TEKSTİL VE MÜHENDİS

(Journal of Textiles and Engineer)

http://www.tekstilvemuhendis.org.tr

TEMPERATURE REGULATING POLYESTER SHORT STAPLE RING SPUN YARNS BY PCM NANOCAPSULE APPLICATION

FDM NANOKAPSÜL UYGULAMASI İLE SICAKLIK DÜZENLEME ÖZELLİĞİNE SAHİP EĞRİLMİŞ POLYESTER RİNG İPLİK ÜRETİMİ

Demet YILMAZ[1*]
Sennur ALAY AKSOY[1]

[1]Süleyman Demirel University, Department of Textile Engineering, Isparta, Türkiye

Online Erişime Açıldığı Tarih (Available online):31 Aralık 2023 (31 December 2023)

Bu makaleye atıf yapmak için (To cite this article):

Demet YILMAZ, Sennur ALAY AKSOY (2023): Temperature Regulating Polyester Short Staple Ring Spun Yarns By Pcm Nanocapsule Application, Tekstil ve Mühendis, 30: 132, 327- 334.

For online version of the article: https://doi.org/10.7216/teksmuh.1406060

TMMOB Tekstil Mühendisleri Odası
UCTEA Chamber of Textile Engineers
Tekstil ve Mühendis
Journal of Textiles and Engineer

Yıl (Year) : 2023/4
Cilt (Vol) : 30
Sayı (No) : 132

Araştırma Makalesi / Research Article

TEMPERATURE REGULATING POLYESTER SHORT STAPLE RING SPUN YARNS BY PCM NANOCAPSULE APPLICATION

Demet YILMAZ[1*]
Sennur ALAY AKSOY[1]
[1]Süleyman Demirel University, Department of Textile Engineering, Isparta, Türkiye

Gönderilme Tarihi / Received: 01.08.2023
Kabul Tarihi / Accepted: 15.12.2023

ABSTRACT: Phase change materials (PCMs) are thermal energy storage materials and therefore they are used for the manufacturing of heat-storage and thermo-regulated textiles. In this study, it was aimed to produce polyester spun yarns with thermo-regulation function via an alternative capsule application method. In the study, PMMA-co-MAA walled nanocapsules were synthesized by emulsion polymerization method and an alternative capsule application method was used to apply PCM nanocapsules into the staple polyester yarn structure during the yarn production process. Ne 30/1 polyester ring spun yarns with knitted twist were produced and some of the PCM nanocapsule and produced yarn properties were analyzed. According to the results, PCM nanocapsules had dimensions around 200-400 nm, uniform size distribution and spherical morphology. They could store approximately 100 j/g heat and had sufficient thermal resistance. With the developed capsule application method, nanocapsules were successfully applied to spun yarn structure and produced polyester yarns exhibited temperature differences in the range of 2-5 °C compared with undoped reference ring spun yarns. The results of the study indicated that this application method could be an alternative to fabricate thermo-regulating fabric surfaces and such integrated yarn materials have demonstrated promising potential for the production of thermoregulating textile material.

Keywords: Functional textiles, ring spinning, microcapsule, phase change materials (PCM), polyester yarn.

FDM NANOKAPSÜL UYGULAMASI İLE SICAKLIK DÜZENLEME ÖZELLİĞİNE SAHİP EĞRİLMİŞ POLYESTER RİNG İPLİK ÜRETİMİ

ÖZ: Faz değiştiren malzemeler (FDM'ler), termal enerji depolama özelliğine sahip malzemelerdir ve bu nedenle ısı depolama ve ısı düzenleme özellikli tekstillerin üretiminde kullanılmaktadır. Bu çalışmada, alternatif bir kapsül aplikasyon yöntemi ile termoregülasyon fonksiyonlu polyester eğrilmiş ipliklerin üretilmesi amaçlanmıştır. Çalışmada, PMMA-ko-MAA duvar nanokapsüller emülsiyon polimerizasyon yöntemiyle sentezlenmiş ve alternatif bir kapsül uygulama yöntemi, iplik üretim sürecinde kesikli polyester iplik yapısına FDM nanokapsülleri aplike etmek için kullanılmıştır. Örme bükümüne sahip Ne 30/1 polyester ring iplikler üretilmiş ve FDM nanokapsül ve üretilen ipliklerin bazı özellikleri çalışmada incelenmiştir. Sonuçlara göre, FDM nanokapsülleri 200-400 nm civarında boyutlara, düzgün boyut dağılımına ve küresel morfolojiye sahiptir. Nanokapsüllerin yaklaşık 100 j/g ısı depolayabildiği ve yeterli termal dirence sahip oldukları tespit edilmiştir. Geliştirilen kapsül uygulama yöntemi ile nanokapsüller eğrilmiş iplik yapısına başarıyla uygulanmış ve üretilen polyester iplikler katkısız referans ring ipliklere göre 2-5 °C aralığında sıcaklık farklılıkları sergilemiştir. Elde edilen sonuçlar doğrultusunda, bu uygulama yönteminin sıcaklık düzenleyici kumaş yüzeyleri elde etmek için bir alternatif olabileceği ve bu tür entegre iplik malzemelerinin, sıcaklık düzenleyici tekstil malzemelerinin üretimi için umut verici bir potansiyel sergilediği sonucuna ulaşılmıştır.

Anahtar Kelimer: Fonksiyonel tekstiller, ring iplikçiliği, mikrokapsül, faz değiştiren malzemeler (FDM), polyester iplik.

Sorumlu Yazarlar/Corresponding Author: *demetyilmaz@sdu.edu.tr*
DOI: *https://doi.org/10.7216/teksmuh.1406060* *www.tekstilvemuhendis.org.tr*

This study was presented at "8th International Technical Textile Congress (ITTC2022)", October 13-14, 2022, Online Congress. Peer review procedure of the Journal was also carried out for the selected papers before publication.

1. INTRODUCTION

Phase change materials (PCMs) are among the smart materials. PCMs can store and release high latent heat energy as their physical state changes under the nearly isothermal condition and therefore show a temperature regulation effect by absorbing and emitting heat energy in a certain temperature range depending on the changes in ambient temperature. Thanks to the heat exchange properties of PCMs, it is possible to improve thermal comfort in clothes and to provide heating and cooling effects [1-3]. Textile materials containing PCMs not only provide dynamic insulation properties (buffering effect against temperature change) in clothing fabrics, but also provide heating or cooling effects in different environmental conditions, in case of sudden temperature changes. Today, the use of PCMs in the textile industry is becoming increasingly important to improve the thermal comfort of clothing and to eliminate the effects such as sweating and sudden changes in body temperature as a heat regulator. Furthermore, the usage of PCMs has gained importance for the protection in extreme conditions and for the performance increase of professional athletes. The majority of PCMs, particularly paraffinic solid-liquid phase change PCMs, are used after microencapsulation. Encapsulation is a packaging technology that a tiny particle or droplet is enveloped by an organic or inorganic wall in order to develop micro or nano-sized capsules. Microencapsulation is an effective method in terms of reducing the interaction of the PCMs with the environment, preventing its separation from the textile structure by flowing when it enters the liquid phase, increasing its permanence in the textile structure, increasing its heat transmission surface and providing a constant volume [4-5].

The application of PCMs to textile structures focuses on synthetic fiber production and fabric finishing. However, the methods used in the current microcapsule application have some important disadvantages. They can be summarized as reduced thermal conductivity, softness, flexibility, strength, breathability or moisture transport capability of textiles, and non-durable thermal properties in the final products [6-12]. In this study, different from present application methods, it is aimed to produce innovative yarns that can offer latent heat storage/dissipation and heat regulation (thermoregulation) properties by applying PCM nanocapsules to the yarns obtained from staple fibers. In literature, Zhang et al. (2006) [13] and Gao et al. (2009) [14] stated that the incorporation of microencapsulated PCM during fiber spinning process is a promising approach which can enhance the life time of the thermo-regulating effect of the woven or knitted fabrics made of such filament. From this point of view, in the study, PCM nanocapsules were applied to polyester staple fibers with an alternative method and ring spun yarns with Ne 30/1 yarn count (knitted twist) were produced. To the best of our knowledge, no article has, to date, focused on integration of the PCMs to the spun yarns from polyester staple fibres and this application is a new method for the thermo-regulating functional yarn production.

2. MATERIALS AND METHODS

2.1. Microcapsules Preparation and Characterization

Emulsion polymerization method was performed to synthesize nanocapsules. In nanocapsule production, wall polymer was synthesized with methyl methacrylate (MMA, Sigma-Aldrich) monomer and methacrylic acid (MAA, Sigma-Aldrich) comonomer. 1-tetradecanol (Alfa Aesar, %97+) was used as the core phase change material (PCM) of the nanocapsules. PEG 1000 (Sigma Aldrich; Merck) was used as emulsifier and ethylene glycol dimethacrylate (EGDM, Sigma-Aldrich; Merck) was used as cross-linker. 2,2-Azobis(2-methyl-propionamidine) dihydrochloride (Acros Organics) was used as initiator in order to form free radicals and initiate addition polymerization via monomeric radicals. In the production of nanocapsules, the wall/core ratio was used as 1/1. In the first stage of production, 32.5 g of 1-tetradecanol was added in a 500 ml of deionized water heated to 50 °C and mixed at 1000 rpm for about 20 minutes. In order to emulsify 1-tetradecanol in the water phase, 10 g of PEG1000 was added to mixture and the emulsion was prepared by stirring at 1000 rpm for 30 minutes. A 29 g of MMA and a 3.5 g of MAA (approximately 12% by weight of comonomer) monomers, a 6.75 g of EGDM cross-linker and a 5 g of initiator were added to the emulsion. After the addition of each component, mixing was done for 5 minutes and finally the temperature was increased to 80 °C. The nanocapsule production process was completed after the reaction, which was carried out at 1000 rpm, at 80 °C for 3 hours. The produced nanocapsules were washed several times with hot water at 70 °C, then rinsed, filtered and stored in a refrigerator (+8 °C).

2.2. Method

In this study, an alternative method was used to impart the microcapsules into the staple polyester fiber bundle before the yarn formation. An alternative application method developed in previous study of the authors was used for production of the PCM nanocapsule doped composite ring yarns [15-16]. The method based on integrating the PCM nanocapsules into the open fibre bundle before yarn twisting during the ring spinning process and hence trapping the capsules in the twisted yarn structure. In the study, yarn production was carried out on a conventional ring spinning machine (Rieter G10 model) due to its widely usage in the spun yarn production and also superior yarn properties. In the method, a dispersion including PCM nanocapsules was prepared and then applied to the polyester fibres during the yarn spinning process via a special apparatus. Nanocapsule dispersion contained surfactant (S), defoamer (D), water and also PMMA-co-MAA/1-tetradecanol nanocapsules. Mechanical homogenizer (IKA ULTRA-TURRAX® T 18 basic) and sonic mixer (BANDELIN SONOPULS HD 4200) devices were used to disperse nanocapsules in the water homogeneously. Nanocapsule concentration was determined by Alay Aksoy et al. as 6% based on their previous findings [17]. After the preparation of microcapsule dispersion, the mixtures were applied to staple fibres

by the developed alternative method. In the study, Ne 30/1 polyester ring spun yarns were produced by using four different feeding rate values from 62.5 mL/h to 77.5 mL/h. Yarn production parameters such as draft and spindle speed were kept constant during the yarn production.

2.3. Test and analysis

The morphological properties of the produced PCM nanocapsules were studied by SEM images taken with LEO 440 Computer Controlled Digital Scanning Electron Microscope (SEM). The nanocapsules' average particle size and particle size distribution diagrams were determined by the particle size analysis device (Malvern MS2000E). The nanocapsules were washed and filtered before measurement and then they were subjected to additional mixing with a homogeniser at a speed of 10000 rpm for 45 minutes. The thermal properties of the produced nanocapsules were investigated by Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) methods. Phase change temperatures and heat storage and dissipation capacities of the nanocapsules were analysed by DSC. The analyses were carried out in nitrogen (N2) atmosphere at a heating/cooling rate of 10 °C/min between -5 °C – +80 °C using the Perkin-Elmer Jade DSC device. TGA analysis was carried out to examine the thermal stability of the produced nanocapsules for possible subsequent textile processes such as washing, finishing. The analyses were carried out in the nitrogen gas environment, at a heating rate of 10 °C/min, in the range of 0-500 °C, using the Perkin Elmer TGA7 device. Chemical structure of PCM nanocapsules were analysed by Fourier Transform Infrared (FT-IR) Spectrometer analysis.

In the study, morphological, thermal and physical properties of the produced polyester yarns were analysed. The yarn samples without nanocapsules were named as a reference or undoped while the samples comprising nanocapsules were called as a doped or composite yarn. At first, yarn images were taken with LEO 440 Computer Controlled Digital Scanning Electron Microscopy (SEM) in order to determine the morphological properties of the nanocapsule doped and undoped reference yarn structure. Thermal History (T-History) test method was used to determine the changes in surface temperatures of yarn samples resulting from absorbed latent heat by the nanoencapsulated PCMs in their structure in variable temperature environments. Yarn unevenness, imperfections (thin-thick places and neps) and hairiness were tested on Uster Tester 3 device at 400 m/min test speed while yarn strength and breaking elongation properties of the yarn samples were tested by Mesdan Lab tensile tester according to ASTM D 2256. Test length was 500 mm and the test speed was 5000 mm/min and 3 tests were carried out for nanocapsule doped and undoped reference yarns.

3. RESULTS AND DISCUSSION

3.1. PCM Nanocapsule Properties

In this section, morphological, thermal and chemical properties of the PCM nanocapsules are discussed.

Morphological properties of PCM nanocapsules

According to the SEM images (Figure 1), it was determined that capsules had nano dimensions and their sizes ranged from approximately 150 nm to 400 nm. The particle sizes and size distributions of the prepared nanocapsules were calculated using particle sizer. The mean and coefficient of variation (CV%) values of capsule diameter values were determined as 78.45 μm and 31.7%, respectively. According to the particle size distribution diagram given in Figure 2, it was determined that capsules exhibited a wide range but a unimodal distribution. The particle size distribution uniformity value was determined as 0.317. The average particle size of 98% of the particles was 127.2 μm. Compared to the SEM images, the particle size measured with the particle size analyzer was found to be higher. This case resulted from different measurement principle of SEM and particle sizer. SEM images show the actual size of the capsules while the particle size analyser measures the clustered capsules as a single capsule. As can be seen from the SEM images, produced capsules had nanoparticle sizes. However, they bonded to each other and formed aggregates after these ultra-small particles were mixed in an aqueous medium.

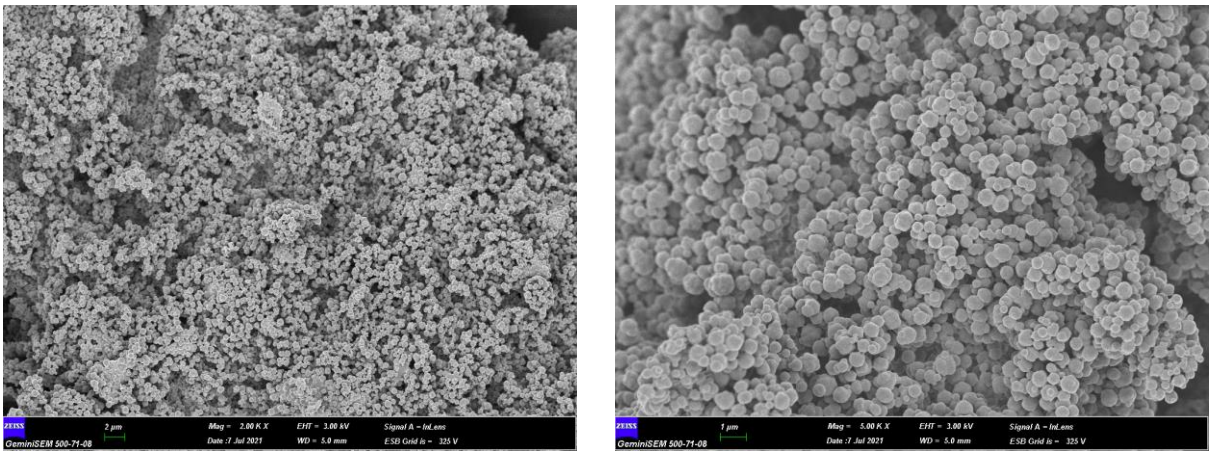

Figure 1. SEM images of the PMMA-co-MAA walled nanocapsules (A: 2000x, B: 5000x)

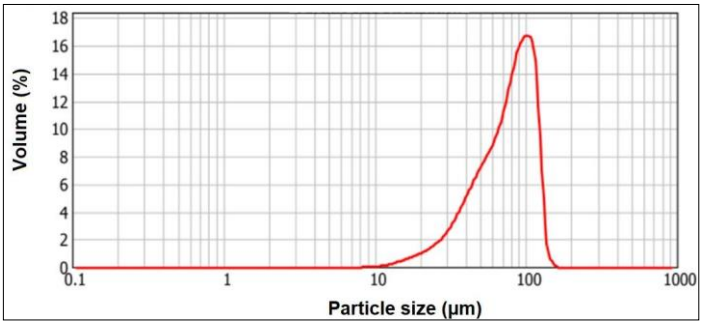

Figure 2. Particle size distribution of PMMA-co-MAA walled nanocapsules

Thermal properties

The curve obtained from the DSC analysis used to determine the thermal energy storage properties of nanocapsules are given in Figure 3. According to the DSC curve given in Figure 3, PMMA-co-MAA walled 1-tetradecanol core microcapsules absorbed 101.7 j/g heat energy at 34 °C. Two solidification peaks occurred during the cooling processes of these nanocapsules. This is a characteristic behaviour of fatty alcohols. Fatty alcohols exhibit two phase transitions during the solidification process, first the liquid-solid phase transition and then the solid-solid phase transition [18]. The liquid-solid and solid-solid transition temperatures during the cooling of nanocapsules were 35 °C and 26 °C, respectively. The total enthalpy of crystallisation for liquid-solid and solid-solid phase transitions was -101.2 j/g. The findings propounded that the produced nanocapsules have transition temperatures suitable for the manufacture of textile-based thermal energy storage materials and these materials can be used in the household or clothing industry due to their sufficient high thermal energy storage capacity.

The curve obtained as a result of the TG analysis performed to determine the thermal resistance of nanocapsules are shown in Figure 4. According to TGA curves, the nanocapsules exhibited two-stage thermal degradation behaviour. The first decomposition step started at 206 °C and ended with a mass loss of 60.3% at 252 °C. This mass loss seen in capsules was due to the thermal breakdown of 1-tetradecanol, which forms the microcapsule core material, due to the increase in temperature and its removal from the capsule wall structure. Pure n-tetradecanol undergoes one-step thermal decomposition, starting at around 135 °C and ending at about 260 °C [19]. Nanoencapsulation into the PMMA-co-MAA wall delayed the thermal degradation of n-tetradecanol and increased its thermal resistance. The second thermal decomposition of the nanocapsules, which started at about 352 °C, was due to the thermal decomposition of the cross-linked PMMA-co-MAA copolymer structure forming the wall structure. Decomposition of encapsulated 1-tetradecanol was delayed due to the presence and thermal resistance of the microcapsule wall structure (decomposition at 206 °C and above). The mass loss values in this step were determined as 31.2% (Table 1). In summary, PMMA-co-MAA walled nanocapsules were found to be suitable for textile processes in terms of thermal resistance.

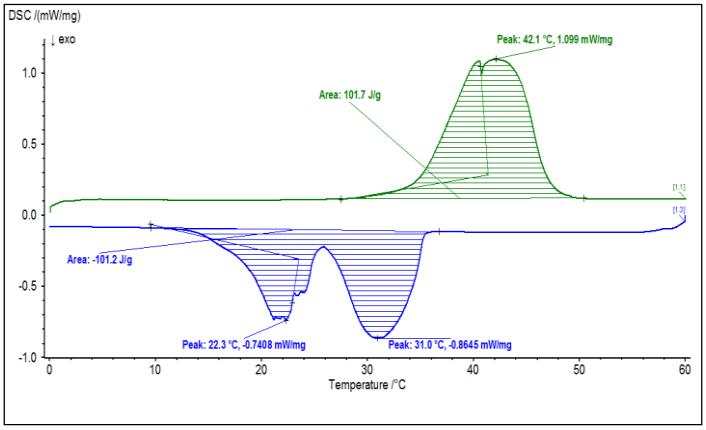

Figure 3. DSC curve of 1-tetradacanol core microcapsules with PMMA-co-MAA wall produced by emulsion polymerization method

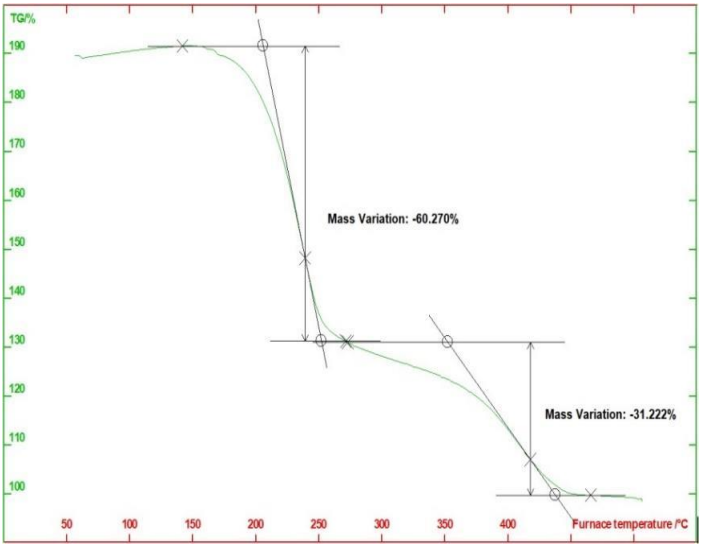

Figure 4. TGA curve of 1-tetradecanol core microcapsules with PMMA-co-MAA walls

Table 1. TGA results of PCM nanocapsules

Material	1. step				2. step			
	T1	$T_{inflexion}$	T2	Mass loss (%)	T1	$T_{inflexion}$	T2	Mass loss (%)
PMMA-ko-MAA/1-tetradecanol	206.1	239.3	252.3	60.3	352.5	417.9	437.8	31.2

Fourier Transform Infrared (FT-IR) Spectrometer analysis

In this section, the results of FT-IR spectroscopy analysis performed to define the chemical structures of the produced nanocapsules are given. The presence of wall and core materials in the structure of nanocapsules was investigated.

In Figure 5, the FT-IR spectrum of PMMA-co-MAA walls/1-tetradecanol core nanocapsules produced by emulsion polymerization method is given. In the spectrum of 1-tetradecanol, which forms the core material of the nanocapsules, the peak at 3330 cm^{-1} wavelength belonged to the -O-H stretch, the triple peaks at 2962-2922-2850 cm^{-1} and the peak at 1467 cm^{-1} belonged to the C-H stretch. In the same spectrum, the peak at a wavelength of 725 cm^{-1} was the characteristic peak of 1-tetradecanol. In the spectrum of the methyl methacrylate monomer, the peak at 1741 cm^{-1} was the stress peak belonging to the carbonyl group. The small peak at 1635 cm^{-1} in the spectrum was the C=C bond stretch peak in the monomer. The peaks between 1100-1300 cm^{-1} belonged to the –C-O stretching vibration in the ester structure. The broad band at 2979 cm^{-1} in the spectrum of the methacrylic acid monomer belonged to the H-bonded –OH stretch of the carboxylic acid group. The peak at 1698 cm^{-1} belonged to the carbonyl group in the carboxylic acid group. The peak at 1625 cm^{-1} was the peak of vinyl group (C=C) stretching. The peak at 1440 cm^{-1} was the -OH bending peak of the carboxylic acid group. The peaks at 1307 and 1211 cm^{-1} wavelengths were carboxylic acid –C-O stretching peaks.

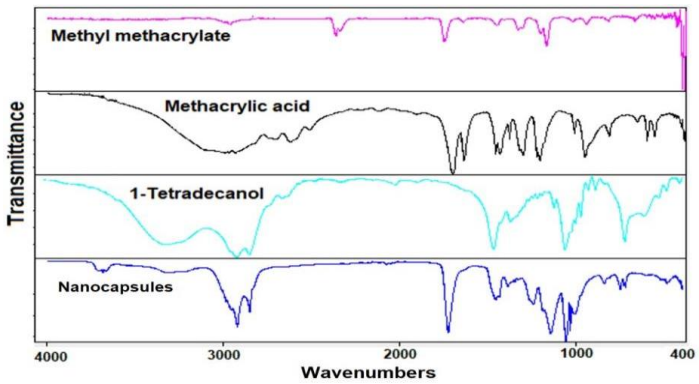

Figure 5. FT-IR spectrum of PMMA-co-MAA walled, 1-tetradacanol core nanocapsules produced by emulsion polymerisation method and materials used in nanocapsule production

When the FT-IR spectrum of the nanocapsules was examined, the peaks at 2953 cm^{-1}, 2919 cm^{-1} and 2849 cm^{-1} wavelengths were the characteristic C-H stretching peaks of 1-tetradecanol fatty alcohol. The peaks at 1461 cm^{-1}, 1456 cm^{-1} and 1435 cm^{-1} were C-H stretching peaks and belonged to the C-H stretching peaks of tetradecanol and methacrylic acid monomers in the structure of nanocapsules. In the spectrum, the sharp peak at a wavelength of 1724 cm^{-1} was the peak belonging to the carbonyl (C=O) group in the nanocapsule wall copolymer structure and was formed by the combination of the carbonyl peaks in the MMA and MAA monomers. The peaks of 1635 cm^{-1} and 1625 cm^{-1} wavelengths, respectively, in the spectra of MMA and MAA monomers were vinyl group (C=C) stretching peaks of methyl methacrylate and methacrylic acid monomers, but they did not appear in the spectra of nanocapsules. This case showed that the polymerization between methyl methacrylate and methacrylic acid monomers took place and the predicted copolymer wall structure (PMMA-co-MAA) was synthesized.

3.2. Yarn properties

In this section, morphological, thermal and physical properties of the PCM nanocapsule applied yarns were analysed. The yarn samples without nanocapsules were named as a reference or undoped while the samples comprising nanocapsules were called as a doped or composite yarn.

Yarn images

When the longitudinal views of the yarns were examined, PCM nanocapsules were easily observed on the surface of all polyester fibers (Figure 6). In the cross-sectional images of the yarns, it was seen that the nanocapsules were attached to the fiber surfaces (Figure 7). In particular, presence of capsule in the yarn structure was getting higher as the feeding rate values were increased from 62.5 mL/h to 77.5 mL/h (Figure 6B). It was determined that the capsules agglomerated, and settled on the surface of the fibers in the capsule cluster form with the increase of the feeding rate values. Capsule clusters were clearly seen on the fibre surfaces and between the fibres for 77.5 mL/h feeding rate. The agglomeration tendency of the capsules is an inevitable problem especially in applications in the form of dispersion in aqueous media. Particularly, decreasing particle size and size distribution homogeneity increases the aggregation tendency. The capsules produced in this study showed a clustering tendency due to their nano size. In short, SEM images showed that PCM nanocapsules could be integrated into polyester ring yarns.

Thermal properties

Thermal properties of undoped and PCM nanocapsule doped polyester ring spun yarns were analysed by Thermal History (T-History) test method. The changes in surface temperatures of yarn samples in variable temperature environments were determined. Undoped and nanocapsule doped yarn samples were firstly conditioned and then temperature changes on the yarn surface were measured with a thermal camera (Fluke TX 500) during the heating of the sample in a warm insulated box. The time-dependent graphs (T-history graphs) of the temperatures measured every 30 seconds with a thermal camera were drawn. In T-History graphs, y-axis shows the temperature measured on the surface of the yarn sample while x-axis shows the measurement time. In the T-history test, the differences on the surface temperatures of the undoped and PCM nanocapsule doped yarns were compared for determination of thermo-regulating effect of the PCM in the yarn structure.

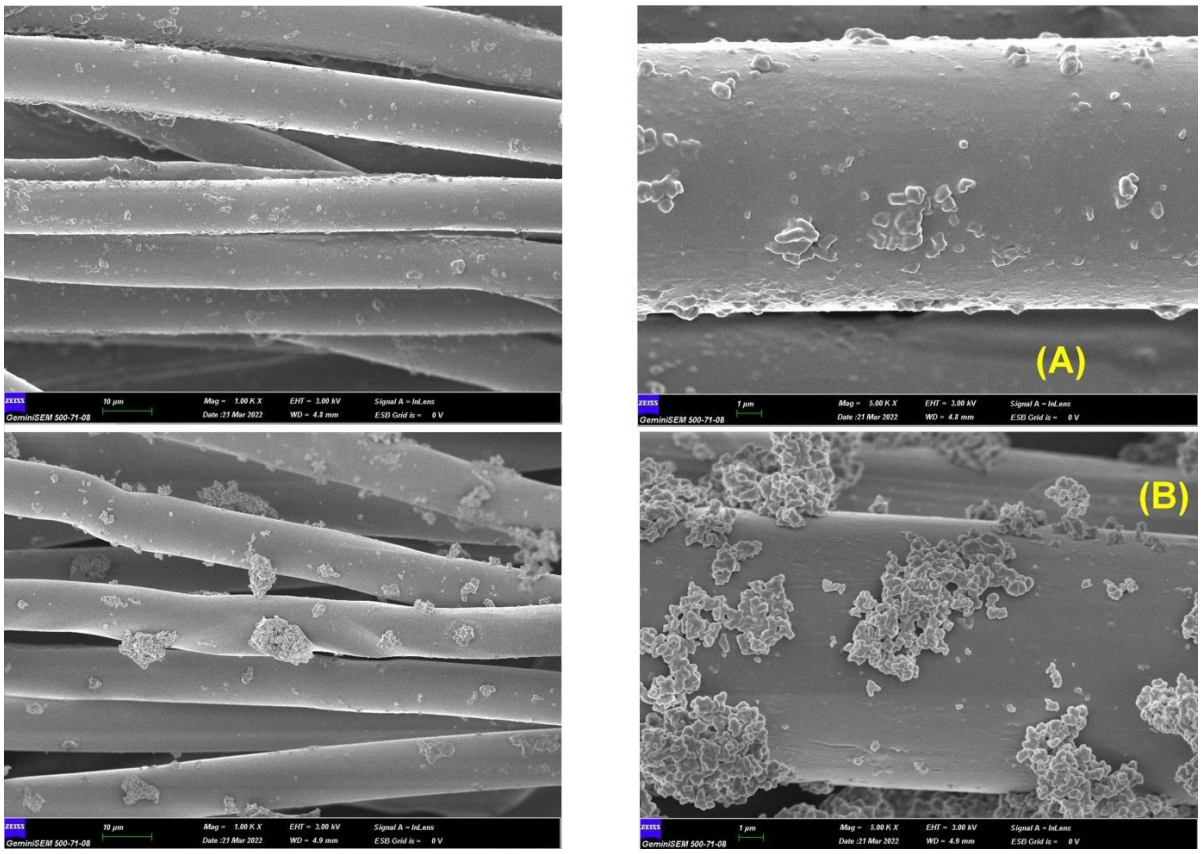

Figure 6. Longitudinal views of PCM nanocapsule loaded Ne 30/1 polyester ring spun yarns (A: 62.5 mL/h, B: 77.5 mL/h feeding rates)

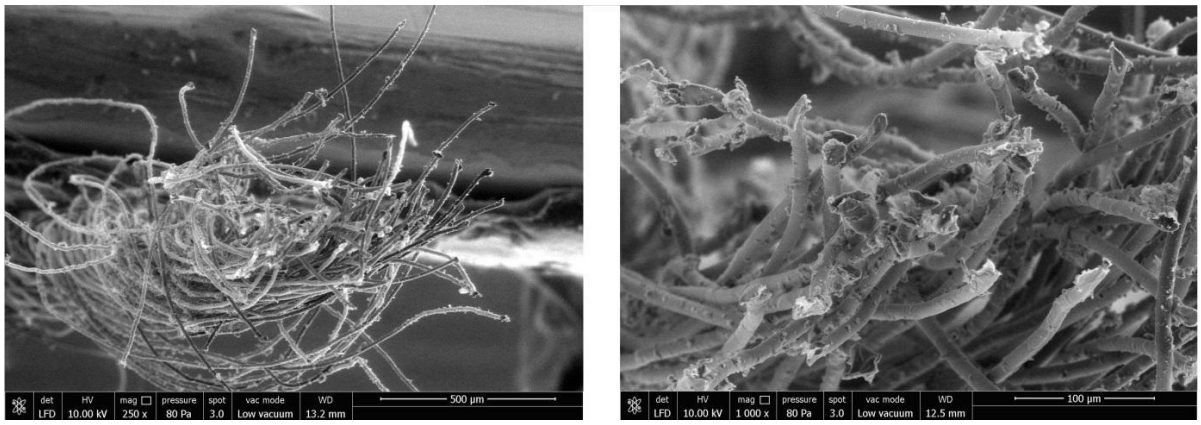

Figure 7. Cross-sectional images of PCM nanocapsule loaded Ne 30/1 polyester ring spun yarns produced at 77.5 mL/h feeding rate

When the undoped and PCM nanocapsule applied yarns were placed in a warm insulated box after the conditioning in a cold environment, their temperatures increased by the time. This case was named as warming-up period. After this point, the rate of increase tended to slow and surface temperature reached to a maximum value at the end of the measurement period. This period was named as saturated surface temperature region. During the warming-up period, surface temperature of the undoped yarn increased rapidly to 21.2 °C in the first 10 minutes while the temperatures were 13.5-17.4°C °C for PCM nanocapsule doped yarns depending on the feeding rates. After this point, the rate of increase tended to slow and saturated surface temperature peaked at 38.1 °C at the end of the measurement period (77th minute) for undoped yarns. As to PCM nanocapsule doped yarns, 32.7-35.5 °C maximum surface temperatures were determined at the end of the measurement period (Figure 8). It was determined that there was a significant difference in the surface temperatures of undoped and PCM nanocapsule yarns. Polyester yarns having PCM nanocapsules had lower surface temperatures during all the measurement process. Temperature differences might be resulted from PCM in the structure. PCM could absorb latent heat from the environment during its melting process in a high temperature

environment and this feature of PCMs provided lower surface temperature values.

In the study, temperature difference value between undoped and PCMs doped yarns was calculated for certain measurement time. As seen in Table 2, at the end of the measurement period, the temperature difference values change between 2.6-4.0 ºC at the feeding rates below 70 mL/h while they were about 4.8-5.4°C at the feeding rates above 70 mL/h. The lowest mean temperature difference value was determined as 2.3° at 62.5 mL/h feeding rate while the highest temperature difference value was determined as 5.5°C at 77.5 mL/h feeding rate.

Table 2. Differences in surface temperatures of virgin and PCM nanocapsule incorporated polyester yarns at different feeding rates for 6% capsule concentration (ºC)

Time (min.)	62.5 mL/h	67.5 mL/h	72.5 mL/h	77.5 mL/h
05:00	1.00	2.20	3.40	1.90
15:00	3.60	7.40	8.00	6.70
30:00	2.90	5.30	5.50	6.20
45:00	2.00	4.30	5.10	5.50
60:00	0.90	4.00	4.80	5.40
75:00	2.30	4.00	4.80	5.40
77:30	2.60	4.00	4.80	5.40

Yarn physical properties

In order to determine the effect of PCM nanocapsule presence on yarn properties, yarn physical properties were investigated. In line with the results obtained in this section, it was also aimed to obtain an idea about the use of the yarns for the production of woven and knitted fabrics. According to the results given in Table 3, it was observed that PCM nanocapsule doped polyester ring spun yarns had higher yarn unevenness and yarn imperfection values. When the tensile properties were examined, it was determined that polyester yarns having PCMs had lower yarn tenacity and slightly higher breaking elongation values compared to undoped polyester yarns. Similar to the results observed in viscose yarns, it was determined that yarn unevenness and faults increased, and yarn strength decreased after capsule application to viscose fibers. In nanocapsule doped yarns, nanocapsule presence and also agglomeration in the nanocapsules might be a reason for the deterioration in yarn unevenness, imperfections and tenacity values [16]. SEM images showed the presence of capsules on the surface of the fibers and capsule aggregation. Therefore, PCM nanocapsule clusters might cause a negative effect of yarn properties. On the other hand, surfactant used for nanocapsule dispersion might reduce fiber-fiber friction and this case might deteriorate the yarn unevenness and tenacity properties [16]. Lord (2003) reported that yarn strength for a staple yarn varies from about 10 cN/tex for the weakest yarns to 30 cN/tex for the best ones [20]. Therefore, the tenacity of PCM doped polyester ring yarns was between 10 and 30 cN/tex and it was evaluated that PCM doped yarns had properties that can be used in weaving and knitting processes.

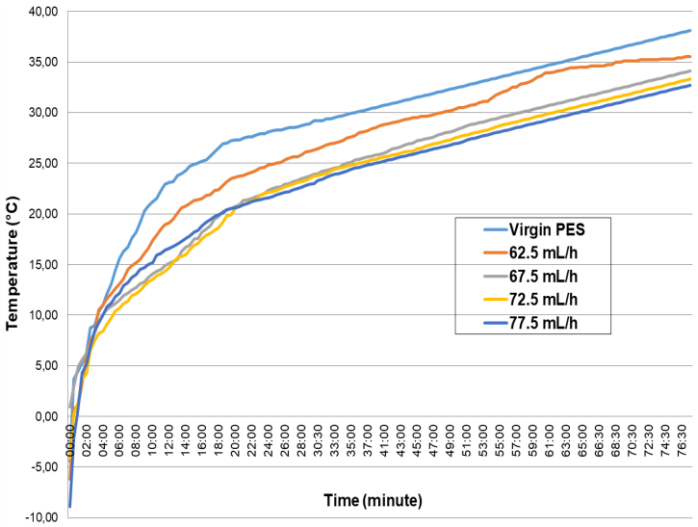

Figure 8. T-history curves of virgin and PCM nanocapsule incorporated polyester ring spun yarns for 6% capsule concentration

Table 3. Yarn properties of undoped and PCM nanocapsule doped polyester ring spun yarns

Feeding rate (mL/h)	CVm (%)	Thin places (-50%)	Thick places (+50%)	Neps (+200%)	Total IPI	H	Tenacity (cN/tex)	Breaking elongation (%)
0 (Undoped)	11.07	0	25	32	57	5.1	26.53	11.58
62.5	12.62	0	70	40	110	5.81	19.58	12.25
67.5	13.07	3.3	56.7	43.3	103.3	5.83	18.49	12.03
72.5	11.78	0	33.3	26.7	60	5.86	20.73	12.45
77.5	11.56	0	50	40	90	5.48	19.86	12.37

4. CONCLUSION

This study focused on the integration of PCM nanocapsules into the polyester staple open fiber bundle during the short staple yarn spinning process via an alternative nanocapsule application method in order to fabricate thermo-regulating polyester surfaces. SEM images indicated the presence of nanocapsules in yarn structure and time-dependent surface temperature (Thermal-history test) measurements showed that PCM nanocapsules incorporated yarns exhibit temperature differences about 2-5 °C compared to undoped yarns during all the measurement period. Cooling effect of PCM in yarn structure provides nanocapsule-doped composite yarns heat up less in high temperature environment compared to undoped polyester yarns. Alternative application method and the produced spun yarns from staple fibres can be a potential to rival the thermally adaptive textile products produced from specially designed synthetic fibers. Such integrated yarn materials have demonstrated promising potential to be used as thermo-regulating textile material.

ACKNOWLEDGEMENT

This work was financially supported by TÜBİTAK 1505 University-Industry Cooperation Support Program (Project No: 5200098). The authors also wish to express their gratitude to ADIM Tekstil San. Ve Tic. A.Ş. (Isparta).

REFERENCES

1. Mattila, H. R. (2006). *Intelligent Textiles and Clothing*, Woodhead Publishing Limited, The Textile Institute, Cambridge, England.
2. Mondal, S. (2008). *Phase change materials for smart textiles – An overview*, Applied Thermal Engineering, 28, 1536–1550.
3. Tao, X. (2008). *Smart Fibres, Fabrics and Clothing*, Woodhead Publishing Limited, The Textile Institute, Cambridge, England.
4. Sarıer, N., & Önder, E. (2007). *The Manufacture of Microencapsulated Phase Change Materials Suitable for The Design of Thermally Enhanced Fabrics*, Thermochimica Acta, 452, 149-160.
5. Önder, E., Sarıer, N., Çimen, E. (2008). *Encapsulation of Phase Change Materials by Complex Coacervation to Improve Thermal Performance of Woven Fabrics*, Thermochimica Acta, 467, 63-72.
6. Cox, R. (1998). *Synopsis of The New Thermal Regulating Fiber*, Outlast, Chemical Fibers International, 48, 475–479.
7. Shin, Y., Yoo, D., Son, K. (2005). *Development of Thermoregulating Textile Materials With Microencapsulated Phase Change Materials (PCM). II. Preperation and Application of PCM Microcapsules*, Journal of Applied Polymer Science, 96 (6), 2005-2010.
8. Zhang, X. X., Wang, X. C., Tao, X. M., Yick, K. L. (2005*). Energy Storage Polymer/MicroPCMs Blended Chips and Thermo-Regulated Fibers*, Journal of Material Science, 40(14), 3729-3734.
9. Salaün, F., Devaux, E., Bourbigot, S., Rumeau, P. (2010). *Thermoregulating Response of Cotton Fabric Containing Microencapsulated Phase Change Materials*, Thermochimica Acta, 506(1–2), 82–93.
10. Sarier, N., & Onder, E. (2012). Organic Phase Change Materials And Their Textile Applications: An Overview, Thermochimica Acta, 540, 7–60.
11. Tözüm, M. S., Alay-Aksoy, S. (2016). Investigation of Tactile Comfort Properties Of The Fabrics Treated With Micro-Capsules Containing Phase Change Materials (PCMs Microcapsules), The Journal of Textile Institute, 107 (9), 1203–12.
12. Yang, K., Venkataraman, M., Zhang, X., Wiener, J., Zhu, G., Yao, J., Militky, J. (2022). Review: Incorporation Of Organic Pcms Into Textiles, Journal of Materials Science, 57, 798–847.
13. Zhang, X. X., Wang, X. C., Tao, X. M., Yick, K. L. (2006). Structures and properties of wet spun thermo-regulated polyacrylonitrile-vinylidene chloride fibers, Textile Research Journal, 76(5), 351-359.
14. Gao, X. Y., Han, N., Zhang, X. X., Yu, W. Y. (2009). Melt-Processable Acrylonitrile–Methyl Acrylate Copolymers And Melt-Spun Fibers Containing MicroPCMs, Journal of Materials Science, 44(21), 5877-5884.
15. Yılmaz, D., Alay Aksoy, S. (2022). Temperature Regulating Polyester Short Staple Ring Spun Yarns By PCM Nanocapsule Application, 8th International Technical Textiles Congress, 13-14 Ekim, İzmir.
16. Yılmaz, D., Özen, Ö., Özkayalar, S., Alay Aksoy, S., Söğüt, B. (2021). An Innovative Method for Microcapsule Based Functional Yarn Production, Journal of Natural Fibers, 19(14), 8051-8064.
17. Anayurt, R. A., Alkan, C., Alay Aksoy, S., Demirbağ, S., Tözüm, M. S. (2017). Influence Of Hydrophilic Comoner On Thermal Properties Of Polymethylemethacrylate/N-Alkanes Microcapsules, Tekstil & Konfeksiyon, 27(2), 163-172.
18. Tözüm, M. S., Aksoy, S. A., Alkan, C. (2018). Microencapsulation Of Three-Component Thermochromic System For Reversible Color Change And Thermal Energy Storage, Fibers and Polymers, 19, 660-669.
19. Tang, J., Fan, C., Lin, Q., Zhou, X. (2014). Smooth, Stable And Optically Transparent Microcapsules Prepared By One-Step Method Using Sodium Carboxymethyl Cellulose As Protective Colloid, Colloids and Surfaces A: Physicochemical and Engineering Aspects, 459, 65-73.
20. Lord, P. (2003). *Handbook Of Yarn Production*, Woodhead Publishing Limited, The Textile Institute, Cambridge, England.