



Polyester Fibres Enhanced with Phase Change Material (PCM) to Maintain Thermal Stability

Marwa A. Ali^a, Khaled M. Seddik^b, and Ahmed G. Hassabo^{c*}

^a Spinning and Weaving Engineering Department, Textile Industries Research Division, National Research Centre, 33-El Behouth St., Dokki, Giza, Egypt, P.O.12622.

^b Clothing and Knitting Industrial Research Department, Textile Industries Research Division, National Research Centre, 33-El-Behouth St., Dokki, Giza, Egypt, P.O.12622.

^c Pre-treatment and Finishing of Cellulose-based Textiles Department, Textile Industries Research Division, National Research Centre, 33-El-Bohouth St., Dokki, Giza, Egypt, P.O.12622.



CrossMark

Abstract

Polyester is one of the textile materials that are widely used, with different forms as textile or yarns or fibres. This depends on the properties of the polyester polymer and the final application that is used in it. Staple and crimps polyester fibres (poly-fil®) have also been used for comfort applications in addition to the durability property. The general use of crimps polyester fibres as alternatives of fillings for pillows and mattresses. This research is aiming to enhance the staple and crimp polyester fibres with Phase Change Material (PCM) to give the ability to change their thermal state in a large range to use it as a filling or compressed sheet for thermal protection of different purposes, regardless of ambient temperatures. So, short and crimps polyester fibres treated in a simple way using Octadecane as (PCM material) loaded on Pectin/Stearic acid and Alginate/Stearic acid to form PCM composite treatment materials. The properties of the fibres were evaluated after treatment with Differential Scanning Calorimetry (DSC), Scanning Electron Microscopy (SEM), in addition to the physico-mechanical properties. It can conclude that; the polyester fibres can be covered with PCM composites and the covered one has a preferable result over its uncovered. Also, after the evaluation of blank/uncovered and covered polyester fibres properties, it was these treatments enhanced the mechanical and physical properties of fibres, and they kept and maintain the fibres crimps shape to achieve the air changing. Additionally, acquisition of the required thermal properties to reach the state of thermal stability.

Keywords: Poly-fil®, Octadecane, Phase Change Material (PCM), Thermal stability, Fillings

1. Introduction

Polyester is one of the textile materials that are used in technical products like ropes, tire reinforcement, safety belts, tapes and fabrics for conveyor belts and in plastic reinforcements with high energy absorption. Polyester is soft and strong, resistant to shrinkage and does not stretch. It is a polymer that is produced from coal, water, air and petroleum products [1-4].

The expression "staple fibre" often refers to a kind of natural fibre like cotton, wool... *etc.*, which can be twisted to form yarn. In 1935, the DuPont Chemical Company created polyester that was strong enough to be twisted into yarn similar to natural fibres. Polyester staple fibre resists wrinkles, mildew, general surface

damage and most chemicals. This material also holds creases and pleats well, as long as they have been heat-set first. The chemical name for the polyester used in fibre production is polyethylene terephthalate (PET). This compound is also used to make plastic soft drink bottles, which can be melted down after use, allowing the PET fibres to be reused [5].

Polyester is used in different types based on its length of fibres, including tow fibre, textile filament, fibre-fill, industrial filament fibre and polyethylene naphthalate (PEN) fibre. These types have different lengths of fibre, resulting in different properties in the final products. Staple fibres are short fibres that have been produced a continuous filament and then cut [4,

*Corresponding author e-mail: aga.hassabo@hotmail.com (Ahmed Hassabo)

Receive Date: 22 August 2021, Revise Date: 23 August 2021, Accept Date: 25 August 2021

DOI: 10.21608/ejchem.2021.92104.4367

©2021 National Information and Documentation Center (NIDOC)

6].

Polyester Fibre-fill is a synthetic fibre used for stuffing pillows and other soft objects such as stuffed animals. It is also used in audio speakers for its acoustic properties. Also, used in technical applications such as stuffing bags, lining some types of soil for cultivation, home textiles, some clothing fillings, shoe fillings. It is commonly sold under the trademark name Poly-fil® or un-trademarked as polyfill [7, 8].

Poly-fil® varies according to the length of the cut, the number of wrinkles, and their height per unit length and usually bright white. These fibres are environmentally friendly, they are non-toxic, odourless, and never mixed with any auxiliary materials or adhesives, each of them is independent and separate, allow breathable and exchange air through it. The fibres have permeable to liquids, but not absorbing them, so it is known to be resistant to water absorption (less than 1% of the same weight). Also, it has fire-resistant, high ability to wash and maintain dry and wet cleaning; so its useful life can reach 30 times more than normal. These fibres are disinfected after production by high temperature and ultraviolet radiation (UV). Usually, these fibres are sold in the form of a stack of fibres or compressed in the form of a non-woven web of different thicknesses, and the fibres are joining together by thermal cohesion [9].

Thermal insulation in textiles is traditionally applied from massive composite materials. Since the late 1980s, a new type of insulation material has appeared on the market, phase change materials (PCMs). Integrated into textile, they can improve its thermal behaviour. The thermal properties of phase change materials allow them to be perceived as the material of choice for thermal insulation of the human body. The possibility of keeping the wearer as long as possible in his thermal comfort zone. Therefore, a

product ideally having a thermal window from 19°C (vasoconstriction temperature) to 37°C should contribute to localized thermal regulation [10-12].

Phase Change' is the process of going from one state to another, *e.g.* from solid to liquid. Standard phase change materials (PCM) are generally a polymer/carrier filled with thermally conductive filler. Such materials collect, discharge, or absorb heat as they oscillate between solid and liquid forms, the PCMs are used, but they never get used up. They discharge heat as they transform to a solid-state and absorb heat as they go back to a liquid state (see **Figure 1**) [13]. The storage of thermal energy by changing the phase of a material at a constant temperature is classified as 'latent heat'. Phase Change Materials are waxes that have the distinctive capacity to soak and emit heat energy without altering the temperature. These waxes include Eicosane, Octadecane, Nonadecane, Heptadecane and Hexadecane. They all possess different freezing and melting points (see **Table 1**) and when mixed in a microcapsule, heat energy will be accumulated and released and maintain their temperature range from 30-34°C, which is very comfortable for the body [11, 12].

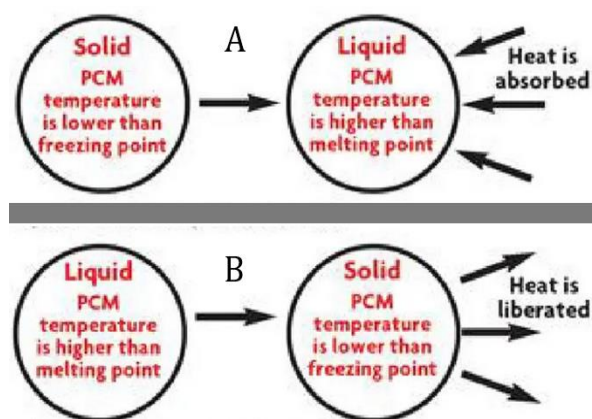


Figure 1: Temperature change effect of PCMs, (A) the cooling effect, and (B) the heating effect.

Table 1: Freezing and melting points of certain PCMs

Phase Change Material	Freezing point (°C)	Melting point (°C)
Eicosane	30.6	36.1
Octadecane	25.4	28.2
Nonadecane	26.4	32.1

The microencapsulated PCM can be combined with melting polymer fibre in various ways, such as; a) microcapsules, where the PCM microcapsules are permanently fixed within the fibre structure during the fibre spinning procedure, b) padding by matrix coating during the finishing process of fibres or yarn or fabrics, where the PCM microcapsules are embedded in a coating compound like acrylic, polyurethane...etc., and c) printing by foam dispersion where microcapsules are mixed into a water-blown polyurethane foam mix and these foams are applied and the water is removed from the system by the drying process of fabric [14-18].

In general, there are three types of phase changes materials; thermally conductive and electrically insulating, and electrically conductive. The main dissimilarity between the thermally and electrically conductive materials is the film or carrier that the phase change polymer is coated with. The electrically insulating material has the lowest amount of voltage isolation properties that can be achieved. [9, 19-21]

Today, many smart applications depend on using PCM like; Automotive textiles, Apparel active-wear... etc. Recently, textiles having Phase Change Materials (PCMs) could find uses in the medical sector to raise the thermo-physical comfort of surgical clothing such as gowns, caps, and gloves [22-24].

This study aims to add a unique and new property to the short and crimps polyester fibres, which is the property of thermal stability; by covered those fibres with PCM composite materials prepared to have the

ability to change of phase state. The polyester fibres gain a smart behaviour of thermal stability after PCM treatment with the difference of ambient temperatures. So, they have more suitable for use in fillings and compressed sheets with multiple thermal applications for thermal isolation and stability.

2. Experimental

2.1. Materials

2.1.1. Textile material

Polyester staple fibres with high crimps along the longitudinal section were used, padding for different products filling was common using special with end-use. All specifications represent in Table 2.

Table 2: General specifications of polyester fibre padding for pillow filling

Properties	Description
Material	100% Polyester
Colour	White
Cut length	25, 32, 51, 64, 76, 102 and 124 mm
Deniers	1.5D to 70 D
Tensile strength	>16 gm/Tex
Elongation	>70%
Crimps	7 to 12 per inch

2.1.2. Chemical materials

Pectin (30,000–100,000) and sodium alginate medium molecular weight were purchased from Fluka. Stearic acid, sodium lauryl sulphate, dichloromethane (DCM), dicyclohexylcarbodiimide (DCC), potassium carbonate (K_2CO_3), and octadecane were purchased from Sigma-Aldrich.

2.2. Methods

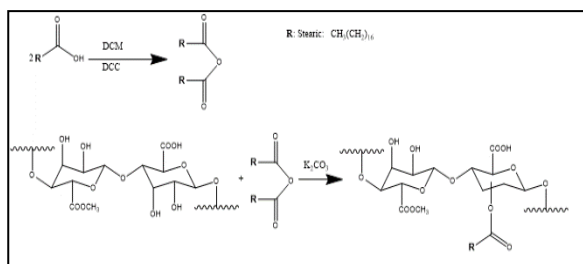
2.2.1. Synthesis of fatty acid anhydrides

10 mmol stearic acid was dissolved in 2 mL dichloromethane and stirred vigorously in an ice-water bath under an argon atmosphere. 5 mmol dicyclohexylcarbodiimide (DCC) was dissolved in dichloromethane. Then soluble DCC was added to the

mixture and continued stirred at ice bath temperature for additionally 2 h. Precipitation was separated by filtration, and then the solvent was evaporated from the filtrate in a vacuum to give the anhydride [25, 26].

2.2.2. Synthesis of pectin-fatty acid esters

General esterification procedure was used as follows: 10 g pectin or alginate, 10 g anhydride and (0.1 eq.) (Scheme 1) were milled using agate mortar. The mixture was heated in an oil bath for 15–25 min. at 160°C. After that, the mixture was cooled to room temperature and washed with chloroform. Obtained ester was dissolved in water and the pH was adjusted to neutral. The final solution was dialyzed in deionized water for 1 day and finally lyophilized for 2 days [25, 26].



Scheme 1: Scheme for preparation of pectin or alginate/stearic acid composites

2.2.3. Synthesis of PCM composite based on pectin-fatty acid ester

PCMs composites were prepared according to our previous work [13, 27] as follows: by mixing pectin or alginate/stearic acid ester with paraffin compounds (n-octadecane; C_{18}) in a molar ratio (1:2; polymer to paraffin) at 110°C for 14 h.

The number of final samples after PCM composite material treatments reached four samples, three samples of them covered with PCM and the last one uncovered, as shown in Table 3.

Table 3: Description of polyester fibres samples

Sample code	Description
Uncovered/Blank	Fibres without treatment.
F/P	Fibres treated with Octadecane hosted/loaded on pectin stearate.
F/S	Fibres treated with Octadecane hosted/loaded on alginate stearate.
F/PS	Fibres treated with Octadecane hosted/loaded on pectin stearate and alginate stearate.

2.3. Evaluation Test

The phase change materials used and their composites were characterized by Fourier Transform Infrared Spectroscopy (FT-IR) analysis to study the chemical changes and interaction phases in the blank and treated yarn samples. The FTIR spectrum was measured using the ATR technique based on the FTIR spectrometer model (JASCO FT-IR-6100), the spectral range 4000-400 cm^{-1} was recorded.

Differential scanning calorimetry (DSC) 131 Evo (SETARAM Inc., France) was used to perform the differential scanning calorimeter analysis. The instrument was calibrated using the standards (Mercury, Indium, Tin, Lead, Zinc and Aluminium). Nitrogen and Helium were used as the purging gases. The test was programmed including the heating zone from 25 to 100°C with a heating rate of 10°C/min. The samples were weighted in Aluminium crucible 120 ul and introduced to the DSC. The thermo-gram results were processed using (CALISTO Data processing software v.149).

Duration index (DI) ($\text{J}/\text{cm}^3/\text{K}$), is a parameter characterising the material and the temperature at which it is aimed at functioning. Its measure to know that, at a constant temperature during the phase change, how long a PCM will remain by equation 1 [28].

$$DI = \Delta H \rho / \Delta T \quad (\text{Eq. 1})$$

Where; ΔH : the enthalpy of PCM change of state, ρ : the PCM density, and ΔT : the temperature difference between measurable temperature and the temperature of interest (ambient, or body temperature).

The total resistance to dry heat transfer (R) is the insulation value of the clothing systems, and it is related to the textile material on which PCM is applied by equation 2;

$$R = (\Delta T \times A) / H, \quad (\text{Eq. 2})$$

Where; A : material of area, the temperature difference of the two sides of the material, $\Delta T = T_F - T_R$ (F , face, and R , rear, of the material) and heat flow (H). The value for textiles is given in "clo" ($\text{m}^2 \cdot ^\circ\text{C}/\text{W}$), 1 clo = $0.155 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (Zero (0) clo corresponds to a naked person and One (1) clo corresponds to a person wearing a typical business suit), which is the unit for clothing insulation adopted from studies of hygienic comfort [29-31].

Scanning Electron Microscopy (SEM) was performed using Philips XL30 scanning electron microscope equipped with a LaB6 electron gun and a Philips-EDAX/DX4. Surface morphologies were imaged at different magnifications following the clarity of the images to study the surface morphology and the cross-section of the composite films, using 30kV accelerating voltage. Samples were fixed with carbon glue and metalized by gold vapour deposition to record images.

Dielectric measurements of materials properties; the polyester fibres samples were pressed into pellets in a circle shape with 14 mm in diameter and (2.2-3.4) mm thickness, by applying a specific pressure. The samples were inserted between two conducting electrodes of 10 mm in diameter forming capacitor. The dielectric properties such as capacitance (C) and loss tangent ($\tan\delta$) can be measured using a network impedance analyzer (KEYSIGHT-E4991B). For the

present samples, the permittivity (ϵ') and AC conductivity (σ_{ac}) were calculated from these parameters at room temperature [32, 33].

Mechanical and physical properties of the fibres and yarns were tested before and after treatment with the phase change materials. All samples were put in the standard atmospheric conditions for 24 hours before testing according to ISO-139 [34]. The tests carried out on the fibres samples are as follows; Fibre diameter measuring according to ASTM-D 276 using Nikon Profile Projector Model V-12 [35], Tenacity and Elongation were determined using Stelometer flat bundle tester with 1/8 inch according to ASTM-D1445-12 [36]; the tenacity was calculated by the following equation:

$$\text{Tenacity at 1/8 gauge (g/Tex)} = \frac{\text{Breaking load (kg)} \times 1.5 \times 10}{\text{Samples weight (mg)}} \quad (\text{Eq. 3})$$

The tests were carried out in Spinning and Weaving Engineering Department Laboratories, Central Unit for Analysis and Scientific Services at Textile Industries Research Division, Textile Laboratories and Nanomaterial Investigation laboratory, Scientific Central of Excellence of Laboratories Network, and Sol-gel Lab and the electric and dielectric measurement unit at National Research Centre (NRC), Egypt.

2.4. Statistical analysis of results

The test results were statistically analysed using Analysis of Variance (ANOVA), the significance level was set at $P \leq 0.05$. LSD (Least Significant Difference) was carried out to obtain the least significant differences between treatments. Finally, evaluation of fibres properties was performed using radar charts to determine the best sample performance after treatment.

3. Results and Discussion

3.1. Characterization of pectin/alginate – stearic acid (Hosting materials)

3.1.1. FT-IR analysis

Pectin stearate and Alginate stearate were characterised using FT-IR. IR spectra for pectin, alginate, stearic acid anhydride, pectin stearate and alginate stearate are illustrated in **Figure 2**. FT-IR spectra of pectin and alginate show peaks at 3402, 2932 cm^{-1} , which is corresponding to –OH and –CH stretching peaks. In addition, another two peaks at 1454 and 1357 cm^{-1} were assigned to CH_2 and –OH peaks, respectively. Furthermore, **Figure 2** confirmed

Table 4 for pectin, alginate, stearic acid, Octadecane (PCM material) and prepared composites with and without Octadecane composite (PCM). The

Table 4, it is clear that the presence of alginate in the final composite form causing an increase in the latent heat of hosting materials more than pectin. Also, the melting temperature of the biopolymer was decreasing as reacting with stearic acid, and further decreasing was occurred after adding Octadecane. The final melting temperature was suitable for phase

the chemical modification of pectin or alginate with a stearic acid anhydride. FT-IR spectra are comprehensive the chemical modification as follows; **For pectin stearate**: 3442 cm^{-1} for O–H, 2923 and 2849 cm^{-1} for C–H, 1729 cm^{-1} for C=O (methyl ester), 1707 cm^{-1} for C=O (fatty acid ester), 1632 and 1431 cm^{-1} for COO^- , 1201 and 1128 cm^{-1} for C–O; **For alginate stearate**: 3438 cm^{-1} for O–H, 2915 and 2842 cm^{-1} for C–H, 1747 cm^{-1} for C=O (methyl ester), 1694 cm^{-1} for C=O (fatty acid ester), 1627 and 1433 cm^{-1} for COO^- , 1204 and 1147 cm^{-1} for C–O.

3.1.2. DSC Analysis

DSC values (T_o ($^{\circ}\text{C}$), T_p ($^{\circ}\text{C}$) and ΔH (J/g)) were collected and listed in DSC results for pectin exhibiting a peak of 137.1 $^{\circ}\text{C}$, which is equivalent to the reported values for pure pectin melting temperature (T_p) [26].

From the data in **Figure 3** and changing material to the textile material and therefore for the body. Furthermore, values of DI of the produced composites with Octadecane shows that the best composite having the highest DI can be arranged as follows: Pectin stearate/Alginate stearate/Octadecane(III*) > Alginate stearate/Octadecane (II*) > Pectin stearate/Octadecane (I*).

Table 4: DSC data for hosting materials with/without Octadecane from 2nd heating

Hosting materials	T_o	T_p	DH	DI* (J/cm ³ K)
Pectin [26]	135.7	137.1	32.12	
Alginate [37]	251.1	288.32	43.24	
Stearic acid [27]	65.2	69.7	166.52	
Octadecane [13]	29.3	33.4	241.44	
Pectin Stearate (I)	30.16	35.17	53.29	6.23
Alginate Stearate (II)	30.14	36.11	57.92	6.75
I + II (III)	30.13	37.69	62.31	7.26
Pectin Stearate/Octadecane (I*)	32.19	40.19	112.34	18.68
Alginate Stearate/Octadecane (II*)	32.67	42.69	188.57	34.84
I* + II* (III*)	32.42	40.19	255.58	44.64

* **Duration index:** based on ΔT from melt point to body temperature (37 $^{\circ}\text{C}$) and average density of 0.8 g/cm³

T_o : Onset Temperature, T_p : Keeping Temperature, ΔH : Enthalpy

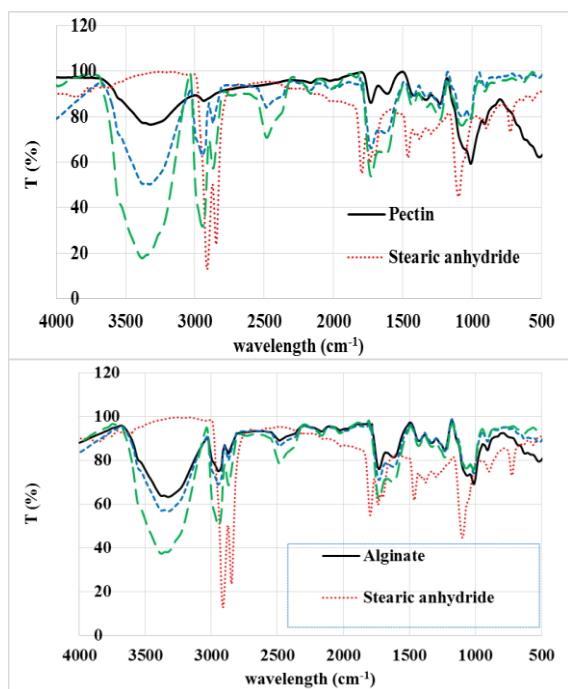


Figure 2: FT-IR spectra of hosting materials with/without Octadecane

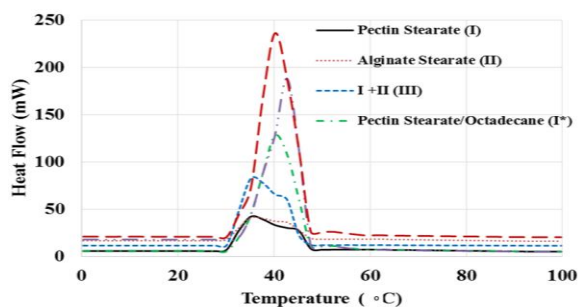


Figure 3: DSC curves for hosting materials with/without Octadecane from 2nd heating

3.2. Evaluation of Polyester Fibres

Heat loss to the environment happens by convection, radiation and evaporation from the skin

Table 5 illustrate the DSC results of covered polyester fibres with Pectin or Alginate/stearic acid with Octadecane. It is observed that covered polyester fibre with these composites imparts the thermo-regulating property to polyester fibre with higher latent heat and DI comparing to uncovered (Blank)

and by the latent heat of perspiration. Regarding thermal protection, the vital undertaking of textile is to make a staple microclimate alongside the skin to support the body or any surface need for thermoregulatory behaviour [38]. At the point when textile apparel is consolidated with PCM material, it can give an improved warm thermal capacity with the current insulation characteristic of the structure to retain the comfortability.

To increase the thermal insulator qualities and to decrease temperature variations, polyester fibre was covered by PCM composite material. The usage of PCM materials is a useful way to store and release heat while changing the ambient temperature [13, 26, 39, 40].

3.2.1. DSC analysis

Figure 4 and On the study of electrical conductivity properties of the polyester fibres at a specific frequency (100 kHz) as a max. range of low frequency. It was found in general that the electrical conductivity decreased after covering with different PCM composite treatments as referred to in Figure 7. Where it was found that the sample F/P showed the lowest electrical conductivity, followed by the sample F/PS and then the sample F/S, respectively compared to the blank sample that showed the highest electrical conductivity. [45, 46]

polyester fibres. Furthermore, covered polyester with Alginate/Pectin/Stearic provide higher latent heat and DI more than covered polyester with Alginate/Stearic and covered polyester with Pectin/stearic as hosting materials. Furthermore, total resistance to dry heat transfer was calculated and confirmed that covered polyester fibres with Pectin/Alginate/Stearic

acid/Octadecane composite make the fibres more comfortable than those covered with other composites. At last, it can infer that; polyester fibres can be covered with PCM composites and the covered one has a preferable result over its uncovered.

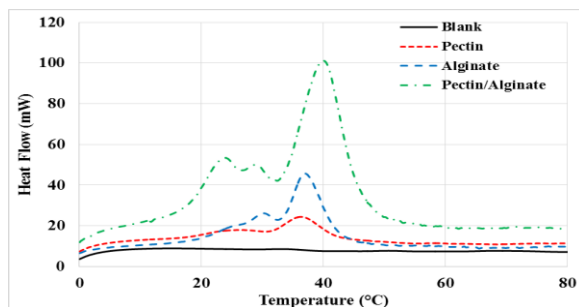


Figure 4: DSC curves for covered polyester fibres with Pectin or Alginate/Stearic acid with Octadecane from 2nd heating.

3.2.2. Characterization of Dielectric Properties of Polyester Fibres

All materials are capable of storing electrical energy when they are exposed to an electric field. The storage capacity varies from one material to another. The dielectric constant is the ratio of the permittivity of a substance to the permittivity of free space. It differs from one material to another as the dielectric constant of polyester is 3.3. [41, 42]

Apart from the dielectric constant, it is also important to consider the dielectric loss and dielectric strength of the material. The dielectric strength is a measure of the voltage that an insulator will withstand before it allows current to flow through it. The dielectric loss refers to the energy that a dielectric material dissipates when a variable voltage is applied. It has an indirect relation with conductive value [43].

Two main forms of loss may dissipate energy within a dielectric material; a flow of charge through

the material causes energy dissipation and Dielectric loss through the movement of charges in an alternating electromagnetic field as polarisation switches direction. Dielectric loss tends to be higher in materials with higher dielectric constants [44]. Consequently, from **Figure 5(A-D)**, it was indicated that the dielectric constant was high in the covered fibre samples F/PS, F/P, and F/S, respectively. So, the dielectric loss was increased with the same arrangement, maybe related to the behaviour of the treatment materials that changed the position of electrical charges on the surface of the fibres.

Figure 6 shows that the conductivity values at low frequency (100-100000 Hz) of blank/uncovered and covered polyester fibres. It was noted that the conductivity value reduced after the cover of fibres, the sample F/P covered with Pectin Stearate/Octadecane showed the lowest conductivity values, followed by sample F/PS covered with Pectin Stearate/Alginate Stearate/octadecane compared to the blank fibres sample that was recorded high conductivity value.

On the study of electrical conductivity properties of the polyester fibres at a specific frequency (100 kHz) as a max. range of low frequency. It was found in general that the electrical conductivity decreased after covering with different PCM composite treatments as referred to in **Figure 7**. Where it was found that the sample F/P showed the lowest electrical conductivity, followed by the sample F/PS and then the sample F/S, respectively compared to the blank sample that showed the highest electrical conductivity. [45, 46]

Table 5: DSC, Duration index and Total Resistance results of covered polyester fibre with PCM composite material (Pectin or Alginate/Stearic acid/Octadecane composite)

Sample description	T ₀ (°C)	T _p (°C)	ΔH (J/g)	DI * (J/cm ³ K)	R ** (clo)
Uncovered/ Blank	36.60	37.00	0.7320	0.29	0.88
Pectin/Stearic/ Octadecane	31.50	36.70	24.044	3.50	0.35
Alginate/ Stearic/ Octadecane	32.91	37.45	64.296	12.58	0.11
Pectin/Alginate/ Octadecane	32.83	40.272	178.641	34.27	0.07

* **Duration index:** based on ΔT from melt point to keeping temperature and average density of 0.8 g/cm³

**R: Total Resistance to Dry Heat Transfer

T₀: Onset Temperature, T_p: Keeping Temperature, ΔH: Enthalpy

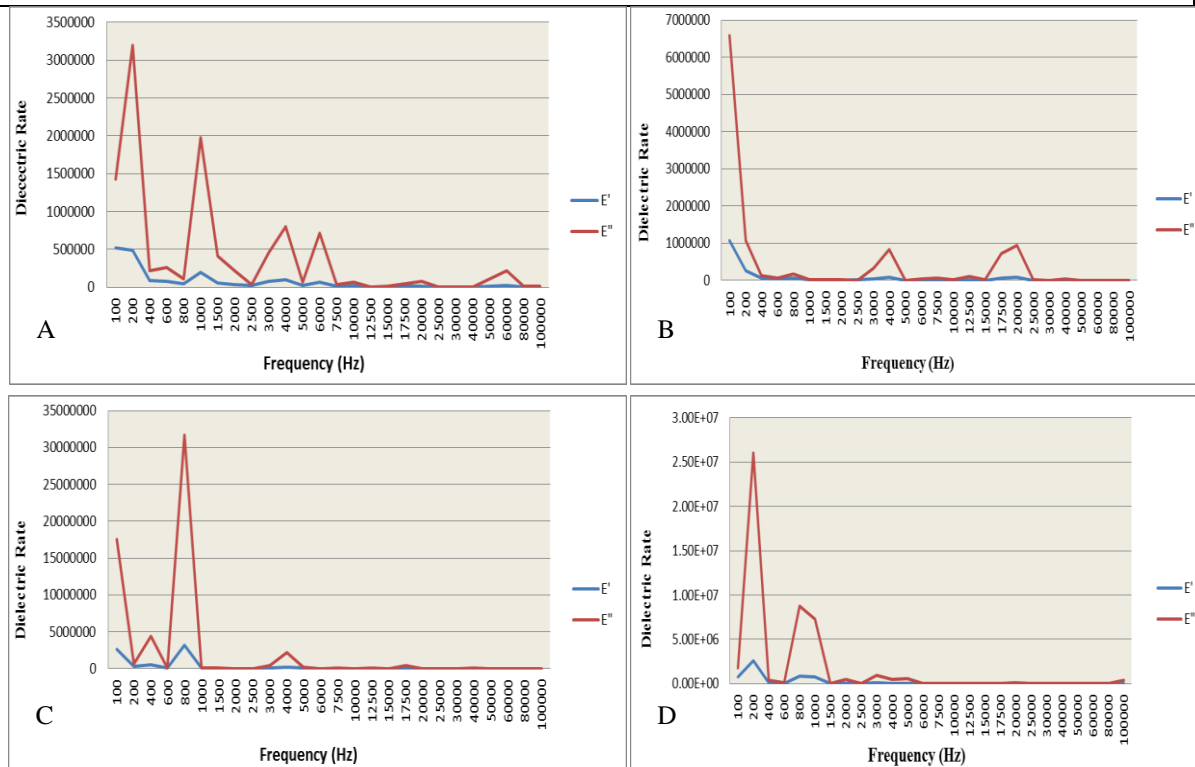


Figure 5: Dielectric properties; (A) Blank fibres, (B) F/P, (C) F/S and (D) F/PS at low frequency range

This means that the polyester fibres after cover tend to the direction of equalizing the charges on their surface or dissipating part of them, which decreased their conductivity and reflected on their ability to heat loss with the change of thermal conditions with positive. May be related to the dielectric loss through the movement of charges in an alternating electromagnetic field as polarisation switches direction after covering for fibres due to the characteristics of PCM composite treatment materials, while the alternating electromagnetic field is staple in the blank of polyester fibres according to the natural electric properties.

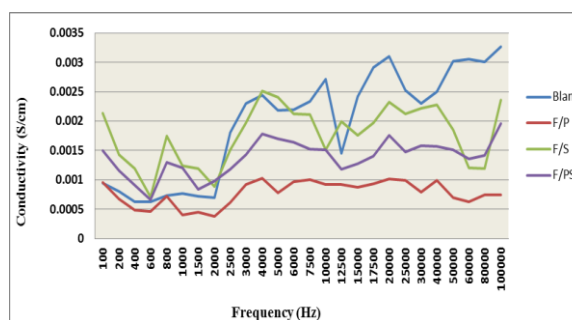


Figure 6: Conductivity for Blank and covered polyester fibres at low-frequency range.

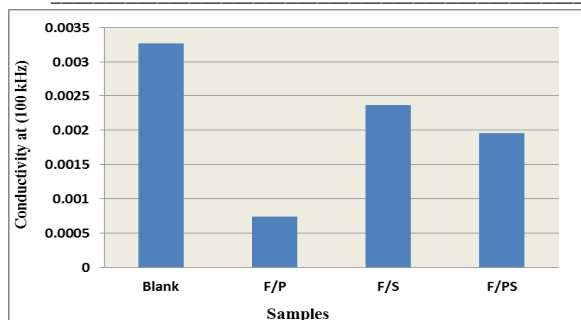


Figure 7: Conductivity behaviour for polyester fibre samples at 100 kHz.

3.2.3. Scanning Electron Microscopy (SEM)

Figure 8(A-D) shows the SEM of the polyester fibre samples before and after applying treatment: (A) blank, the covered fibres with Octadecane as PCM material hosted on three composite materials; (B) Pectin Stearate/ Octadecane, (C) Alginate Stearate/ Octadecane and (D) Pectin Stearate/Alginate Stearate/Octadecane. **Figure 8(B-D)** points to the high deposition of the prepared PCM composites, with which the fibres were covered compared to the untreated fibres shown in **Figure 8(A)**. Also, the covering of polyester fibres with Alginate Stearate/Octadecane in **Figure 8(C)** showed high and uniform distribution of the composite material on the surface of polyester fibres.

3.3. Mechanical and Physical Properties of Polyester Fibres

3.3.1. Fibres Length Measurement

Figure 9 shows that the fibre length before (with

crimps) and after straitening, it was noted that the difference in length of the blank fibres was the greatest compared to the difference in length of covered fibres with different PCM composite materials. This could be related to the intensity of the crimps on blank polyester fibres as shown in **Figure 10**, which means that different PCM composite treatment materials have partially smoothed out several crimps along the polyester fibre length, especially with Octadecane (PCM material) loaded on pectin stearate separately and on both pectin stearate and alginate stearate (F/PS sample), due to the high density of the composite materials.

3.3.2. Crimps Number Per Length of Staple Fibres

Figure 11 points to the difference in shape between fibres before and after covering, where we can notice that the height of the crimps decreased significantly along the length of the covered polyester fibres. As it became flatter than the blank fibre at the up and down of the crimp shape, **Figure 11** and **Table 6**, which leads to increasing the length of the fibre. **Figure 12** shows the difference between crimps number per length of blank and covered fibres, it was found that the number of crimps increased although there is a decrease in the height of crimps especially for the F/P sample treated with Pectin Stearate/Octadecane. This is due to the different viscosities of PCM composite treatment materials and their densities.

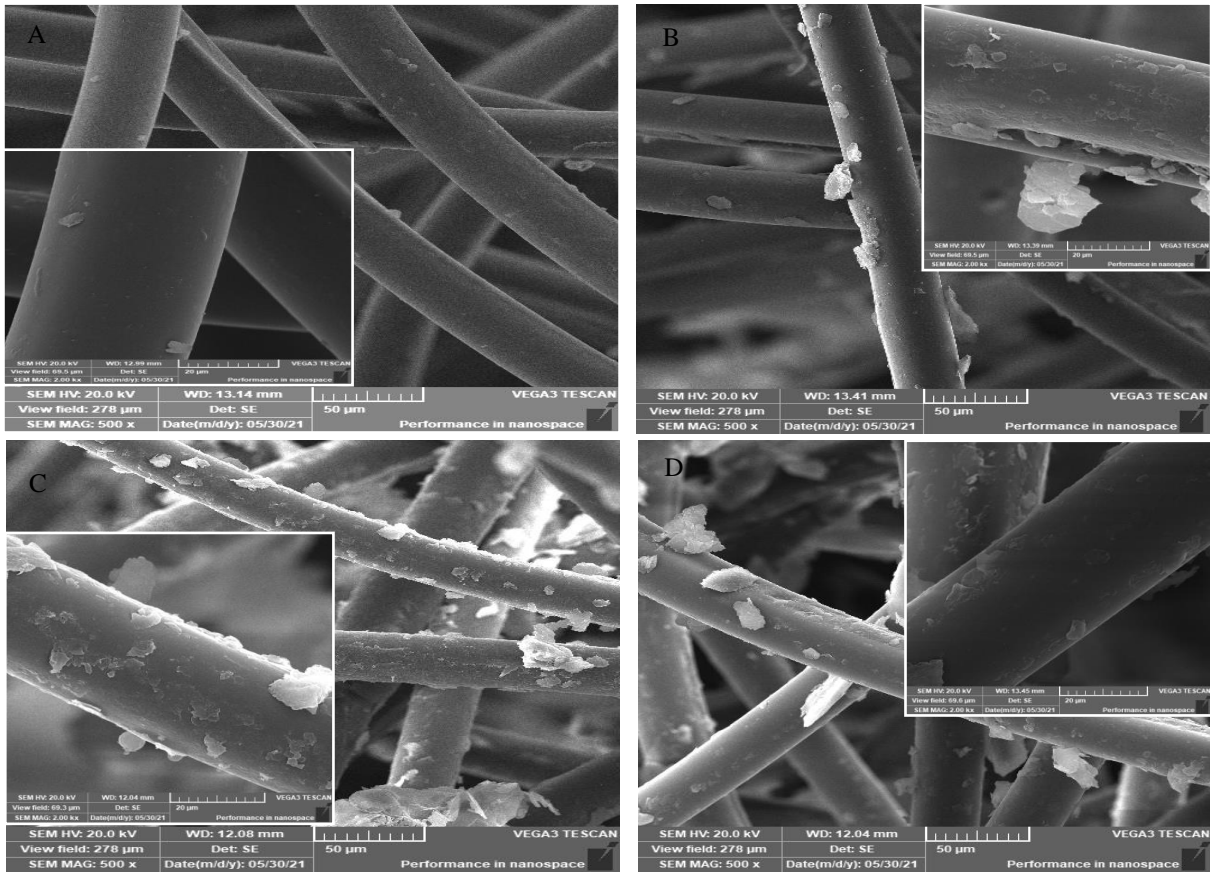


Figure 8: SEM for crimped polyester fibres before and after applying different treatment

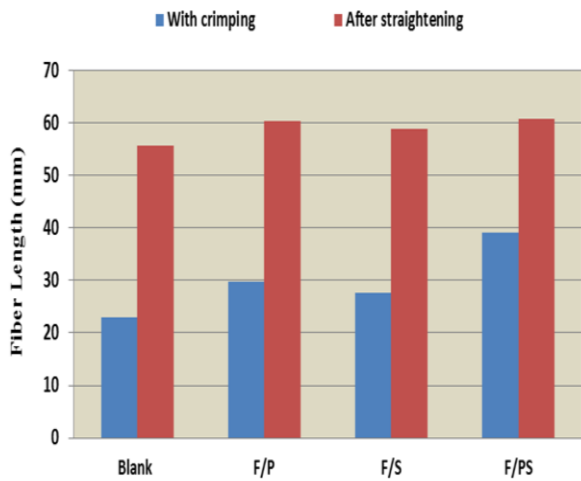


Figure 9: Fibre length of blank and covered fibres before and after straightening

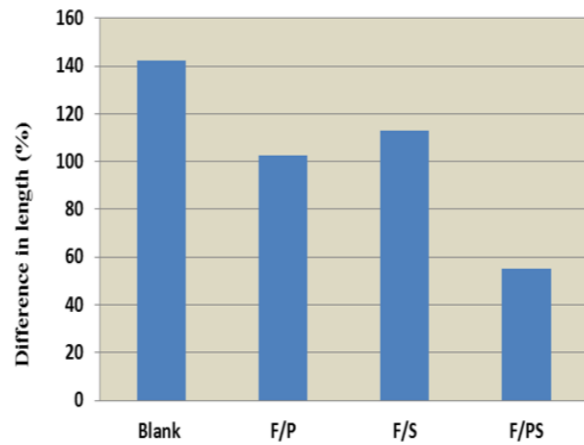


Figure 10: The difference between fibre length with crimps and after straightening

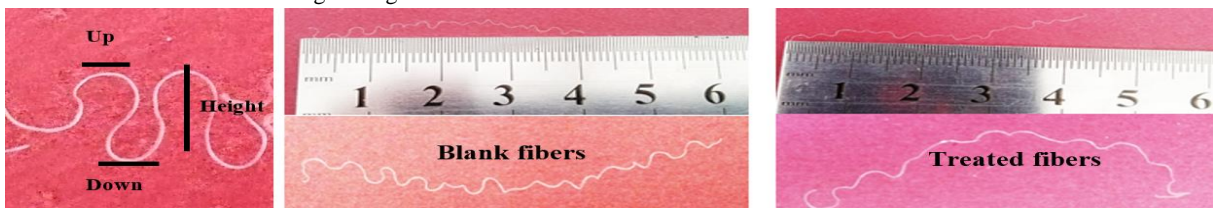


Figure 11: The difference between crimps along the fibre length before and after treatment

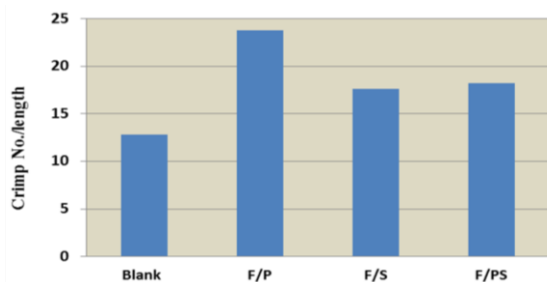


Figure 12: Crimps number per length of blank and covered polyester fibres

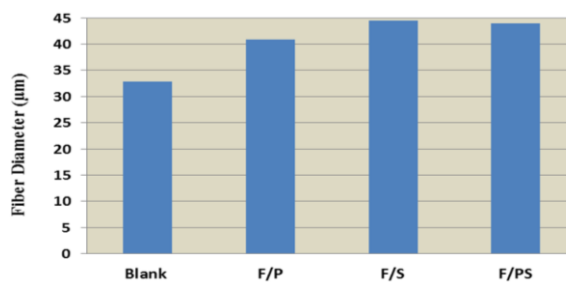


Figure 13: Fibre diameter of blank and covered polyester fibres

Table 6: Description of crimps shape before and after covering of fibres

Sample code	Height of crimps (mm)	Length of crimp cross-section (mm)	
		up	down
Blank	4-4.5	2	3
F/P	0.5-2.5	2.0- 2.5	1.0-2.0
F/S	0.5-3.5	3.0-5.0	2.0-3.0
F/PS	0.5-3	2.0-3.0	2.0-0.5

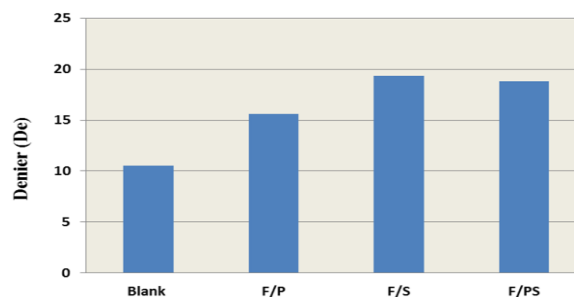


Figure 14: Difference in denier of blank and covered polyester fibres

3.3.3. Fibres Diameter and Denier

It was shown from **Figure 13** the direct positive relationship between increasing in diameter of fibres after covering and increasing of fibre denier in **Figure 14**. The F/S samples covered with Alginate Stearate/Octadecane showed more increase in diameter compared to the other covered samples, due to the high viscosity of alginate.

Figure 15 (A&B) presents the microscopic images of polyester fibres before and after covering. The images demonstrated the deposition of the PCM composites on the surface of the fibre after processing.

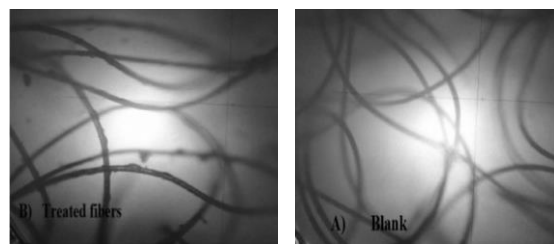


Figure 15: The microscopic images of polyester fibres before and after treatment

3.3.4. Fibres Tenacity and Elongation

Figure 16 illustrates the tenacity values of blank and covered polyester fibres, it is shown that the F/P sample treated with Pectin Stearate/Octadecane was the lowest sample affected by treatment, its tenacity didn't weak with treatment when compared with that of the blank sample, where kept with great tenacity value. While the samples F/PS and F/S that covered with Pectin Stearate/Alginate Stearate/Octadecane and Alginate Stearate/Octadecane, respectively lose more strength after treatment. This may be due to the effect of the treatment composite materials on the mechanical properties by negative during deposition on the fibre surface.

Figure 17 points to the elongation percentage of blank and covered polyester fibres. It was found that the F/PS sample showed the highest elongation % value after treatments. The elongation is indirectly related to tenacity values. So, the F/P sample achieved the lowest elongation %, whereas the F/PS and F/S samples showed lower elongation (%) respectively compared to the blank sample. This may be due to the density of PCM composite materials during deposition.

3.4. Study of the Effect of Treatments on the Fibres Properties

Table 7 points to the significant effect of different PCM treatments with various composite materials on polyester fibres properties. The results present that treatments had a highly significant effect on crimps and diameter properties, whilst achieving a significant effect on the max strain. Furthermore, it was noted that there is a non-significant effect of treatments on fibres' length after straightening and on their tenacity results.

Table 8 demonstrates L.S.D. values of the significant effect according to the ANOVA test, as well as the differences between means (averages) of samples at a single test. [47] The findings show that there is a change in behaviour of fibre properties after treatment as follows;

Length of fibres with crimps: blank fibres differ in behaviour and values with the samples F/P and F/PS, while the F/S sample differs in behaviour and values with the samples F/P and F/PS, which clarify that the treatments obtained a great effect on length fibres with crimps.

Diameter: blank fibres differ in behaviour and values with the other treated fibres, on the other hand, there are not any differences between treatments effects on fibres diameter.

Max Strain: blank fibres did not differ in values with the other treated fibres, but on the other way treated samples differ in behaviour and values with each other, where significant differences occurred between F/PS samples and F/P, F/PS samples.

3.5. Evaluation of Polyester Fibres Properties

Figure 18 and **Table 9** point to the evaluation of blank and treated polyester fibres properties in terms of the radar chart area and quality factor. It was revealed that the F/P sample (polyester fibres covered with Octadecane loaded on pectin stearate) showed the biggest radar chart area and the highest quality factor, followed by F/PS sample (polyester fibres covered with Octadecane loaded on pectin stearate and alginate stearate together), as these treatments enhanced the mechanical and physical properties of fibres. Also, they kept and maintain the fibres crimps shape to achieve the air changing. Additionally, acquisition of the required thermal properties by processing to reach the state of thermal stability with different statuses and environments.

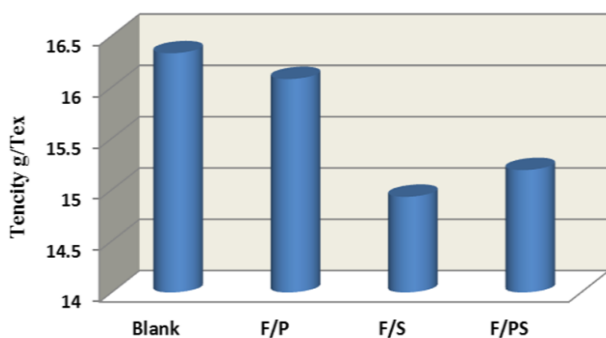


Figure 16: Tenacity values of blank and covered polyester fibre

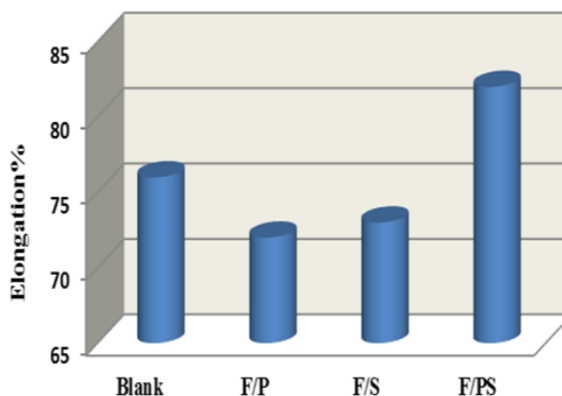


Figure 17: Elongation percentage of blank and covered polyester fibres

Table 7: Significant effect of treatment on polyester fibres properties

Properties	P-value	Significance
Length of fibres with crimps	0.00055	**
Length of fibres after straightening	0.113924	NS
Diameter	5.89E-07	**
Max Strain	0.039499	*
Tenacity	0.109229	NS

** Highly Significant * Significant NS; Non-significant

Table 8: Least significant differences (L.S.D.) analysis

Properties	L.S.D.	Differences				
		Blank	F/P	F/S	F/PS	
Length of fibres with crimps	7.17	Blank	0	10.3	2.8	16.1
		F/P	10.3	0	7.5	5.8
		F/S	2.8	7.5	0	13.3
		F/PS	16.1	5.8	13.3	0
Diameter	3.75	Blank	0	8	11.6	11
		F/P	8	0	3.6	3
		F/S	11.6	3.6	0	0.6
		F/PS	11	3	0.6	0
Max Strain	2.31	Blank	0	1.33	1	2
		F/P	1.33	0	0.33	3.33
		F/S	1	0.33	0	3
		F/PS	2	3.33	3	0

Table 9: Radar area and quality factor values of polyester fibres

Evaluation	Blank	F/P	F/S	F/PS	Optimum
Radar area	20213	20614	16932	20369	27363
Quality factor	.82	.09	.47	.38	
Order	73.87	75.34	61.88	74.44	100
Order	3	1	4	2	-

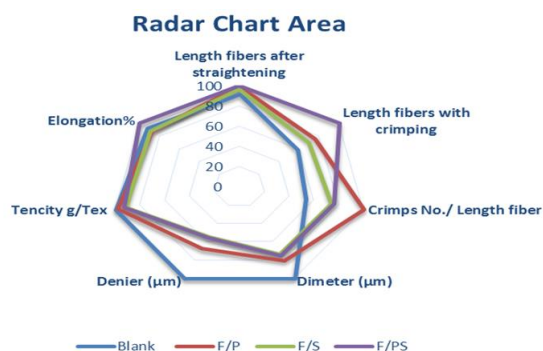


Figure 18: Radar chart for evaluation of polyester fibres

4. Conclusion

This study aims to add a unique and new property to the short and crimps polyester fibres, known as the thermal stability property, using PCM composite material (Octadecane loaded on Pectin or Alginate, or they both together). The covered polyester fibres that can be used in filling for pillows and mattresses or compressed sheets represent that the treatments had a highly significant effect on fibres crimping and diameter properties, while achieved a significant effect on the max strain. Furthermore, it was found that the treatments had no significant effect on fibres' length and tenacity results. Generally, after treatment; the fibres' heat properties were improved, and their conductivity was decreased.

5. Conflict of interest

We confirm that there is no conflict of interest.

6. Acknowledgements

The authors gratefully acknowledge the internal project No. 120306 at National Research Centre for providing the financial support and the availability of various specialized laboratories to conduct the necessary analyzes for this study.

7. References

- [1] S. Fakirov, Biodegradable Polyesters, Wiley-VCH Verlag GmbH & Co. KGaA, Boschstr2015.
- [2] M.A. Ali, N.M. Aly, A.A. Abou El-Kheir, Imparting antibacterial activity, UV-protection properties and enhancing performance of casein modified polyester fabrics, *J. Text. Inst.* (2020) 1-13.
- [3] M.S. Kamal, E. Mahmoud, A.G. Hassabo, M.M. Eid, Effect of Some Construction Factors of Bi-layer Knitted Fabrics Produced for Sports Wear on Resisting Ultraviolet Radiation, *Egy. J. Chem.* 63(11) (2020) 4369 - 4378.
- [4] M.Y. Soliman, H.A. Othman, A.G. Hassabo, A Recent Study for Printing Polyester Fabric with Different

- Techniques, *Journal of Textiles, Coloration and Polymer Science* (on line 2021).
- [5] A.R. Horrocks, S.C. Anand, Handbook of Technical Textiles, Second Edition ed., Woodhead Publishing2016.
- [6] V.A. Goldade, N.S. Vinidiktova, *Crazing Technology for Polyester Fibers*, The Textile Institute Book Series, Woodhead Publishing2017.
- [7] L. Erlam, How to Make a Pillow With Polyfill, *SFGATE* 11(4) (2017).
- [8] Z.M. Elgory, K.M. Seddik, M. Yahia, L.K. El-Gabry, The Enhancement of the Functional Properties of Polyester Microfiber Single Jersey Using Some Nano-materials, *Egy. J. Chem.* 63(1) (2020) 145-154.
- [9] D.M. Hamdy, A.G. Hassabo, pH and Temperature Thermosensitive for Modification of Cotton Fabric (A Review) *Biointerf. Res. Appl. Chem.* 12(2) (2022) 2216 -2228.
- [10] Y. Lin, G. Alva, G. Fang, Review on thermal performances and applications of thermal energy storage systems with inorganic phase change materials, *Energy* 165 (2018).
- [11] S. Zhang, D. Swarhout, T. Noll, S. Gelderbloom, D. Houtman, K. Wall, *Silicone Phase Change Thermal Interface Materials: Properties and Applications*, 2003.
- [12] F. Salaün, *Phase Change Materials for Textile Application*, 2019.
- [13] A.G. Hassabo, *Synthesis and Deposition of Functional Nano-Materials on Natural Fibres* RWTH Aachen University, Germany, 2011, p. 154.
- [14] E. Onder, N. Sarier, E. Cimen, Encapsulation of Phase Change Materials by Complex Coacervation to Improve Thermal Performances of Woven Fabrics, *Thermochemic. Acta* 467 (2008) 63 – 72.
- [15] S.K. Ghosh, *Functional Coatings: by Polymer Microencapsulation*, Wiley-Vch Verlag GmbH & Co. KGaA, Weinheim, 2007.
- [16] N.N. Vijayaraaghavan, G. Duraisamy, Phase changing materials for application in textiles, *Synthetic Fibres* 35 (2006) 11-16.
- [17] N. Sarier, E. Onder, The Manufacture of Microencapsulated Phase Change Materials Suitable For the Design of Thermally Enhanced Fabrics, *Thermochemic. Acta* 452(2) (2007) 149 – 160.
- [18] A.R. Patil, S.U. Patel, H.G. Patil, Theoretical analysis for controlling the system temperature by using phase change material, in: *W.J.o.S.a. Technology* (Ed.) A National Conference on Advances in Mechanical Engineering (NCAME-2012) R. C. Patel Institute of Technology, Shirpur, Dist. Dhule, Maharashtra, India, 2012, pp. 36 - 43.
- [19] A.L. Mohamed, A.G. Hassabo, Review of silicon-based materials for cellulosic fabrics with functional applications, *Journal of Textiles, Coloration and Polymer Science* 16(2) (2019) 139-157.

- [20] H. Fahmy, h. Okda, M. elrafie, A. Hassabo, m.a. youssef, Synthesis and application of new silicone based water repellents, *Egy. J. Chem.* (2021).
- [21] A.L. Mohamed, M.E. El-Naggar, A.G. Hassabo, Preparation of Hybrid Nano-Particles to Enhance the Electrical Conductivity and Performance Properties of Cotton Fabrics, *Journal of Materials Research and Technology* 12 (2021) 542-554.
- [22] R.A. Scott, *Textiles for protection*, Woodhead Publishing Limited in association with The Textile Institute Woodhead Publishing Limited Abington Hall, , Abington Cambridge CB1 6AH England, 2005.
- [23] E. Onofrei, A.M. Rocha, A. Catarino, *Textiles Integrating Pcms - A Review*, *Buletinul Institutului Politehnic Din Iași Publicat De Universitatea Tehnică „Gheorghe Asachi” Din Iași Secția LVI (LX)(2)* (2010) 99 - 110.
- [24] B. Pause, *Textiles with improved thermal capabilities through the application of phase change material (PCM) microcapsules*, *Melliand. Textil. Int.* 81(9) (2000) 753-754.
- [25] A.G. Hassabo, A.L. Mohamed, *Enhancement of Thermo-Regulating Textile Materials Using Phase Change Material (PCM)*, *Evolution in Polymer Technology Journal* 2(1) (2019) 180009 (1-11).
- [26] A.G. Hassabo, A.L. Mohamed, *Enhancement the thermo-regulating property of cellulosic fabric using encapsulated paraffins in modified pectin*, *Carbohydrate Polymers* 165 (2017) 421-428.
- [27] A.G. Hassabo, *New approaches to improving thermal regulating property of cellulosic fabric*, *Carbohydrate Polymers* 101(0) (2014) 912-919.
- [28] B. Mottinger, *Space Hardware Design Final Project*, ASEN 4512, University of Colorad, USA, 1999.
- [29] D.F. Doerr, *Heat Stress Assessment and a Countermeasure*, *Biomedical Laboratory Kennedy Space Center*, West Melbourne, FL 32912-0642, 1997, p. 2.
- [30] E.A. McCullough, B.W. Jones, *A Comprehensive Data Base For Estimating Clothing Insulation*, *The American Society of Heating Refrigerating, and Air-Conditioning Engineers, Inc.*, 1984, p. 161.
- [31] H. Shim, E.A. McCullough, B.W. Jones, *Using Phase Change Materials in Clothing*, *Text. Res. J.* 71(6) (2001) 495-502.
- [32] O. El-Sayed, W. Mousa, A. Zeinert, A. Lahmar, M. El Marssi, I. Battisha, *Calcination temperature effect on dielectric, structural and morphology properties of BaTiO₃ nano-structure prepared by modified sol-gel technique*, *Adv. Nat. Sci.: Nanosci. Nanotechnol.* 11 (2020) 015015.
- [33] M.F.A. Rahman, M.J. Abu, M.F. Ain, J.J. Mohamed, Z.A. Ahmad, *Effect of Calcination Temperature on Dielectric Properties of CaCu₃Ti₄O₁₂ Ceramics*, *Proced. Chem.* 19 (2016) 910-915.
- [34] ISO 139: 2005, *Textiles — Standard atmospheres for conditioning and testing*, *Deutsches Institut fur Normung E.V. (DIN)*, 2019.
- [35] *ASTM Standard Test Method (D276 - 12)*, *Standard Test Methods for Identification of Fibers in Textiles*, 2020.
- [36] *ASTM Standard Test Method (D1445 - 95)*, *Standard Test Method for Breaking Strength and Elongation of Cotton Fibers (Flat Bundle Method)*, 2017.
- [37] S.R. Abulateefeh, M.O. Taha, *Enhanced drug encapsulation and extended release profiles of calcium-alginate nanoparticles by using tannic acid as a bridging cross-linking agent*, *J Microencapsul* 32(1) (2015) 96-105.
- [38] N. Sarier, E. Onder, *Organic phase change materials and their textile applications: An overview*, *Thermochimica Acta* 540 (2012) 7-60.
- [39] A.G. Hassabo, A.L. Mohamed, H. Wang, C. Popescu, M. Moller, *Metal salts rented in silica microcapsules as inorganic phase change materials for textile usage*, *Inorganic Chemistry: An Indian Journal* 10(2) (2015) 59-65.
- [40] S. Mondal, *Phase change materials for smart textiles - An overview*, *Applied Thermal Engineering* 28(11-12) (2008) 1536-1550.
- [41] M.A. Saad, F. Metwally, S.Y. Gad, K.M. Mansour, M.A. Ali, *Effect of using Trilobal® polyester on the functional performance of fencing suit, RJTA ahead-of-print(ahead-of-print)* (2020).
- [42] J. Gaiya, W. Eze, T. Oyegoke, A. Alewo, I. Madufor, T. Bello, *Assessment Of The Dielectric Properties Of Polyester/Metakaolin Composite*, *European Journal Of Materials Science And Engineering* 6 (2021) 19-029.
- [43] J.G. SPEIGHT, *Monomers, Polymers, and Plastics*, *Handbook of Industrial Hydrocarbon Processes* 2020, pp. 597- 649.
- [44] Y. Wilms, S. Fedorovich, N. Kachalov, *Methods of reducing power losses in distribution systems*, *MATEC Web of Conferences* 141 (2017) 01050.
- [45] R.F. El-Newashy, S. Mowafi, M. Abou Taleb, H. El-Sayed, *Enhancing Electrical Conductivity Attributes of Knitted Polyester Fabrics Using ZnO Nano-particles*, *Egy. J. Chem.* 63(9) (2020) 3191- 2198.
- [46] M. Abou Taleb, S. Mowafi, H. El-Sayed, R.F. El-Newashy, *Facile development of electrically conductive comfortable fabrics using metal ions*, *J. Indust. Text.* (2019) 1–21.
- [47] K. Seddik, F. Bassyouni, Z. Elgory, L. El-Gabry, *Characterization of New Coloured Materials on Different Fabrics and Application on Wool fabrics to comfort and Ultraviolet protective garment*, *Egy. J. Chem.* 63(7) (2020) 2751 - 2761.