Development of Thermoregulating Textile Materials with Microencapsulated Phase Change Materials (PCM). IV. Performance Properties and Hand of Fabrics Treated with PCM Microcapsules

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ABSTRACT: Polyester knit fabrics were treated with phase-change-material microcapsules by a pad–dry–cure method with a polyurethane binder. The treated fabrics were evaluated in terms of the thermal properties, air permeability, moisture vapor permeability, moisture regain, low-stress mechanical properties, and hand, with respect to the add-on of microcapsules. The surface morphology of the treated fabrics was investigated with scanning electron microscopy. The low-stress mechanical properties of the treated fabrics, including the tensile, shear, bending, surface, and compression properties, were measured with the Kawabata evaluation system for fabrics (KES-FB). As the add-on increased, the heat storage capacity of the treated fabrics increased. The treated fabric with 22.9% add-on was capable of absorbing 4.44 J/g of heat. The air permeability and moisture vapor permeability decreased, whereas the moisture regain increased, with an increase in the add-on. The tensile linearity and geographical roughness increased, whereas the resilience, bending, and shear properties decreased with an increase in the add-on. The fabrics became stiffer, less smooth, and less full as the add-on increased, and thus the total hand value decreased. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 97: 910–915, 2005

Key words: mechanical properties; stress; thermal properties

INTRODUCTION

Phase-change materials (PCMs) have been used as thermal storage and control materials because of the heat absorption and release that occur upon a change of phase.[1,2] In 1987, the microencapsulation technology of PCMs was developed and incorporated with textile materials.[3] Currently, for garments and home furnishing products, microencapsulated PCMs are incorporated into acrylic fibers or polyurethane foams or are embedded into a coating compound and topically applied to a fabric or foam.[4] Some researchers have tried to apply PCM technology to protective garments worn in extreme environments, from cold water to hot deserts.[4–6]

Many studies have been done on PCM fabrics and garments. Pause[7] developed the concept of dynamic thermal insulation with the insulation value of PCM fabrics. Hittle and Andre[8] used the index of the temperature regulation factor to measure the temperature-regulating ability of PCM fabrics. An evaluation for PCM garments was conducted by Shim et al.[9] to measure PCM effects during environmental transients. Kim and Cho[10] carried out wear trials of PCM garments and found that the changes in the mean skin and microclimate temperature with PCM garments were less than the changes with non-PCM garments. Yin et al.[11] also found that the rate of temperature increase of a garment with a higher PCM add-on level was lower than that of a garment with less PCM. Most research has concerned the effects of thermal properties of PCM materials on wearing comfort.

In addition to the thermal properties, the air permeability, moisture vapor permeability, and moisture regain of materials also influence the heat balance of the body and, consequently, affect clothing comfort.[12] Fabric hand determines the tactile comfort perceived by humans and is incorporated with mechanical property (tensile, bending, shear, compression, and surface) measurements by the Kawabata evaluation system. Although PCM microcapsules impart thermoregulating properties to materials and thus improve the thermal comfort of clothing, they can affect other comfort-related properties and hand of the materials adversely, especially when the topical application of microcapsules results in drastic changes in the surface

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TABLE I
Characteristics of Eicosane-Containing Microcapsules

Size (μm)	T_m (°C)	T_c (°C)	ΔH_f (J/g)	ΔH_c (J/g)
1.89	36.9	31.7	134.3	132.9

Eicosane ΔH_f = 263.7 J/g. T_m = melting temperature; T_c = crystallization temperature; ΔH_f = heat of fusion; ΔH_c = heat of crystallization

characteristics of materials. The extent of change in these properties depends on the loading amount of PCM microcapsules. Therefore, the performance properties of fabrics treated with PCM microcapsules need to be measured and considered before use in a garment.

In our laboratory, PCM microcapsules were synthesized and applied to polyester knit fabrics topically to develop thermoregulating textile materials. In a previous study,[13] the PCM microcapsules were characterized with respect to the structure, morphology, size distribution, thermal properties, and stability. The laundering durability of the treated fabrics was also evaluated. This report focuses on the effects of the PCM microcapsule add-on level on the air permeability, moisture vapor permeability, moisture regain, low-stress mechanical properties, hand, and thermal properties of the treated fabrics.

EXPERIMENTAL

Materials

The fabric was a scoured and bleached 100% polyester knit (68 × 58/in.^{2}) with a weight of 195 g/m^2 and a thickness of 1.47 mm. Melamine–formaldehyde microcapsules containing eicosane were manufactured by *in situ* polymerization according to a previous study.[13] The characteristics of the prepared microcapsule are summarized in Table I. All the chemicals were reagent-grade.

Application of the microcapsules to the fabrics

The manufactured microcapsules, mixed with a polyurethane binder (Snotex P110, Dae Young Chemical Co, Ltd., Seoul, South Korea), were applied topically to the polyester knit fabric with a pad–dry–cure method. The procedures are described in detail elsewhere.[13]

Evaluation of the treated fabrics

The surface of the microcapsule-treated fabrics was observed with a scanning electron microscope (JSM-5400, JEOL, Inc., Tokyo, Japan). The heat storage capacity and phase-change temperatures were measured with differential scanning calorimetry. The heating and cooling rate was 2°C/min up to 50°C under an atmosphere of N$_2$. The air permeability (Frazier method; ASTM test method D737-96), moisture vapor permeability (ASTM test method E96-95), and moisture regain (ASTM test method D885-98) were measured with standard procedures. The low-stress mechanical properties of the treated fabrics, including the tensile, shear, bending, surface, and compression properties, were measured with the Kawabata evaluation system for fabrics (KES-FB). Primary hand values (HVs), including Koshi (stiffness), Numeri (smoothness), and Fukurami (fullness), and the total hand values (THVs) were calculated from the mechanical properties with the KN-203-LDY and KN-302-WINTER equations, respectively.[14]

RESULTS AND DISCUSSION

Thermal properties of the treated fabrics

Table II shows the melting temperature and heat storage capacity versus the add-on of the microcapsules. As the add-on increases, the heat storage capacity of the treated fabric increases. Therefore, during the phase-change process, the rate of the temperature rise of the treated fabrics with a higher microcapsule add-on level is expected to be lower than that with fewer microcapsules.[10,11] The treated fabric with 22.9% add-on is capable of absorbing 4.44 J/g of heat if the microcapsules on the fabric undergo a melting process. The heat of absorption by the microcapsules delays the microclimate temperature increase of clothing and results in a decrease of the sweat release from skin.[4] This leads to enhanced thermophysiological comfort and prevents heat stress.

The selection of a PCM should take into account the end use of the textile material. For example, if the textiles are used for underwear, a PCM with a phase change occurring in the range of skin temperatures should be selected. On the other hand, for the lining material of a ski suit, a PCM needs to phase-change at a much lower temperature.[15] The melting temperature of the treated fabric, 35°C, is slightly lower than that of the microcapsules. It can be speculated that a trace amount of impurities, possibly from the shells of microcapsules, may transfer into eicosane when the treated fabrics are cured at 150°C. This would cause

TABLE II
Heat Capacity (ΔH_f) and Melting Temperature (T_m) of the Treated Fabrics Depending on the Add-On

Add-on (%)	T_m (°C)	ΔH_f (J/g)
5.3	35.31	0.91
11.1	34.85	2.15
18.1	35.33	4.10
22.9	34.91	4.44

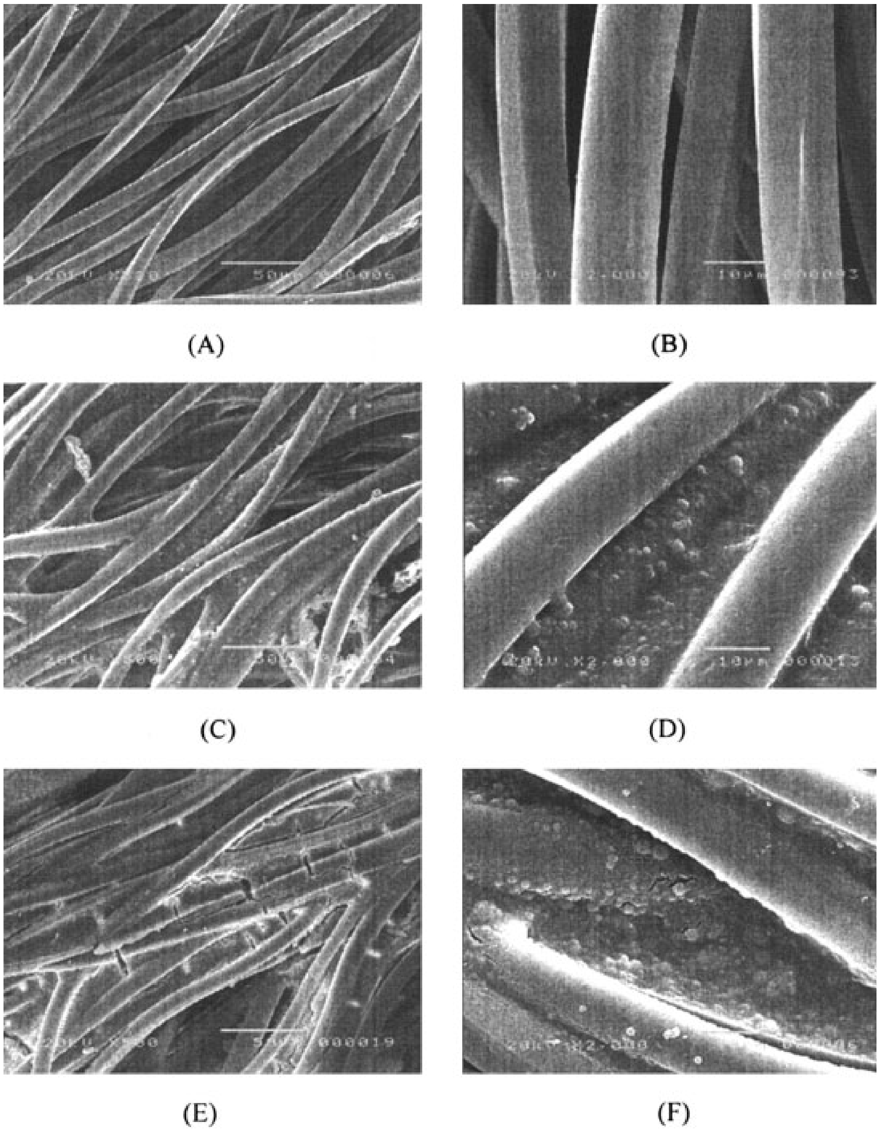

Figure 1 SEM photographs of an untreated sample at (A) 500× and (B) 2000×, a sample with 5.3% add-on at (C) 500× and (D) 2000×, and (c) a sample with 22.9% add-on at (E) 500× and (F) 2000×.

the melting temperature of the microcapsule-treated fabrics to decrease. Because of the melting temperature of the fabrics treated with the microcapsules, the treated fabrics would be appropriate for outwear use in a warm environment.

Scanning electron microscopy (SEM) observation of the treated fabrics

Figure 1 shows the micrographs of the surfaces of treated fabrics obtained from SEM observations. With 5.35% add-on, microcapsules with a binder fill up some of the interstices between fibers. As the add-on increases, more and more interstices are filled, and the microcapsule–binder layer covers most of the fabric surface at 22.9% add-on. Small cracks can be observed on the layer at 22.9% add-on. The surface morphology of the fabric is extensively changed by the microcapsule treatment, and this change affects the overall properties of the fabric.

Air permeability and hygroscopic properties

Figures 2–4 show the air permeability, moisture vapor permeability, and moisture regain as functions of the microcapsule add-on, respectively. As the add-on increases, the air permeability and moisture vapor permeability decrease. The air permeability and moisture vapor permeability decrease by 28 and 20% at 22.9% add-on, respectively, in comparison with those of the untreated sample. There are some factors affecting the air permeability and moisture vapor permeability of the fabric, such as the fabric structure, thickness, and

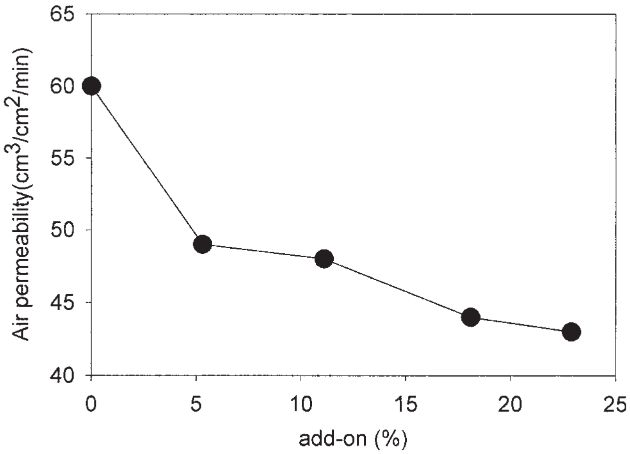

Figure 2 Air permeability of the treated fabrics versus the microcapsule add-on.

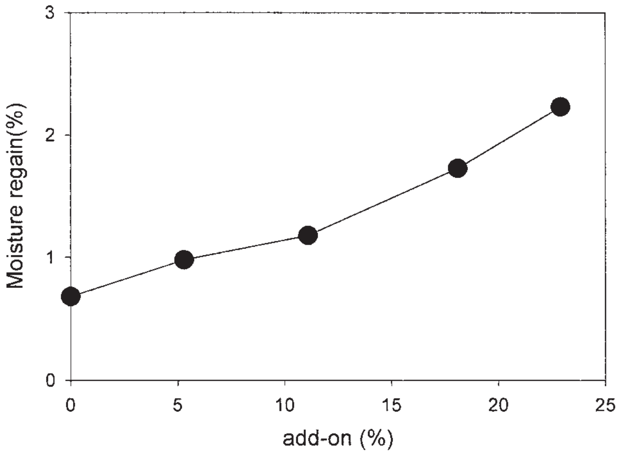

Figure 4 Moisture regain of the treated fabrics versus the microcapsule add-on.

surface characteristics (pore size and porosity).[12] As shown in the SEM pictures of Figure 1, the microcapsules and binder fill up pores of the treated fabric and, consequently, change the surface morphology and increase the thickness of the fabric. These changes lead to a decrease in the air permeability and moisture vapor permeability. The moisture vapor permeability determines heat released by means of evaporative heat reflux[15] and affects the formation of condensation in a garment system.[12] Therefore, the reduction of the moisture vapor permeability affects the thermal comfort of a garment adversely. For better comfort properties, we need to explore fabric treatment methods that do not block pores of the fabric too much. On the other hand, the treated fabrics become more hygroscopic with increasing add-on. The moisture regain of the treated fabric with 22.9% add-on increases up to 228% in comparison with that of the untreated sample. More hygroscopic material removes sweat more effectively from the skin or adjacent environment and helps with more effective wet heat loss through evaporation, leading to a pleasant microclimate in clothing.[16] It has been speculated that the hydrophilicity of the treated fabrics increases because of methylol groups in the shell material (melamine–formaldehyde) of the microcapsules[17] and hydrophilic binder.

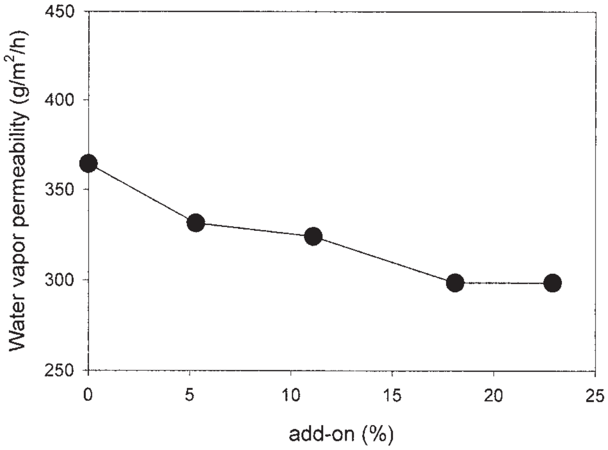

Figure 3 Moisture vapor permeability of the treated fabrics versus the microcapsule add-on.

Low-stress mechanical properties and hand

Table III shows the low-stress mechanical properties of the treated fabrics versus the add-on of microcapsules. The tendency of curling on the edge of the control knit fabric prevented us from measuring its tensile energy (WT) low-stress mechanical properties. Therefore, comparisons are made between the treated fabrics with different levels of add-on.

The tensile properties indicate the extensibility and recoverability of fabric from external stress.[14] As the add-on increases, the tensile linearity (LT) increases, and this results in a stiffer feel at a higher add-on. The tensile resilience (RT) decreases as the add-on increases up to 18.1%, and this indicates the reduction of recoverability from tensile deformation.

The bending properties are related to the wear performance of clothing, including wrinkle properties and drapability. The bending stiffness (*B*) and bending hysteresis (2HB) increase as the add-on increases. The treated fabrics become stiffer and more inelastic in bending with the increase of add-on.

The shear properties are accompanied by biaxial tensile properties and also are related to the drapability and shape of clothing.[14] The shear rigidity (*G*), shear hysteresis (2HG), and shear hysteresis at a 5° shear angle ($2HG_5$) also increase with the increase of add-on. A larger *G* value makes the fabric stiff, and a larger 2HG value causes inelastic behavior in shearing. A larger $2HG_5$ value causes inelastic properties in

TABLE III
Low-Stress Mechanical Properties of the Treated Fabrics

Mechanical properties		Add-on (%)			
		5.3	11.1	18.1	22.9
Tensile	LT	0.590	0.697	0.723	0.746
	WT (gf cm/cm^2)	22.29	26.43	26.26	22.45
	RT	44.08	35.68	33.96	35.43
Bending	B (gf cm^2/cm)	0.175	0.187	0.189	0.255
	2HB (gf cm^2/cm)	0.1726	0.1909	0.1920	0.2051
Shear	G (gf/cm deg)	1.08	1.09	1.20	1.36
	2HG (gf/cm)	3.03	3.11	3.70	3.97
	2HG5 (gf/cm)	3.14	3.28	3.86	4.25
Compression	LC	0.498	0.447	0.495	0.501
	WC (gf cm/cm^2)	0.277	0.281	0.278	0.281
	RC	52.77	52.01	49.60	47.21
Surface	MIU	0.322	0.316	0.239	0.297
	MMD	0.0272	0.0303	0.0420	0.0529
	SMD (μ)	6.93	7.35	7.93	7.66

WT = tensile energy

shearing and wrinkling problems. Both the bending and shear properties increase with the increase of add-on, and this indicates a decrease in the recovery from deformation and elasticity.

The compression properties are related to the fullness and bulkiness of the fabric. The linearity in compression (LC) increases as the add-on increases. A larger LC value causes a hard feeling in compression. The compression energy (WC) is similar, regardless of the add-on. The compressional resilience (RC) decreases with an increase in the add-on. This means that recoverability from compressional deformation decreases as the add-on increases, so the treated fabrics show inelastic compression properties. It is thought that the bulkiness of the treated fabrics decreases because of the reduction of recovery from compressional deformation as the add-on increases.

The surface properties are related to the smoothness of the fabric. As the add-on increases, the frictional smoothness (MIU) decreases and then increases at 22.9% add-on, whereas the geometrical roughness (SMD) increases and then decreases at 22.9% add-on. The surface frictional roughness (MMD) increases with the increase of the add-on. As shown in Figure 1, at a lower add-on, the microcapsules exist sparsely in the intersection of yarns, and this results in a roughening effect on the fabric surface. This roughening surface might impart more contact points between the fibers and yarns and thus enhance the fiber-to-fiber and yarn-to-yarn interfriction.[18] On the other hand, at a higher add-on (22.9%), the microcapsules and binder fill up more interstices between fibers or yarns and spread into a more continuous form on the fabric surface; this reduces SMD. Kim and Cho[10] found that the surfactant treatment made fabrics smoother and softer even though the add-on was increased, and a better THV resulted.

Figure 5 shows the effects of the add-on on primary HVs. Koshi is a feeling combined mainly with B and is influenced by bending and shear properties. It is related to a moderate space between the human body and the outer garment that allows freer body movements.[15] Numeri indicates smoothness and softness, which are influenced by the surface properties. Fukurami indicates bulkiness and resilience and is related to the compression properties. As the add-on increases, Koshi increases because of the increase in the bending and shearing properties. The reduction of MIU and the increase in the roughness can be attributed to the reduction of Numeri. On the other hand, Fukurami decreases because of the increase in LC and the decrease in RC with an increase in the add-on. Overall, THV decreases with an increase in the add-on, as shown in Figure 6. THV of the treated fabrics

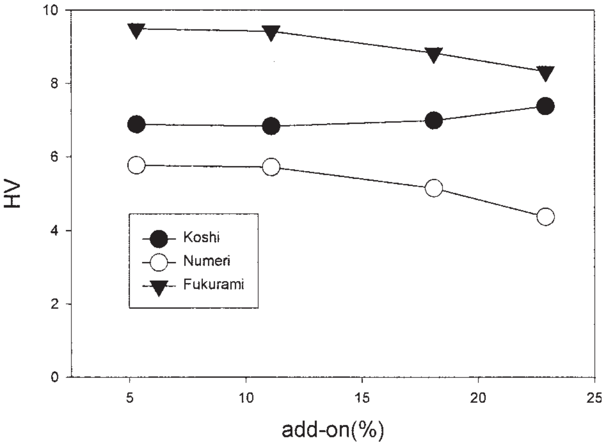

Figure 5 Primary HV of the treated fabrics versus the microcapsule add-on: (●) Koshi, (○) Numeri, and (▲) Fukurami.

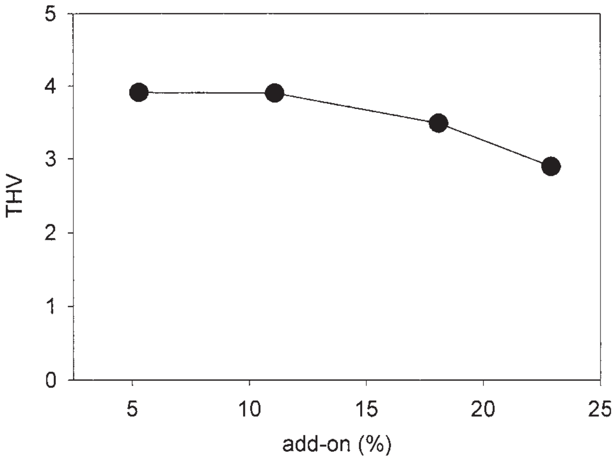

Figure 6 THV of the treated fabrics versus the microcapsule add-on.

ranges from 3.91 to 2.90, being above average (3.0) and slightly below average on Kawabata's scale from 0 (not useful) to 5 (excellent). For better hand of the treated fabric, the inclusion of a softener in the treatment bath formulation might be considered as for durable-press and flame-retardant finishes.

CONCLUSIONS

The heat storage capacity of treated fabrics increases with an increase in the microcapsule add-on. A treated fabric with 22.9% add-on is capable of absorbing 4.44 J/g of heat if the microcapsules on the fabric undergo a melting process. The air permeability and moisture vapor permeability decrease by 28 and 20%, respectively, at 22.9% add-on. The moisture regain of the treated fabrics increases progressively up to 228% in comparison with that of the control fabric. As the add-on increases, Koshi increases, whereas Numeri and Fukurami decrease. Overall, THV decreases.

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