Physical and Mechanical Properties of Thermostatic Fabrics Treated with Nanoencapsulated Phase Change Materials

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ABSTRACT: Textiles treated with nanoencapsulated phase change materials (nanoPCMs) were used to examine their suitability as clothing materials to prepare thermostatic clothes for absorbing or releasing heat according to heat fluctuation between the body and the environment. To this end, the physical and mechanical properties of fabrics treated with nanoPCMs, such as nano-nonadecane and nano-octadecane, were evaluated after we confirmed the morphology and thermal efficiency of the nanoPCMs. The nanoPCMs were almost spherical, with an irregular size distribution between 200 and 400 nm. The heat of fusion and peak temperature of melting for nano-nonadecane, nano-octadecane, and a balanced mix were measured at 102.6 J/g and 33.6°C, 144.7 J/g and 29.8°C, and 137.4 J/g and 31.8°C, respectively. However, the heat of fusion of the vapor-permeable and water-repellant (VPWR) fabrics treated with the nanoPCMs were only 6.8, 4.0, and 3.6 J/g, respectively, because the weight of fabric was added per unit area. The air permeability of the specimens without nanoPCMs was the lowest; that of the VPWR fabrics with nanoPCMs was relatively higher. The water vapor transmission of the VPWR fabrics with nanoPCMs was higher than the fabric without nanoPCMs, and the water resistance decreased in the same order. Compared to the mechanical properties of the fabric without nanoPCMs, the stiffness and roughness of the fabrics with nanoPCMs were improved, but the resilience and smoothness of the fabrics were slightly decreased. Consequently, the physical and mechanical properties of VPWR fabrics with nanoPCMs were superior to those of the fabric without nanoPCMs. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 121: 3238–3245, 2011

Key words: mechanical properties; nanotechnology; thermal properties; thermodynamics

INTRODUCTION

The thermal protection of clothing is a critically important factor for the safety and thermal comfort of human beings.[1] Dry thermal insulation, moisture and vapor resistance, heat exchange with clothing, compression, and air permeability can be factors affecting the thermal comfort properties of clothing.[2] Phase-change materials (PCMs) can regulate microclimate conditions by reversible phase changes, such as solid to liquid and liquid to solid, during heat fluctuation between the environment and a human body.[3] Linear-chain hydrocarbons, known as *paraffin waxes* [i.e., alkanes (C_nH_{2n+1})], are used exclusively for textile and clothing materials because they not only have substantial latent heat, excellent and uniform thermal properties, good chemical stability, and low vapor pressures but are also environmentally friendly, nontoxic, and reusable and prolong the thermal comfort of the wearer.[4,5] PCMs in clothing can be useful to thermal comfort by offering thermal regulation because clothing treated with PCMs are expected to play a role in actively regulating microclimate conditions through absorbing excess heat, releasing heat, and minimizing sweating.[6] Actually, many research studies of PCMs in textiles and their applications have used textiles or clothing treated with microencapsulated phase-change materials (microPCMs)[7–10] since microPCMs were applied by Vigo and Frost[11,12] to textiles because the thermal properties of protective clothing can be significantly improved by the incorporation of microPCMs. Currently, the thermal properties of PCMs are widely used in different types of garments by direct incorporation into fibers and foams or coating onto fabrics.[13] However, until now, the decrease of fabric hand, which is closely related to wear comfort, and a low thermal efficiency should be improved. A better way for one to increase the respective performances in clothing are to choose the proper PCMs according to an application, to extend the thermostatic range, and to maintain the phase-change effect without breaking or taking PCMs off of their fabrics.[14,15] If

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TABLE I
Mechanical Parameters Measured with the KES-FB Instruments

Equipment	Property	Parameter	Unit
KES-FB1	Tensile	Elongation at the maximum load	%
		Tensile linearity	—
		Tensile energy	gf cm/cm^2
		Resilience	%
KES-FB2	Bending	Bending rigidity	gf cm^2/cm
		Hysteresis of the bending moment	gf cm/cm
KES-FB1	Shearing	Shear stiffness	gf/cm deg
		Hysteresis of the shear force at 0.5°	gf/cm
KES-FB4	Surface	Coefficient of friction	—
		Mean deviation of the coefficient of friction	—
		Geometrical roughness	μm
KES-FB3	Compression	Linearity of compression	—
		Compression energy	gf cm/cm^2
		Compression resilience	%
KES-FB3	Thickness	Thickness at 0.5 gf/cm^3	mm
	Weight	Weight per unit of area	g/cm^2

encapsulated PCMs are controlled on the nanoscale, the duration is improved because they are not easily left out of the fabric, even with strong external forces; nanoencapsulated phase-change materials (nanoPCMs) will percolate further inside the fibers than microPCMs. The thermal effectiveness can be elevated by an increase in the amount of capsule adopted per unit area.[16] Moreover, the thermostatic effect can be extended by the use of multiple PCMs, which refers to the use of over two kinds of PCMs.[17]

However, research addressing clothing materials treated with nanoPCMs or the use of multiple PCMs has rarely been performed in the textile field. To date, most studies have been more focused on the thermal efficiency than on the physical and mechanical properties of treated fabrics. However, both the wearability and functionality should be simultaneously considered, in that a human works and lives in various combinations of environmental conditions and physical activities. Therefore, in this study, we examined the physical and mechanical properties of thermostatic fabrics treated with nanoPCMs to evaluate their suitability as a smart clothing materials. Polyester knitted fleece fabrics were treated with multiple nanoPCMs (nano-octadecane and nano-nonadecane) customized by environmental conditions and application. Then, the morphology and thermal efficiency of the nanoPCMs and the physical and mechanical properties of the nanoPCM fabrics were evaluated with standard methods.

EXPERIMENTAL

Materials

We chose the PCMs by considering body temperature in static and dynamic conditions according to changes in the ambient conditions.[18,19] Then, an expert customized the nanoPCMs. The synthesized nanoPCMs, containing nonadecane and octadecane with two walls through double nanoencapsulation with acrylic and melamine, were used as shell materials:[20] 50% octadecane and 30% nonadecane were encapsulated as the core materials. The PCMs barely leaked out because the nanocapsules were contained two walls. The synthesized nanoPCMs had an effect on the high thermal response caused by superior thermal conductions. The fusion of nano-octadecane started at 22.40°C and peaked at 29.76°C, and the heat of fusion (ΔH_f) was 144.70 J/g. The melting of nano-nonadecane started at 27.37°C and peaked at 33.58°C, and ΔH_f was 102.60 J/g. In the case of mixed nanoPCMs (nonadecane and octadecane), melting started at 23.43°C and peaked at 31.8°C, and ΔH_f was 137.40 J/g.

Specimens

The treatment of nanoPCMs was carried out simultaneously with a vapor-permeable and water-repellant (VPWR) finish for the active discharge of moisture from perspiration. The VPWR fabrics were classified by their mixture contents: (1) VPWR fabric laminated with simple microporous films (WRF (VPWR finish only)), (2) VPWR fabric bonded with microporous films containing nano-nonadecane (FNN (VPWR with nano-nonadecane)) or nano-octadecane (FNO (VPWR with nano-octadecane)), and (3) VPWR fabric laminated with microporous films containing a mixture of nano-nonadecane and nano-octadecane in a 1 : 1 ratio (FNM (VPWR with nano-octadecane nano-nonadecane)). We prepared the VPWR nanoPCMs membranes by mixing 25% nanoPCMs with 75% oil-soluble polyurethane by controlling the amount and thickness of the mixtures. Then, they were laminated on a polyester knitted fleece that had an adhesive on

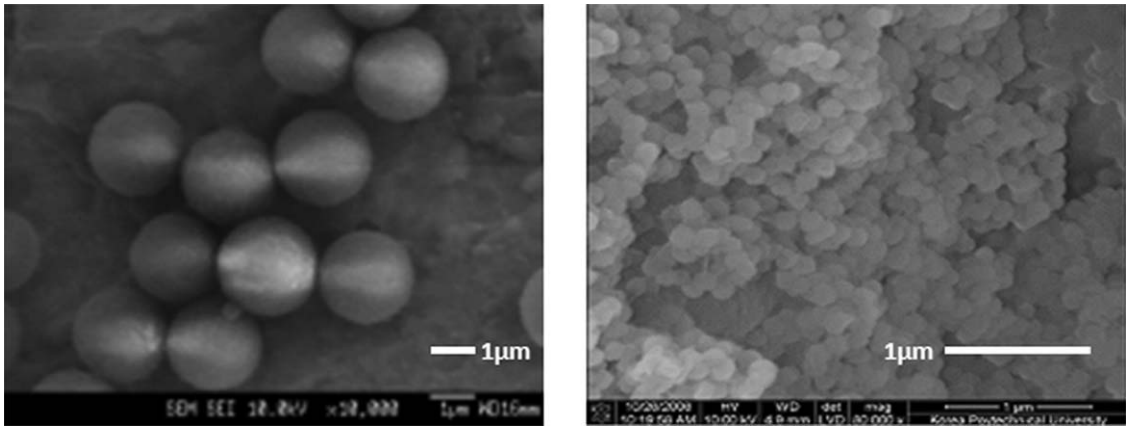

Figure 1 Structures of (a) microPCMs (10,000×) and (b) nanoPCMs (80,000×).

one side. The thickness of the fabric was 1.04 mm, and the weight was 12.60 g/m^2. Thermostatic membranes were laminated onto the adhesive side of the fabric at 120°C for 20 s at a pressure of 15 gf/cm^2 and washed to remove impurities.

Measurement of the nanoPCMs and VPWR textiles containing nanoPCMs

The mean diameter and shape of the nanoPCMs and the surface of the treated fabrics were observed with a scanning electron microscope (JSM 820; JEOL, Tokyo, Japan). The air permeability (Frazier air permeability tester, cm^3 s^{-1} cm^{-2}) of the fabrics was examined with ASTM D 737-2004. Specimens were maintained in standard conditions (temperature = 21 ± 1°C, relative humidity = 65 ± 2%) for 24 h; then, conditioned fabrics were tested at a water pressure differential of 125 Pa/38 cm^2. The water vapor transmission (WVT) was evaluated according to ASTM E 96-2000, procedure E (the desiccant method; controlled chamber temperature = 38 ± 1°C, relative humidity = 90 ± 2%), and calculated with the following equation:

$$\mathrm{WVT}\,(\mathrm{g/m^2/24\,h}) = \frac{24M}{ST}$$

where M is the weight change (g), S is the test area (m^2), and T is the exposure duration (h).

Water resistance (mm H_2O) was measured according to ISO 811-1981 (hydrostatic pressure test). The increasing water pressure was 60 ± 3 cm H_2O/min, the temperature was 20 ± 1°C, and the circular area below the test specimen was 100 cm^2. The mechanical properties of the specimens were measured with the Kawabata Evaluation System for Fabrics (KES-FB; KN-402WKT, Kato Tech Co., Ltd., Kyoto, Japan);[21] these properties included the tensile, shear, bending, and compression properties, the geometrical roughness, the thickness, and the weight.[22] Four basic KES-FB instruments simulated the modes of fabric deformation at the load level used when the fabric was evaluated by hand (Table I). Each sample was measured under standard conditions (temperature = 20 ± 2°C, relative humidity = 65 ± 2%) for at least 24 h after and before cutting and testing. Specimens with dimensions of 20 × 20 cm^2 were used. The test results for the physical and mechanical properties were the averages of three independent replicates.

RESULTS AND DISCUSSION

Morphology of the nanoPCMs and surface characteristics of the fabrics treated with nanoPCMs

Figure 1 shows the images of the microPCMs [Fig. 1(a), 10,000×[17]] and nanoPCMs [Fig. 1(b), 80,000×] magnified by SEM. Both encapsulated PCMs had almost spherical shapes, but the area of nanoPCMs was about 1/100 times smaller than that of the microPCMs. Nano-PCMs had almost spherical shapes and an irregular size distribution between 200 and 400 nm in diameter. This irregularity was advantageous because combining large and small capsules allows the application of more capsules per unit area, raises the thermal efficiency, and extends the surface area.

According to images magnified 300× by SEM, the untreated fabrics and fabrics treated with nanoPCMs are demonstrated in Figure 2. Although the fibers of the untreated fabric were entangled [Fig. 2(a)], the surface of WRF was relatively smooth [Fig. 2(b)]. The FNO, FNN, and FNM specimens exhibited clusters of nanoPCMs [Fig. 2(c–e)]. The original shape of the nanoPCMs at the surface of the fabric remained without breaks after heat curing and washing; this suggested preserved heat properties.

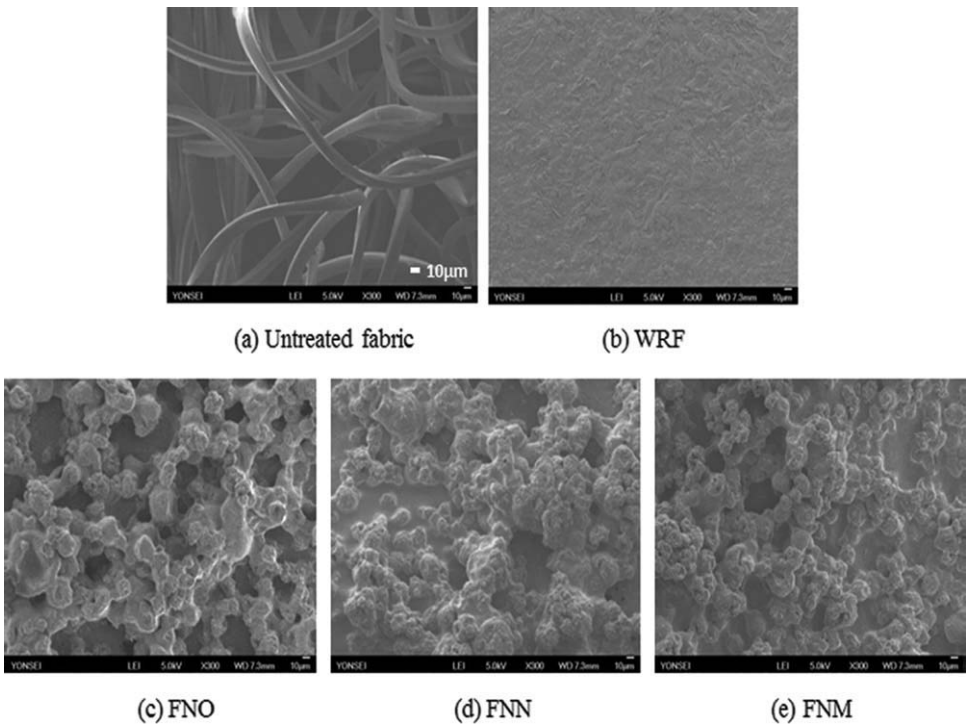

Figure 2 SEM images of surfaces of fabrics treated or not treated with nanoPCMs (300×): (a) untreated fabric, (b) WRF, (c) FNO, (d) FNN, and (e) FNM.

Thermal efficiency of the nanoPCMs and treated fabrics

Table II shows the thermal characteristics of the PCMs and the treated fabrics as measured by differential scanning calorimetry. We found that octadecane in the nanocapsules melted from 22.4°C with a ΔH_f of 144.7 J/g; nano-nonadecane absorbed heat from 27.4°C with a ΔH_f of 102.6 J/g. The mix of nanoPCMs (nonadecane plus octadecane) stored heat from 23.4°C because the PCMs started melting and ΔH_f was 137.4 J/g. With regard to the specimens, FNO started to store heat from 25.7°C with a ΔH_f of 4.0 J/g; FNN began to absorb extra heat from 29.3°C with a ΔH_f of 6.8 J/g. In the case of FNM, the fabric could absorb heat from 27.1°C, and the thermal enthalpy was 3.6 J/g. The add-ons were, respectively, 8.6, 8.2, and 7.9%. The thermal efficiency of the fabrics was lower than that of nanoPCMs because of the additional fabric weight per unit area. However, the thermostatic range of multiple PCMs was wider than that of the single use of PCMs, and this means that any thermostatic effect can be expected to continue longer or extend more widely than the use of single PCMs.

Physical properties of VPWR fabrics containing nanoPCMS

One-way analysis of variance and Tukey honestly significant difference post hoc testing with SPSS Statistic 18 were used to analyze the differences of physical properties of the VPWR fabrics with nanoPCMs. As

TABLE II
Thermal Characteristics of the Fabrics Treated with Nano-PCMs

		Fabrics treated with nanoPCMs				
Specimen	PCM concentration (%)	Melting temperature (°C)	ΔH_f (J/g)	Weight (mg/cm^2)	Thickness (mm)	Add-on (%)[a]
WRF	—			18.60	1.10	—
FNO	25	28.1	4.1	16.93	1.07	8.6
FNN	25	33.5	6.8	16.72	1.08	8.2
FNM	25 (1 : 1)	32.5	3.6	16.60	1.04	7.9

For *n*-octadecane ($C_{18}H_{38}$), the melting temperature was 28.2°C, and ΔH_f was 244 J/g; for *n*-nonadecane ($C_{19}H_{40}$), the melting temperature was 32.1°C, and ΔH_f was 222 J/g; for nano-octadecane, the melting temperature was 29.8°C, and ΔH_f was 144.7 J/g; for nano-nonadecane, the melting temperature was 33.6°C, and ΔH_f was 102.6 J/g; and for mixed nanoPCMs (nano-octadecane and nano-nonadecane), the melting temperature was 31.8°C, and ΔH_f was 137.4 J/g.

[a] $\text{Add} - \text{on}\,(\%) = (\boldsymbol{a} - \boldsymbol{b})/\boldsymbol{b} \times 100$ where a and b are the weights before and after finishing, respectively.

shown in Table III, all of the physical properties, such as air permeability ($F = 279.98$), porosity ($F = 4.00$), WVT ($F = 7141.49$), and water repellence ($F = 226.69$), were significantly different among the groups ($p < 0.01$). The post hoc test indicated that each group of air permeability, WVT, and water repellence differed significantly from the others except for the difference of water repellence between FNN and FNM. In case of the porosity, the difference between WRF and FNO was only significant ($p < 0.05$).

Air permeability

The air permeability of a fabric increases with the amount of air passing through a fabric, and it is controlled by physical factors, such as density, thickness, pore size, and pore distribution. The air permeabilities of FNO (1.15), FNN (0.72), and FNM (1.42) were higher than that of WRF (0.27) [Fig. 3(a)]. These data indicated that more air passed through the fabrics treated with nanoPCMs, such as FNO, FNN, and FNM, than through the fabric without nanoPCMs (WRF). Figure 3(b) demonstrates the diameters of the fabric pores under 0–150 psi (CFP-1500AEL capillary flow porometer). The pore size of VPWR fabric is usually controlled in the range 0.002–10 μm[23] because water vapor is approximately distributed by 0.004 μm in general. The pores for FNO (0.10–1.41 μm), FNN (0.07–1.15 μm), and FNM (0.11–0.98 μm) were bigger than those of WRF (0.01–0.40 μm), as the space among the nanoPCMs was reduced by their spherical shape.

WVT and water resistance

Clothing comfort depends on the thermal and WVT influence on the heat and moisture inside of the microclimate.[24] If a garment has a great WVT when perspiration occurs, thermal comfort can be maintained. In particular, the WVT of sportswear should be over 4000 $g/m^2/24$ h.[25] Compared to WRF (3089), the values of WVT for FNO (4835), FNN (5981), and FNM (5486) are high and over 4000 [Fig. 4(a)]. This result contradicts previous studies that indicate that the WVT of VPWR fabric, including microPCMs, is inferior because of micropore clogging by the mixture of microPCMs and binder.[15] The water resistance of VPWR clothing, such as mountain-climbing wear or raincoats, should be over 1000 mm H_2O. Compared to WRF (1310), FNO (1110), FNN (990), and FNM (970) have cooler water resistance [Fig. 4(b)]. Performance was, thus, opposite that observed for WVT but remains close to 1000 mm H_2O. It means that VPWR fabrics containing nanoPCMs (FNO, FNN, and FNM) discharged moisture in the microclimate well, whereas water from external environments was barely absorbed inside.

TABLE III
Results of One-Way Analysis of Variance and Tukey Honestly Significant Difference Post Hoc Testing of the Physical Properties

Property	Multiple comparison			
Air permeability ($cm^3/s\ cm^2$; $F = 279.98$)	WRF^a (mean = 0.27, SD = 0.03)	FNO^b (mean = 1.15, SD = 0.06)	FNN^c (mean = 0.72, SD = 0.04)	FNM^d (mean = 1.42, SD = 0.89)
Porosity (μm; $F = 4.00$)	WRF^a (mean = 0.09, SD = 0.12)	FNO^b (mean = 0.30, SD = 0.23)	FNN^{ab} (mean = 0.26, SD = 0.30)	FNM^{ab} (mean = 0.40, SD = 0.35)
WVT ($g/m^2/24$ h; $F = 7141.49$)	WRF^a (mean = 3089, SD = 3.51)	FNO^b (mean = 4835, SD = 8.62)	FNN^c (mean = 5981, SD = 2.00)	FNM^d (mean = 5485, SD = 4.04)
Water resistance (mm H_2O; $F = 226.69$)	WRF^a (mean = 1310, SD = 9.61)	FNO^b (mean = 1110, SD = 9.07)	FNN^{cd} (mean = 990, SD = 15.62)	FNM^{cd} (mean = 970, SD = 29.50)

The p values for the properties are less than 0.01. When the superscript letters are the same, the means are not significantly different; when the superscript letters are different, the means are significantly different ($p < 0.05$).

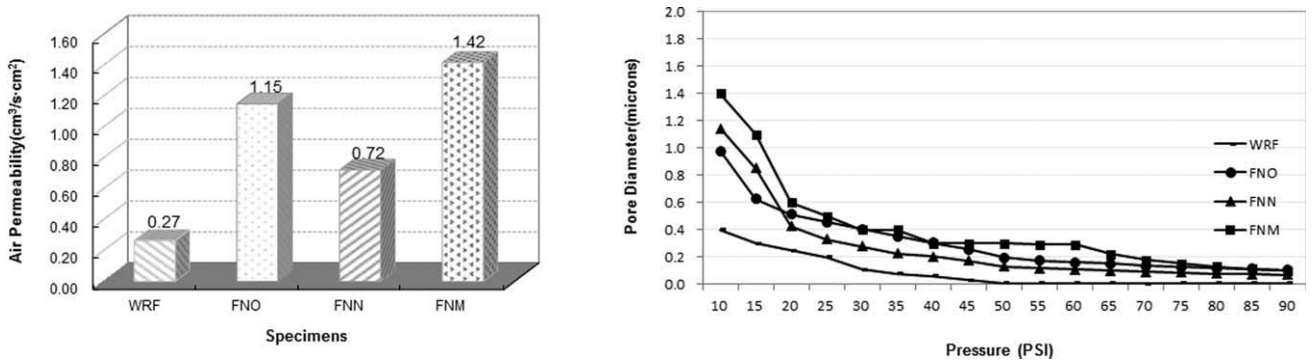

Figure 3 Comparisons of (a) the air permeability and (b) the porosity for all specimens.

Mechanical properties of the VPWR fabrics containing nanoPCMs

The mechanical properties of the specimens are presented in Table IV, and each data value is the average of three replicates.

Tensile properties are the relationship between the applied force and tensile strain, or the resulting tensile force, when a fabric is stretched in a certain direction, and they are related to elongation and recovery and affect body movement.[26] The elongations at the maximum load (the extensional strain with a tensile load of 500 gf/cm) of the specimens from largest to smallest were 11.84% for FNM, 11.25% for FNN, 11.01% for WRF, and 10.30% for FNO; the standard deviation (SD) was 0.48 in comparison with values obtained in previous research (0.92).[17] Micro-PCMs were coated on the polyester fabric by a screen-print method in the previous study, and the mixture of microPCMs clogged the intersections of two yarns. In comparison with the untreated fabrics (0.60), the tensile linearity (the linearity of the load–extension curve) of the treated fabrics (0.56 for FNO, 0.54 for FNN, and 0.52 for FNM) was reduced because there was less stiffness. The tensile energy (the energy per unit of area in extending fabric to 500 gf/cm) and resilience (percentage energy recovery from tensile deformation) presented similar tendencies to the tensile linearity.

Bending properties show the degree of fit between a body and clothing, and they are related to the drapability, the tactile sensation, and wrinkles. A clothing material is stiff when bending rigidity (average slope of the linear regions of the bending hysteresis curve to 1.5 cm^{-1}) and hysteresis of the bending moment (average width of the bending hysteresis loop at 0.5 cm^{-1} curvature) are large.[27] The bending properties are affected by contact pressure, the density between warp and weft, and yarn thickness. The hysteresis of the bending moment represents the relationship between bending modifications and bending energy during recovery. If the bending properties of a fabric are high, then the fabric is stiff. The bending rigidity (0.058 gf cm^2/cm for WRF, 0.04 gf cm^2/cm for FNO, 0.04 gf cm^2/cm for FNN, and 0.05 gf cm^2/cm for FNM) and the hysteresis of the bending moment (0.11 gf cm/cm for WRF, 0.08 gf cm/cm for FNO, 0.07 gf cm/cm for FNN, and 0.08 gf cm/cm for FNM) of the treated fabrics were superior to that observed for the untreated ones (bending rigidity = 0.02 gf cm^2/cm, hysteresis of the bending moment = 0.03 gf cm/cm). These results show that the stiffness of the fabrics was increased by our treatments and that the creases under identical external forces were reduced as the specimens rigidified because of the treatments.

Shear properties relate to extended rotation with a certain angle on one side of a specimen after the other

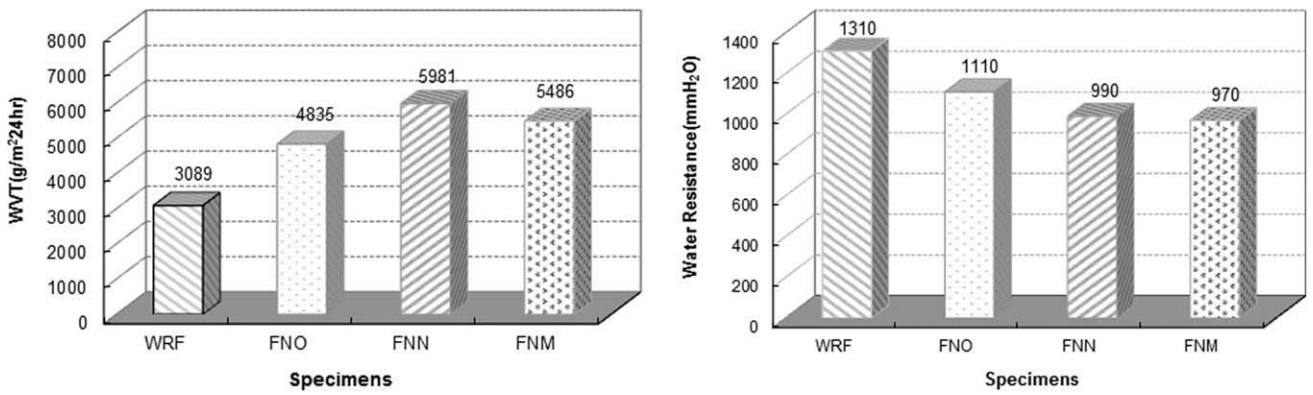

Figure 4 Comparisons of (a) the WVT and (b) the water resistance for all specimens.

TABLE IV
Mechanical Properties of the Fabrics Containing Nano-PCMs

Property		Untreated fabric	WRF	FNO	FNN	FNM
Tensile	Elongation at the maximum load (%)	11.27	11.01	10.30	11.25	11.84
	Tensile linearity	0.60	0.64	0.56	0.54	0.52
	Tensile energy (gf cm/cm^2)	9.05	9.23	7.57	8.02	8.07
	Resilience (%)	45.08	59.15	53.14	54.15	54.49
Bending	Bending rigidity (gf cm^2/cm)	0.02	0.06	0.04	0.04	0.05
	Hysteresis of the bending moment (gf cm/cm)	0.03	0.11	0.08	0.07	0.08
Shearing	Shear stiffness (gf/cm deg)	0.93	3.84	2.69	2.56	2.74
	Hysteresis of the shear force at 0.5° (gf/cm)	1.91	5.05	4.01	3.74	3.88
Surface	Coefficient of friction	0.27	0.28	0.28	0.29	0.29
	Mean deviation of the coefficient of friction	0.01	0.01	0.01	0.01	0.01
	Geometrical roughness (μm)	3.66	3.83	3.74	4.01	3.75
Compression	Compression linearity	0.54	0.54	0.55	0.56	0.53
	Compression energy (gf cm/cm^2)	0.55	0.50	0.47	0.48	0.44
	Compression resilience (%)	48.73	48.21	49.04	48.32	49.09
	Thickness at 0.5 gf/cm^3 (mm)	1.04	1.10	1.09	1.08	1.04
	Weight per unit of area (g/cm^2)	12.60	18.60	16.93	16.72	16.60

side is fixed with a certain load and are affected by the form stability, combination of body lines, drapability, and external shape as they are related, with modifications, according to the body movements.[28] The shear stiffness (average slope of the linear regions of the shear hysteresis curve to a ±2.5° shear angle) depends on the flexibility of cross threads at the intersection points, where the hysteresis values of the shear force (average width of the shear hysteresis loop at ±5° shear angle) of WRF were the highest (3.84 and 5.05), and those of the untreated fabric were the lowest (0.93 and 1.91). This meant that shape modification to the bias direction of VPWR and the nanoPCM finished fabrics was more difficult as they were harder and stiffer than the untreated fabric.

Surface properties are related to fabric smoothness, and the fabric surface is smooth when the coefficient of friction between the fabric surface and a standard contactor and its mean deviation are small. These properties have an important influence on hand value, as it is a physical property related to smoothness or flatness. Generally, the more a fabric surface is smooth or flat, the more the values of the surface properties remain small. The coefficient of friction and its mean deviation of the fabrics were highly similar and barely differed. In addition, the geometrical roughness (variation in surface geometry of the fabric) related to the surface smoothness of each fabric surface presented similar tendencies, except for FNN (4.01). Thus, relatively uniform films were laminated on the fabrics, but the surface of FNN had an irregular fabric surface.

Compression properties are related to the fabric bulkiness, volume, and recovery after being pressed by external forces or pressures, as these affect the wearability and softness. The compression linearity (linearity of compression–thickness curve) of the fabrics was similar to that of the untreated fabric, but the compression energy (energy in the compressing fabric under 5 kPa) of the treated fabrics was slightly inferior: the bulkiness of the fabric was decreased by VPWR finish with nanoPCMs. This meant that the volume of the fabrics was barely changed, but the softness of the treated fabrics was decreased or, alternatively, their hardness increased.

The thickness (mm at 0.5 gf/cm^3) and weight (g/cm^2) of the treated fabrics were greater than those of the untreated fabric (1.04 mm at 0.5 gf/cm^3 and 12.60 g/cm^2). When we compared the thickness and weight of the treated fabrics in order from lowest to highest, these values were obtained: WRF (1.104 mm at 0.5 gf/cm^3 and 18.60 g/cm^2), FNO (1.086 mm at 0.5 gf/cm^3 and 16.90 g/cm^2), FNN (1.08 mm at 0.5 gf/cm^3 and 16.72 g/cm^2), and FNM (1.04 mm at 0.5 gf/cm^3 and 16.60 g/cm^2). This meant that FNO, FNN, and FNM were thinner and lighter than WRF because of the amount of nanoPCMs (25%) inside of the finishing mixture.

CONCLUSIONS

The suitability of thermostatic clothing materials treated with nanoPCMs was confirmed by tests of the physical and mechanical properties of the materials because both wearability and functionality are very important factors for clothing with smart functions. The experimental results demonstrate that the air permeability of the fabrics with nanoPCMs surpassed that of the fabric without nanoPCMs; with FNM having the greatest air permeability, and the porosity affected the air permeability. Compared to the fabric without nanoPCMs, the WVT of fabrics with nanoPCMs were relatively high (>4000 g/m^2 24 h). The water resistance of WRF was the highest,

and those of FNO, FNN, and FNM were decreased. After the treatments, the stiffness or roughness of the fabrics with nanoPCMs was improved, but the resilience or smoothness was slightly decreased. The physical and mechanical properties of the VPWR fabrics with nanoPCMs were greatly improved compared to the VPWR fabric without nanoPCMs. The adaptability was confirmed as a multifunctional clothing material. The VPWR fabric treated with nanoPCMs could be anticipated to be a suitable clothing material for outdoor active sportswear because WVT and the resistance properties were suitable, as were the thermostatic properties contributed by the nanoPCMs. In a future study, physiological experiments should be performed with clothing made of VPWR nanoPCM fabrics to ascertain whether this functional clothing satisfies comfort requirements for its many potential uses in the apparel industry.

References

1. Layton, J. Text Prog 2001, 31, 1/2.
2. Parsons, K. Human Thermal Environments: The Effects of Hot, Moderate and Cold Environments on Human Health, Comfort and Performance; Taylor & Francis: New York, 2003.
3. Ying, B.; Kwok, Y.; Li, Y.; Yeung, C.; Song, Q. Int J Cloth Sci Technol 2004, 16, 84.
4. Weder, M. Text Month 2001, 2.
5. Bendkowska, W.; Wrzosek, H. Fiber Text East Eur 2009, 17, 5.
6. Outlast. http://www.outlast.com (accessed Nov 2010).
7. Shin, Y.; Yoo, D.; Son, K. J Appl Polym Sci 2005, 96, 2005.
8. Bryant, Y.; Colvin, D. 1988, Patent; US 4,756,958.
9. Pause, B. J Coated Fabrics 1995, 25, 59.
10. Wang, S.; Li, Y.; Hu, J. Y.; Tokura, H.; Song, Q. W. Polym Test 2006, 25, 580.
11. Vigo, T.; Frost, C. Text Res J 1982, 52, 633.
12. Vigo, T.; Frost, C. J Coated Fabrics 1983, 12, 243.
13. Mondal, S. Appl Therm Eng 2008, 28, 15.
14. Choi, Y. Seoul National University, 2006, Thermal Properties of Heating Protective Textiles Coated with Phase Change Materials, Master Thesis.
15. Chung, H.; Cho, G. Text Res J 2004, 74, 571.
16. Ramjunar, S.; Hussain, M. Nonwoven Ind 2006, 37, 48.
17. Choi, K.; Cho, G.; Kim, P.; Cho, C. Text Res J 2004, 74, 292.
18. Kim, B.; Kim, J.; Ahn, H.; Lee, Y.; Lee, Y.; Lee, C. Human Physiology; KMS: Seoul, 2002.
19. Na, J. Sports Physiology; Daekyung Books: Seoul, 2003.
20. Oh, J. 2006, Patent; KR 10-0555881-0000.
21. Kawabata, M. The Standardization and Analysis of Hand Evaluation; Hand Evaluation and Standardization Committee: Tokyo, 1980.
22. Matsudaira, M.; Niwa, M. J Text Machinery Soc Jpn 1985, 31, 53.
23. Cho, G. Advanced Textile Materials; Sigma: Seoul, 2006.
24. Cho, G.; Choi, J.; Lee, J.; Lee, S. J Korean Soc Cloth Text 1992, 16, 237.
25. Kim, G. J Korean Fiber Soc 1987, 24, 10.
26. Sung, S.; Kouh, J.; Kwon, O. J Korean Soc Cloth Text 1987, 11, 79.
27. Kwon, O.; Cho, H. J Korean Fiber Soc 1994, 31, 10.
28. Kim, H.; Ryu, H. Fibers Polym 2008, 9, 574.