Wearing Comfort of Temperature-Adaptable Textiles by Dual-Phase Coatings between Phase-Change Materials and Silicon Carbide Particles

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ABSTRACT: Two different thermally enhancing coating materials, namely, phase-change materials (PCMs) and silicon carbide (SiC), which are both capable of managing heat storage, were coated directly onto breathable waterproof nylon, either alone or together. The comfort properties of 20 wt % PCM-coated fabric (20PCM) and 20 wt % PCM/SiC dual-coated fabric (SC–20PCM) were compared with those of a control in a human clothing environment (HCE) system and a wear trial test. The changes in the heat and moisture transfer were examined by measurement of the microclimate temperature (T_{mi}) and microclimate relative humidity (RH_{mi}) of the coated fabrics with an HCE system. In addition, T_{mi}, RH_{mi}, and subjective sensations in the wear trials were evaluated. With dry heat transfer in the HCE, the thermal insulation decreased in following order: SC–20PCM > 20PCM > Control. However, SiC could not function in the presence of simulated perspiration. The moisture-buffering capacity in the outermost layer decreased when the fabrics were coated with 20PCM and SC–20PCM. In the wear trials, the subjects were unable to distinguish any difference in the thermal comfort between the garments, even though the T_{mi} of the SC–20PCM garments was 2.5°C higher than that of the control garments. Moreover, they did not report any significant differences in the humidity or comfort sensations between the test garments. J Appl Polym Sci 000: 000–000, 2012

Key words: coatings; surface modification; thermal properties

INTRODUCTION

The rapidly increasing interest in outdoor sporting activity has led to the increasing use of functional clothing with effects on the temperature, sweat absorbency, and stretchability. For outdoor winter sportswear, the effect of temperature is one of the most important performance aspects. Intelligent functioning with maintenance of comfort is also of importance because environmental conditions are liable to change during outdoor activities.

In general, conventional thermal insulation depends on air trapped in the clothing system, which is related to the thickness, fabric density, and clothing layers.[1–4] However, these factors are not sufficient to meet the consumer demand for better or more intelligent control of temperature.

Phase-change materials (PCMs) are intelligent additives that are well known for their temperature adaptability because they absorb or desorb the heat to and from the environment and keep the human body in a comfortable zone. Nevertheless, their effects are controversial because the range of temperature changes depends greatly on the quantity of material applied to the clothing system or fabrics.[5] Moreover, when PCMs are applied to fabrics, the relative location of the PCM-containing clothing layer is very important for determining the extent of its property effect. It was previously reported[6] that when sweat is transported through the clothing layers under extremely cold conditions, moisture vapor accumulates inside the outermost, water-repellent membrane and freezes, which blocks the pores, disturbs heat and moisture transfer, and decreases the level of comfort.[7–10] It has been suggested that the membranes should be protected from the accumulation of water vapor through an increase in the surface temperature above the freezing point. The application of PCMs to fabrics has been proposed to minimize these phenomena. As PCMs in the outermost layer do not make a significant contribution to the heat released from the body, another potential thermal material is needed to produce thermally enhanced winter jackets.

Ceramic powders, such as zirconium, magnesium oxide (MgO), and silicon carbide (SiC), have been

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reported to be suitable additive materials because of their far-IR radiation effects and high emissivity at room temperature.[11] They have been applied to textiles, despite their decreasing hand value.[12] A previous study[13] reported that in terms of far-IR emission, ceramics are better than other thermal materials. The increasing addition of ceramics to coating systems increases the thermal insulation of the fabric when the fabric is coated with a polyurethane (PU) resin.[12] Experiments with thermal manikins have revealed improved surface temperatures and heat storage performances of fabrics with the incorporation of ceramics.[14]

In this study, coating samples were prepared with PCM [20 wt % PCM-coated fabric (20PCM)] and 20 wt % PCM/SiC (SC–20PCM) to improve the temperature of water-repellent outdoor jackets with this specific thermal potential.[15] The thermal effects of the samples were tested under transient conditions because the temperature adaptability could not be confirmed through a newly developed human clothing environment (HCE) simulator, which could simulate the dynamic/transient conditions in which outdoor sports people move through various temperature zones. Consequently, the specific study objectives were to examine the effects of the PCMs and ceramics on the microclimate temperature (T_{mi}) and moisture transport in winter jackets and to determine how the temperature and moisture transfer affected the subjective sensations under transient conditions. The results obtained were expected to determine the serviceability of the PCMs on the outer shell of the winter garments when these PCMs were incorporated into water-repellent, finished fabrics that were dual-coated with silicate.

EXPERIMENTAL

Materials and fabric preparations

The 100% nylon jacket fabric was pretreated with a breathable waterproof finish. The air-textured warp yarn consisted of 70 D full dull (fabric count = 155) and a weft of 160 D full dull (fabric count = 155). This nylon substrate was used to test the thermal comfort properties after the different coating methods. The fabric coating compositions and procedures were described previously.[15] Briefly, the coating solution was composed of microencapsulated PCMs and silicate, in which the PCMs (A-83, melting temperature = 28.28) at 5–30 mm were obtained from HUMANTECH PLUS CO., LTD, Sungnam, Kyeonggi, Korea, and SiC was supplied by UK Abrasives, Inc., Northbrook, Illinois, USA (average particle size = 7–10 mm, as measured by a Gracell particle analyzer, Symantec Co., Germany) and was used to make samples with the direct roller coating method. The film thickness was preserved with a roller for all samples. In addition, as in our previous research, we determined the permeability as the maximum pore size at the bubble point and the mean flow pore size of each sample from capillary flow porometry; our previous article also covers the PCMs and preparations in detail.[16] After both layers were coated, the fabrics were dried and cured at 160°C for 30 min before further tests. The control fabric, 20PCM, and SC–20PCM were subjected to HCE simulations and subjective wear trials.

Heat and moisture transport determined by the HCE simulator

A new test method and an instrument called an HCE simulator were developed to evaluate the heat and moisture management capacity of the fabrics. The HCE simulator were used to examine the differences in the heat- and moisture-transport phenomena according to the characteristics of each specimen under transient conditions. The HCE consisted of a temperature-control unit, a sweating hot plate, two environmental chambers, a data-logging system, and a sweating apparatus (ISM 937, ISMATEC, Glattbrugg, Switzerland).[10] The sweating hot plate simulated the skin and maintained a comfortable condition of 33°C. The temperature in the chamber ranged from −30 to about +18°C and from 10 to 50°C for the cold and warm environments, respectively, with a relative humidity (RH) of 30–98%, respectively, with an accuracy of ±2% RH and ±0.5°C. To simulate a sweat pulse, a definite amount of water was spread from six nozzles to wet the absorbent fabrics with the apparatus controlling the sweat pulse. The temperature and humidity were measured constantly by sensors (CHS-APS., XD3; TDK Co., Tokyo, Japan) located on each layer during the test period. All of the collected data were retained in a computer connected to a data logger.

Detailed test procedure by HCE

The tested fabrics were mounted on a sweating hot plate, and the sensors were located between fabric layers, as shown in Figure 1.

One chamber was set at −10 ± 0.5°C to simulate an extremely cold environment, and another was set at 35 ± 0.5°C to simulate a warm environment with the same humidity of 50 ± 5%. The hot plate was preserved at 33 ± 0.5°C to simulate the skin temperature. To simulate perspiration, 1.2 mL of water was spread over the fabric surface through six nozzles after 10 min, when the fabric was exposed to the warm environment, which covered approximately 15% of the test area. After the fabric was stabilized in the warm environment for 30 min, the fabric was moved quickly to the cold chamber, after which T_{mi}

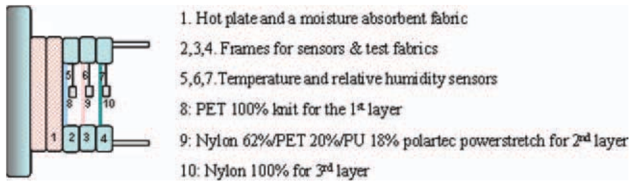

Figure 1 Schematic diagram of sweating skin and each location of the layered fabrics and sensors. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

was observed for 30 min. The T_{mi} and RH in each fabric layer were recorded every 15 s. Figure 2 shows the overall test protocol.

Determination of the thermal insulation and moisture-buffering capacity

The thermal insulation was calculated with Eq. (1), and the values for comparing dimensions were obtained from Eq. (2). The dimensions obtained from the graph indicated that the fabric with larger dimensions had superior thermal insulation, as shown in Figure 3(a):

$$\text{Thermal insulation} = \frac{A_2}{A_1} \times 100 \quad (1)$$

where A_1 is the area formed by the control and A_2 is the area of either 20PCM or SC–20PCM:

$$A = \int_a^b f(x)dx \quad (2)$$

where A, a, and b are the area under the curve, x is the curves gradient, the transient point, and the time to equilibration, respectively. The moisture-buffering capacity of the RH in the outermost layer in the fabrics tested was calculated on the basis of Eq. (3) to determine the decrease in the minimum and recovery humidities, as shown in Figure 3(b):

$$B = \frac{\tan \beta \times \Delta P_{i-m}}{\Delta P_r} \quad (3)$$

where B is the moisture-buffering capacity, $\tan \beta$ is the initial decrease in the microclimate relative humidity (RH_{mi}), $\Delta P_{i\text{-}m}$ is the relative humidity difference between the initial and minimum states, and ΔP_r is the relative humidity difference between the minimum and recovery states.

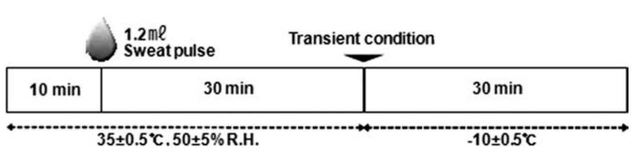

Figure 2 Test protocol in the HCE simulator.

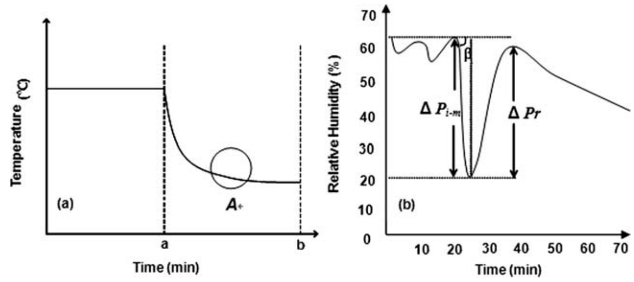

Figure 3 Determination of the thermal insulation and moisture-buffering capacity.

Subjective wear trials

The test garments were jackets made from the control, 20PCM, and SC–20PCM fabrics. The jackets had long sleeves, a hood, waist strings, and a hem to block ventilation and ensure a proper fit to each subject. Underneath the jackets, the subjects wore underwear with polyethylene terephthalate (PET) knitted shirts for the first layer, and Polartec power stretch (62% nylon/20% PET/18% PU) shirts for the second layer. All subjects wore their own underwear, socks, and running shoes. Table I lists the characteristics of the experimental garments.

Eight male subjects ages 21 to 27 years participated in this experiment. The subjects had an average height and weight of 179.6 cm and 72.5 kg, respectively. All subjects were given a full explanation about the purpose and procedures of the test, after which all subjects provided informed consent. However, the subjects were not provided with details about the clothing materials to prevent any influence on their subjective ratings.

Test protocol and subjective sensations

The experiments were carried out in a walk-in environmental test chamber (EBL-5HW2P3A-22), with the temperature of the chamber conditioned at −10 ± 0.1°C to simulate an extremely cold environment. The room temperature and humidity were maintained at 25 ± 1°C and 35 ± 10%, respectively. After each subject had put on the experimental garments and the sensors were located on the back of the subjects' clothing layer, the subjects were preconditioned at room temperature for 10 min. The subjects followed the 60-min test protocol,[4] as shown in Table II, which consisted of the following five periods: a 10-min rest in a chair at room temperature, a 10-min rest in a chair at −10 ± 0.1°C, 15 min of running at 7.0 km/h on a treadmill (Tunturi Electronic J4F, Finland), a 15-min rest in a chair at −10 ± 0.1°C, and a 10-min rest in a chair at room temperature. T_{mi} and RH were measured in every layer of the clothing during the experiments. We determined the amount of sweat accumulated within each

TABLE I
Characteristics of the Experimental Clothing Used in the Wear Trials

Layer	Garment	Fabric composition		Thickness (mm)	Weight (g/m^2)
First	Undershirt	100% PET		0.58	134.8
Second	Shirt	62% Nylon /20% PET/18% PU 18%		0.80	215.6
		Control	100% Nylon	0.15	96.8
Third	Jacket	20PCM	100% Nylon	0.16	93.33
		SC–20PCM	100% Nylon	0.16	104.7

clothing item (the undershirts, Polartec power stretch shirts, and experimental garments) by weighing the garments before and after the test. The subjects evaluated the thermal, humidity, and comfort sensations during each test period by answering three questions with the 7-point rating scale shown in Figure 4.

Statistical analysis

The data was analyzed with a one-way analysis of variance to detect significant differences between the test garments and the interactions between the garment type and test period.

RESULTS AND DISCUSSION

Measurement of T_{mi} by dry heat transfer in the HCE simulator

To investigate the heat- and moisture-transport phenomena of the 20PCM and SC–20PCM in the three-layer fabric system, the fabrics were mounted on a hot plate, and the temperature changes in the transient state were compared. Figure 5 shows the T_{mi} change between the hot plate and the first, second, and third layers under the transient conditions in the HCE simulator. The three fabric layers were exposed to a hot chamber (35 ± 0.5°C and 50 ± 5%) for 30 min and moved quickly into the cold chamber to be held for 30 min. The first air layer, between the hot plate and the PET knit, was similar in the tested fabrics; this was due to the temperature-control system of the hot plate and the absence of an effect by the outermost layer of the coated fabrics. The second layer, between the PET knit and the Polartec power stretch, was also similar, even though the temperature was lower than that of the first layer under cold conditions. The temperature of the third layer, the outermost air area in the fabrics, decreased in the following order: SC–20PCM > 20PCM > Control.

The thermal insulation in the three tested fabrics in the outermost layer was calculated from eqs. (1) and (2) and is presented in Table III. The areas under the curve during the 30–60 min of the trial were 1234.14 and 1322.74 for 20PCM and SC–20PCM, respectively; these values were 8.01 and 15.7% higher, respectively, than that of the control. These results were attributed to the increasing heat released from the PCMs and the decreasing pore size or slightly increased thickness with coating, as similarly reported in another article.[15,16] These two factors in combination may help explain the results for SC–20PCM.

Measurement of T_{mi} by wet heat transfer in the HCE simulator

Figure 6 shows the T_{mi} changes in each layer of the fabric when perspiration was simulated. The first and second air layers were affected by the sweat pulse, and the temperature was increased slightly by water vapor. The outermost layer was unaffected by the sweat pulse, and the decrease in the temperature in 20PCM was the smallest among the three fabrics tested. In addition, the area under the curve of the three fabrics tested when perspiration was simulated was obtained from eqs. (1) and (2). As shown in Table IV, the calculated thermal insulation among the control, 20PCM, and SC–20PCM during wet heat transfer was 1417.98, 1500.72, and 1443.96, respectively. This suggested that the thermal insulations of SC–20PCM and 20PCM were 1.83 and 5.84% higher than that of control, respectively. Therefore, wet heat transfer deteriorated the thermal insulation of the

TABLE II
Test Protocol in the Wear Trials

Rating period	Time (min)	Activity	Temperature (°C)
1	10	Rest	25 ± 1
2	10	Rest	−10.0 ± 0.1
3	15	Exercise	−10.0 ± 0.1
4	15	Rest	−10.0 ± 0.1
5	10	Rest	25 ± 1

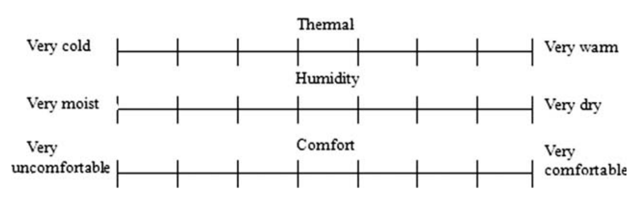

Figure 4 Thermal, humidity, and comfort sensation scale.

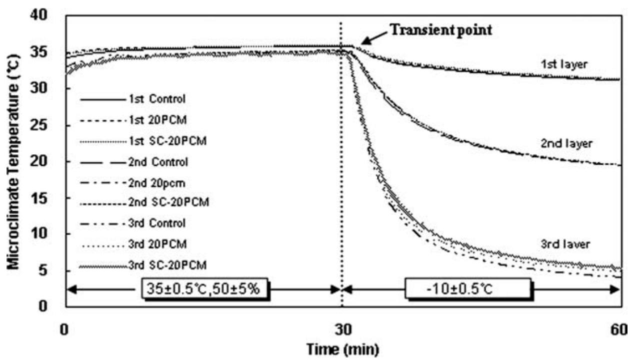

Figure 5 T_{mi} changes in each fabric layer by dry heat transfer in an HCE simulator.

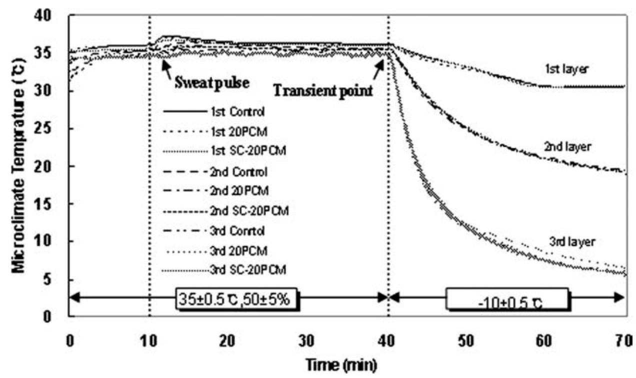

Figure 6 T_{mi} changes in each fabric layer by wet heat transfer in an HCE simulator.

control fabrics. This was attributed to the effect of moisture in the removal of heat away from the body; this emphasized the importance of sweat-transfer mechanisms of cold-weather clothing. Another interesting result was the higher T_{mi} of 20PCM compared to that of the SC–20PCM fabric.

An excessively small pore size, such as that in breathable membranes, was reported to lead to condensation blockage of the pores when a sweaty body was moved from a warm to extremely cold environment; this prevented water-vapor transport.[9] In this case, the dual coating appeared to affect the condensation of water molecules inside the breathable waterproof fabric and prevent the function of PCMs. As discussed in the introduction, the relative location of the PCM-containing clothing layer is important for enabling the PCMs to exert their maximum capacity. The action of SiC might be another possible explanation because the temperature of SiC decreased during condensation and prevented any far-IR emission.

RH_{mi} and moisture-buffering capacity

Figure 7 shows the RH_{mi} change in the outermost layer. When the sweat pulse was not very high, RH_{mi} was significantly affected by the temperature, and when the PCMs showed a higher temperature in the outermost layer, the RH_{mi} was the lowest, with the assumption that some amount of condensation occurred.

To compare the moisture management properties at outermost layer under transient conditions, the moisture-buffering capacity was calculated from Eq. (3). When the PCM or PCM/SiC was coated to the fabric, the value of the moisture-buffering capacity decreased, as shown in Table V. It could be estimated that the effect of the PCM or PCM/SiC coating on the moisture management capacities of the clothing system was important. As a result, the moisture-buffering capacity of the PCM-coated fabric showed the highest value; the capacity was affected in the following order: PCM-coated fabric > Control > PCM/SiC-coated fabric (52.26 > 35.30 > 25.18).

T_{mi} change in the wear trials

Figures 8, 9, and 10 present the average T_{mi} changes in the subjects over 60 min, which show the T_{mi} changes between each layer under transient conditions. T_{mi} varied considerably from subject to subject. However, when averaged, T_{mi} was similar in the first and second air layers, regardless of the garments. Little difference was observed between the skin and the first layer 10 min after the subjects were moved from the warm to the cold environment. During and after the exercise period, SC–20PCM showed a slightly higher T_{mi} than 20PCM or the control. The T_{mi} of 20PCM was higher than that of the other two fabrics in the second air layer at rest when the subjects were moved from the warm to the cold environment; this was similar to the results of the HCE tests. The same phenomenon was observed in the outermost layer, with T_{mi} of 20PCM being slightly higher than that of SC 20PCM under

TABLE III
Thermal Insulation among the Three Test Fabrics under Dry Heat Transfer

	Control	PCM	SC–20PCM
Area under curve from 30 to 60 min[a]	1142.63	1234.14	1322.74
Thermal insulation	100.00	108.01	115.76

[a] Calculated by eqs. (1) and (2).

TABLE IV
Thermal Insulation among Three Test Fabrics at Wet Heat Transfer

	Control	PCM	SC–20PCM
Area[a] under the curve from 30 to 60 min	1417.98	1500.72	1443.96
Thermal insulation	100.00	105.84	101.83

[a] Calculated by eqs. (1) and (2).

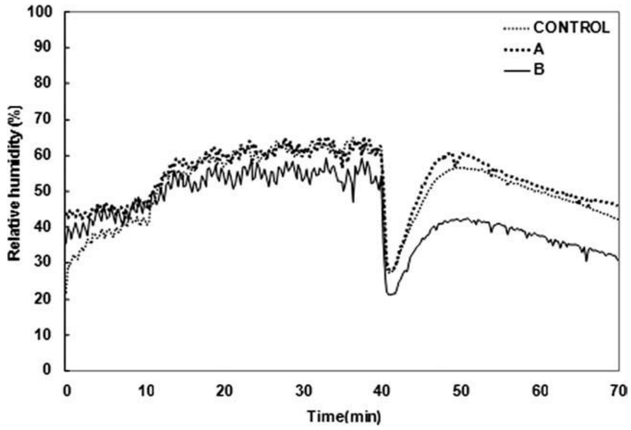

Figure 7 RH_{mi} under the outermost layer.

transient conditions. However, during the exercise period, T_{mi} of SC–20PCM was much higher than that of 20PCM, probably because of the heat generated by the body and the lower amount of heat transferred by the smaller pore size. This suggests that PCM functioned at both the transient and rest states and that the porosity of the fabric increased the temperature during exercise. Furthermore, the high temperature of SC–20PCM was most likely due to the decrease in porosity rather than to the synergistic effect of the dual coating and/or properties of SiC; this suggested that the heat loss through the PCM fabric was smaller than that through the non-PCM fabric. These results agreed well with a previous report in which in a sudden warm/cold change, the presence of PCMs in the fabric caused a temporary heating effect.[17]

Subjective sensations

For the heat balance and release/storage for thermal comfort, the maintenance of a constant body temperature is essential for human function. The normal body temperature of 37°C increases to 39–40°C after physical exercise. To equilibrate the body temperature, the human body produces and dissipates different amounts of heat, depending on the environmental temperature. Depending on the physical workload, a human produces around 100 W of heat in the rest state and up to 600 W in action. This heat is dissipated to prevent the body temperature from increasing and to maintain a state of equilibrium. The factors affecting the heat balance are the heat

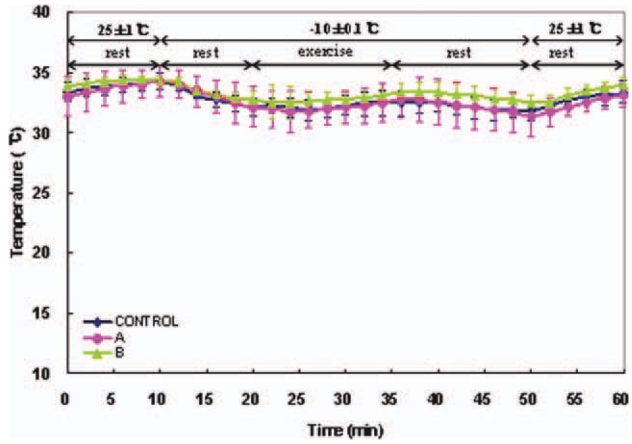

Figure 8 T_{mi} between the skin and first layer under transient conditions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

produced by physical activity, the amount of sweat, the environmental conditions, such as temperature, wind, and humidity, clothing layer system, and individual differences in the human body. Therefore, the heat balance is a critical factor for maintaining the thermal comfort of clothing, and new materials are needed to maintain the heat balance in the human body.

During the 1-h experiment, the subjects answered questions about the subjective thermal, humidity, and comfort sensations during each period. Figure 11 shows the subjective thermal sensations. The value of SC–20PCM was highest at every period; this indicated a stable state after they wore the experimental garments, but there was no significant difference between the experimental garments. In particular, the thermal scale was approximately 5 in period 4; this indicated that the subjects may have experienced a slightly warm sensation because that period was preceded immediately by the 15-min

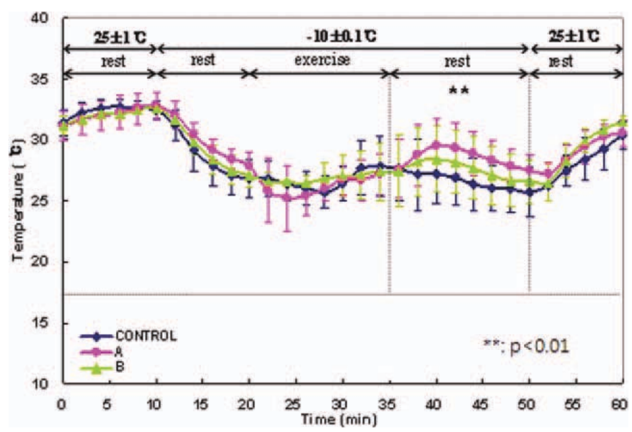

Figure 9 T_{mi} between the first and second layers under transient conditions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE V
Moisture-Buffering Capacity of the Humidity

	Control	PCM	SC–20PCM
Moisture-buffering capacity[a]	35.30	52.26	25.18

[a] Calculated by Eq. (3).

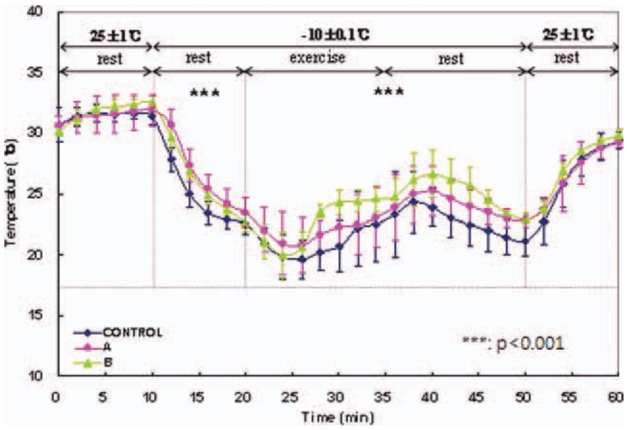

Figure 10 T_{mi} between the second and third layers under transient conditions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

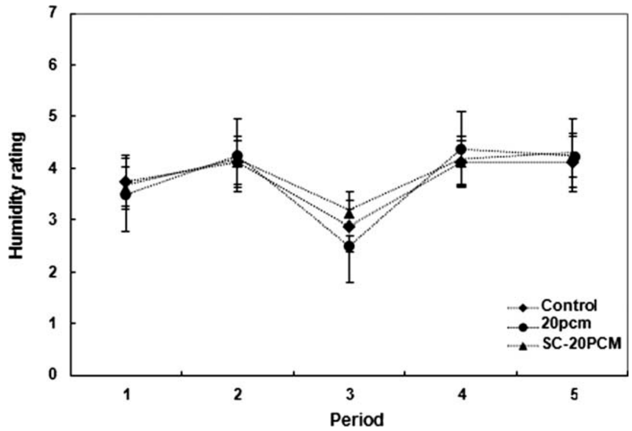

Figure 12 Perception of the humidity sensation.

exercise period. However, a difference of 2.5°C in the outermost layer during exercise could not have affected the subjective thermal sensation. Figure 12 presents the humidity sensations. All of the values were similar except for those of period 4. The slight difference in this period resulted from the individual variations, regardless of the PCM or PCM/SiC coating. Figure 13 shows the comfort sensations of the experimental garments. However, this result was not statistically significant. No difference was observed in period 2, which was expected to be the most important period for demonstrating the effects of the coatings. Moreover, the subjects felt the same in the transient state, regardless of the garments they wore. On the other hand, during exercise, the SC–20PCM was slightly warmer than the 20PCM.

CONCLUSIONS

Pretreated, breathable, waterproof fabrics and garments were selected to compare and analyze the effects of PCMs and SiC on the thermal insulation under transient conditions and the changes in physical properties. The thermal properties were measured in an HCE simulator to analyze the heat and moisture transfer of the fabrics tested. In addition, the subjective sensations of the experimental garments were determined by wear trials. The 20PCM and SC–20PCM fabrics showed differences in T_{mi} and RH_{mi} in the HCE simulator test. The 20PCM and SC–20PCM fabrics decreased the dry heat transfer by 8 and 15.8%, respectively, compared to that of the untreated fabrics by the effects of PCMs, SiC, and the reduced porosity. However, when perspiration was simulated, 20PCM exhibited the highest thermal insulation, probably because the dual coating removed the influence of the PCMs. In the outermost layer, the buffering capacity of the moisture management decreased in the following order: 20PCM > Control > SC–20PCM. The wear trials showed similar results in terms of thermal insulation at the transient period at rest, whereas the effect on the temperature of SC–20PCM was higher during exercise because of the reduced porosity. The subjects reported no significant difference in the thermal, humidity, and comfort sensations between the garments. Although the temperature difference between the control and treated fabric was

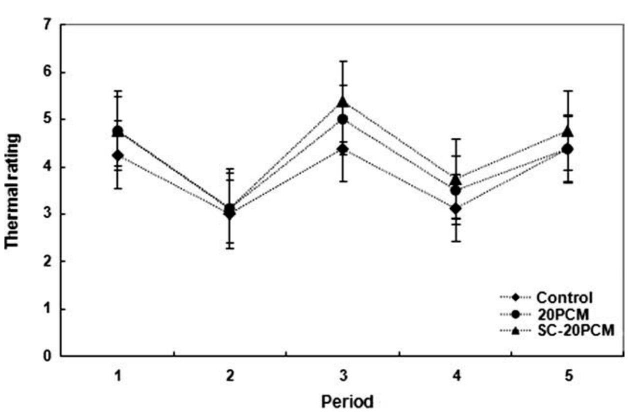

Figure 11 Perception of the thermal sensation.

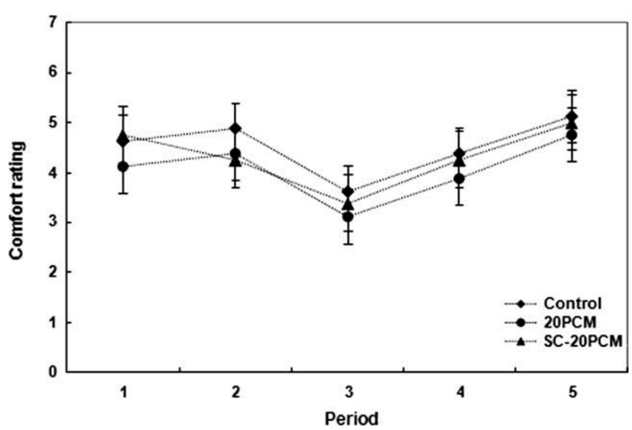

Figure 13 Perception of the comfort sensation.

approximately 2.5°C, it was not statistically significant, and there was no remarkable difference between the subjects. The humidity and comfort sensations in the untreated and thermally treated fabrics were similar because of variations in perspiration between the subjects, regardless of the garment type, and because the difference between 20PCM and SC–20PCM was too low to affect the subjective sensation in the range of the human body's ability to adapt to temperature changes. In further study, to make more thermally insulated garments, various contents of PCMs and SiC should be applied to control the temperature adaptability.

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