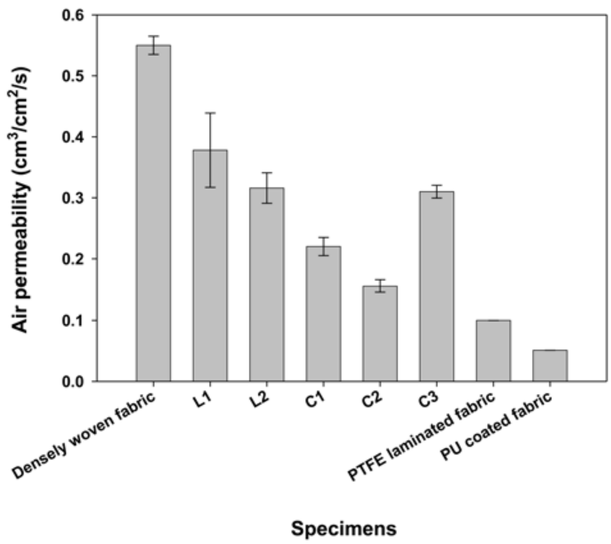


**Figure 3.** Air permeability of electrospun nanofiber web layered fabric systems and conventional waterproof breathable fabrics.

Figure 3 illustrates that layered fabric systems with high web density (L2) give lower air permeability than layered fabric systems with low web density (L1), which may be attributed to the reduced pore sizes. The type of substrate fabric also had an influence on the air permeability of the layered fabric systems. The layered structure, in which densely woven fabric was used as a substrate (C1), exhibited higher air permeability than the one in which the regular polyester fabric was used as a substrate (C2), given that the same kind of nanofiber web was used in those systems. Interestingly, we found that the three-layer system (C3) gave higher air permeability than the two-layer system (C2). To gain an insight, pore size distribution was measured on these layered fabric systems. Capillary flow porometry was used to measure pore diameters of only through-pores at the most constricted part of the pore for the fabric systems. As shown in Figure 4, C3 exhibited a narrow pore size distribution with the pore size ranging from 0.39 to 0.66 $\mu$m. The diameter at the maximum pore size distribution for C3 was 0.46 $\mu$m. On the other hand, smaller pores with the pore size ranging down to 0.15 $\mu$m were observed for C2, exhibiting a wider pore size distribution. The diameter at the maximum pore size distribution for C2 was 0.41 $\mu$m. It appears that C3 contains a greater portion of relatively large pores than C2, and these large pores may lead to the higher air permeability, as compared with C2. Air permeability is obtained from the rate of air flow through a fabric at a given pressure differential between the two fabric surfaces. For this type of air flow at a given pressure, resistance to flow through an

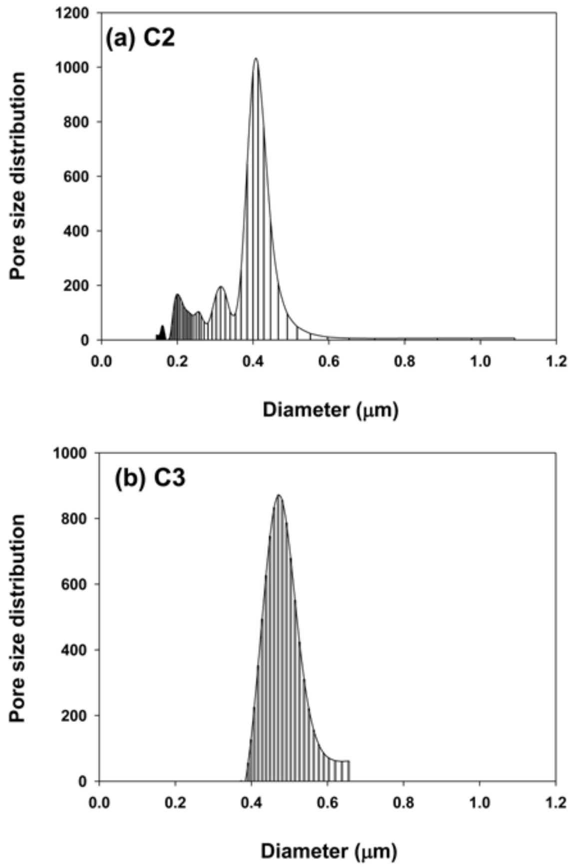


**Figure 4.** Through-pore size distribution of layered fabric systems with an electrospun polyurethane web layer.

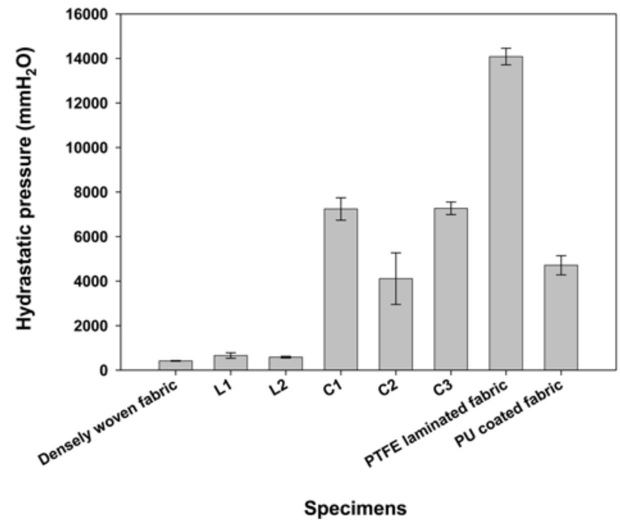


**Figure 5.** Resistance to water penetration of electrospun nanofiber web layered fabric systems and conventional waterproof breathable fabrics.

individual pore decreases considerably as the pore diameter increases. Thus, pore size has a considerable impact on air permeability, and especially large pores contribute significantly to air permeability. The tri-laminate system, C3, underwent the lamination process twice, which might have created physical changes to the nanofiber web, resulting in larger pores.

### Resistance to Water Penetration

Resistance to water penetration of the electrospun nanofiber web layered fabric systems and the conventional waterproof breathable fabrics is given in Figure 5. PTFE membrane laminated fabrics showed the highest resistance to water penetration, followed by C1 and C3. Generally, mass-produced nanofiber web laminated fabric systems, C1, C2, and C3, exhibited a higher or comparable range of water resistance to that of coated fabrics. On the other hand, lab-scale nanofiber web layered fabric systems exhibited low values similar to that of densely woven fabrics. This might be due to the uniformity of the mass-produced nanofiber web and the lamination process employed to the mass-produced nanofiber web layered fabric systems. In general, mass-produced nanofiber webs are manufactured under a better controlled environment, including a controlled atmosphere, in comparison to lab-scale nanofiber webs; thus, the uniformity of the web would be better maintained in the mass-produced nanofiber web. Also, the strong adhesion of the nanofibrous web to the textile basis may have been achieved because of the laminating process, resulting in enhanced barrier performance in the mass-produced nanofiber web layered fabric systems.

Liquid penetration through porous materials is commonly described by classical mathematical models, which can explain the relationship between liquid penetration resistance and the properties of the material and the liquid. The Laplace equation, $P=2\gamma\cos\theta/r$, describes liquid penetration into the material. $P$ is the pressure necessary to draw a liquid through a pore, $\gamma$ is the surface tension of the liquid, $\theta$ is the contact angle at the liquid/material interface, and $r$ is the radius of the pore. The Poiseuille equation, $Q=[\pi r^4/8\eta]$ $(\Delta P/L)$, describes liquid flow through a pore. $Q$ is the liquid flow rate, $\Delta P$ is the pressure difference across the pore length, $\eta$ is the viscosity of the liquid, and $L$ is the pore length. As shown in the equations, factors including surface tension and viscosity of the challenge liquid, the interaction between the liquid and the surface of the material (as defined by the contact angle), the pore geometry of the material, and the material thickness contribute to liquid penetration through materials.

Among the three different types of mass-produced nanofiber web laminated fabric systems, C3 exhibited greater water resistance than C2. The thickness of C3 was more than twice the thickness of C2 (see Table 1), and this may be a contributing factor in restricting liquid penetration through the material. The two-layer structure in which a densely woven fabric was used as a substrate (C1), exhibited much higher water resistance than C2, the two-layer structure in which a regular polyester woven fabric was used as a substrate, which might be associated with the geometric structure of the substrate fabric and the interaction between the liquid and the surface structure of the substrate. In fact, C1 provided similar water resistance to that of C3, the three-layer structure. This finding indicates that it would be possible to construct a two-layer nanofiber composite with the same level of waterproofness as a three-layer nanofiber composite, without losing hand and drape, if a proper substrate fabric is selected. This implies the importance of choosing an appropriate substrate material that can maximize the performance in a composite structure. In this study, the base fabrics with no surface treatments were used since we wanted to examine the effect of nanofiber webs on the protection and thermal comfort performance, excluding any effect from finishing. We expect that water repellent finishing on the base fabric would further enhance the protection performance of the layered fabric systems.

**Comparative Evaluation of Different Waterproof Breathable Materials**

Waterproofness and breathability are two mutually contradictory performance characteristics; thus, it is important to maintain the balance between these properties. To assess and compare the overall performance of the newly developed waterproof breathable materials, waterproofness performance was plotted against air and moisture vapor transport properties

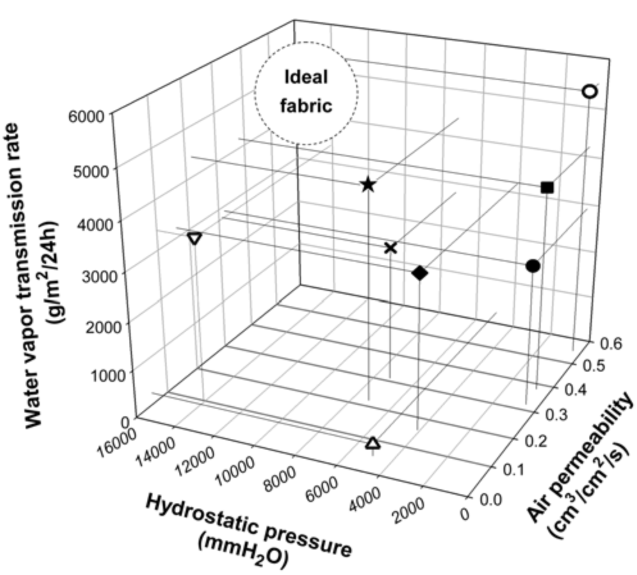


**Figure 6.** Resistance to water penetration, water vapor transmission rate and air permeability of layered fabric systems with an electrospun nanofiber web, as compared with conventional waterproof breathable fabrics; (○) densely woven fabric, (■) L1, (●) L2, (★) C1, (◆) C2, (×) C3, (▽) PTFE laminated fabric, (△) PU coated fabric.

and compared with conventional waterproof breathable fabrics (Figure 6). Densely woven fabrics, microporous membrane laminates, and hydrophilic nonporous PU coated fabric are typical waterproof breathable fabrics on the market. In the review article on waterproof breathable fabrics [16], the authors pointed out that there is still ample scope for further technical and commercial developments in waterproof breathable fabrics. This is clearly shown in Figure 6, in which typical waterproof breathable fabrics currently in use are located along the planar edges. Densely woven fabrics exhibit high water vapor transmission rate and air permeability, but very low resistance to water penetration, whereas microporous PTFE membrane laminated fabrics provide the highest resistance to water penetration, but very low air permeability. PU coated fabrics exhibit low water vapor transport and air permeability and about mid-range resistance to water penetration. Figure 6 clearly indicates that a large "window of opportunity" exists for development of materials that could provide a combination of high barrier performance and thermal comfort. New waterproof breathable materials should be targeted to this area of need in order to provide consumers with materials offering enhanced barrier and comfort performance.

As shown in Figure 6, electrospun nanofiber web layered fabric systems are successfully located in the target zone, filling the void space. In particular, mass-produced nanofiber web layered fabric systems, C1, C2, and C3, exhibit a higher level of protection than densely woven fabrics and offer a higher degree of breathability and comfort than microporous membrane laminates and coated fabrics. On the other hand, lab-scale nanofiber web layered fabric systems, L1 and L2, exhibit a high level of air and moisture vapor transport properties, but have a low waterproofness performance similar to that of densely woven fabrics. This confirms that the lamination process and uniformity of nanofiber web are essential for enhanced barrier performance.

Ideal waterproof breathable materials should prevent penetration of water, while allowing the release of moisture vapor and air to provide thermal comfort (Figure 6). The mass-produced nanofiber web layered fabric systems exhibit waterproofness and breathability performance much closer to that needed for the ideal zone. Figure 6 illustrates that a waterproof breathable material with "ideal" behavior of high protection and high air and water vapor permeability for thermal comfort could be developed using electrospinning. It also shows that we could achieve different breathability and barrier performance levels by controlling the composite structure design, such as layer structure and substrate fabrics in the layered fabric systems.

## Conclusion

There is a large demand for waterproof breathable products, and waterproof breathable fabrics are being used not only in high performance work and sportswear, but also in everyday fashion wear. This research investigated the use of electrospinning in creating waterproof breathable materials that offer different levels of breathability and waterproofness to meet diverse end uses and consumer needs. Layered fabric systems, based on electrospun nanofiber webs with varying composite structures, substrate fabrics, and different levels of nanofiber web density, were developed, and the breathability and waterproofness were examined. The breathability and waterproofness of the layered fabric systems were compared with those of waterproof breathable fabrics currently in use, including densely woven fabric, microporous membrane laminated fabric, and hydrophilic nonporous PU coated fabric.

Different performance levels were achieved by varying the layer structure and substrates in the electrospun nanofiber web layered fabric systems. Composite structure design had a considerable influence on the degrees of breathability and waterproofness. This finding implies that nanofiber webs should be incorporated into layered composite structures in such a way as to achieve a combination of high barrier and comfort performance. The uniformity of the nanofiber web manufactured on a mass-scale and the subsequent lamination process, which gave strong adhesion of the nanofibrous web to the substrate fabric, also affected the breathability and waterproofness. Among the various layered fabric systems that we developed, the best combination of waterproofness and breathability was achieved in C1, a mass-produced nanofiber web layered fabric system. This result opens the possibility of engineering a composite structure based on electrospun nanofibers that will enhance thermal comfort while providing high levels of protection.

The comparison of waterproofness and breathability performance between the new materials and the traditional waterproof breathable materials on the market showed that waterproof breathable materials capable of filling the gap in barrier/comfort performances of existing waterproof breathable materials can be engineered using electrospinning. The introduction of this new type of waterproof breathable materials may provide alternatives in this market and offer a range of choices for consumers.

## Acknowledgements

This work was supported by the Korea Research Foundation Grant, funded by the Korean Government (MOEHRD, Basic Research Promotion Fund) (KRF-2008-331-C00328).

## References

1. G. R. Lomax, *J. Coated Fabrics,* **15**, 40 (1985).
2. A. Mukhopadhyay and V. K. Midha, *J. Ind. Text.,* **37**, 225 (2008).
3. D. H. Reneker and I. Chun, *Nanotechnology*, **7**, 216 (1996).
4. X. Qin and S. Wang, *J. Appl. Polym. Sci.*, **109**, 951 (2008).
5. A. Martins, J. V. Araujo, R. L. Reis, and N. M. Neves, *Nanomedicine*, **2**, 929 (2007).
6. J. Park, J. Moon, S. Lee, S. H. Kim, T. Zyung, and H. Y. Chu, *Mater. Lett.*, **64**, 255 (2010).
7. S. Lee and S. K. Obendorf, *Text. Res. J.,* **77**, 696 (2007).
8. S. Ramakrishna, K. Fujihara, W. E. Teo, T. C. Lim, and Z. Ma, "An Introduction of Electrospinning and Nanofibers", pp.275-340, World Scientific Publishing Co. Pte. Ltd., London, 2005.
9. Y. K. Kang, C. H. Park, J. Kim, and T. J. Kang, *Fiber. Polym.,* **8**, 564 (2007).
10. S. Lee, D. Kimura, A. Yokoyama, K. Lee, J. C. Park, and I. Kim, *Text. Res. J.,* **79**, 1085 (2009).
11. S. Lee, D. Kimura, K. H. Lee, J. C. Park, and I. S. Kim, *Text. Res. J.,* **80**, 99 (2010).
12. K. Graham, M. Gogins, and H. Schreuder-Gibson, *Int. Nonwovens J.,* **13**, 21 (2004).
13. M. E. Whelan, L. E. MacHattie, A. C. Goodings, and L. H. Turl, *Text. Res. J.,* **25**, 197 (1955).
14. L. I. Weiner, *Text. Chem. Color.,* **2**, 378 (1970).
15. S. Backer, *Text. Res. J.,* **18**, 650 (1948).
16. A. Mukhopadhyay and V. K. Midha, *J. Ind. Text.,* **38**, 17 (2008).