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Processing and Characterisation of the Copper Treated Polylactic Acid and Cotton Fabrics: Thermophysiological Comfort Properties

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The main objective of this study is to develop a novel copper treatment method and characterise the effect of treatment on the thermophysiological comfort properties of the treated fabrics. It is also aimed to analyse and evaluate the thermophysiological properties of the PLA fabrics. The study was conducted by using polylactic acid (PLA), cotton and their blend yarns. The knitted fabrics, single pique, were made from these yarns by using weft knitting machine. The fabrics were treated with two copper solution concentrations (5 % and 10 %) at 20 minutes ultrasonic energy. The results show that the treatment has a critical effect on the tested fabrics in terms of thermal conductivity, thermal resistance, thermal absorbtivity, water vapour permeability, and heat loss. The results also clearly demonstrated that the PLA fabric was successfully treated with the copper solution, and the coated fabrics showed significant change as compared to their untreated counterparts in terms of tested parameters.

Keywords: thermophysiological properties, ultrasonic energy, treatment, poly (lactic acid) (PLA), knitted fabrics.

1. INTRODUCTION

A wide range of smart products have been successfully produced by different coating methods and commercialised such as fire-retardant fabrics, waterproof fabrics, and biomedical applications. Some of the coated products have been developed to minimise the risk of the bacteria, which occurs in a hospital environment. To prevent forming of reservoirs of bacteria, surfaces such as bed rails, bedside tables and door handles, must be cleaned and disinfected properly. However, some bacteria now have the ability to survive even after thorough treatment with disinfectant [1]. Thus there is a greater need for biocidal surfaces to help reduce cross-contamination. This has led researchers to investigate antimicrobial agents such as copper to produce biocidal surfaces. Copper has been identified as being effective against a broad spectrum of microorganisms such as *Clostridium difficile* [2], *Escherichia coli O157:H7* [3], *Influenza A* (H1N1) [4], *Listeria monocytogenes* [5], and methicillin-resistant *Staphylococcus aureus*.

Polylactic acid (PLA) fibre is one of the fastest growing biodegradable fibre types in the current trends where researchers are actively trying to introduce novel application areas as an alternative source to synthetic fibres. PLA is linear aliphatic thermoplastic polyester derived from 100 % renewable sources such as corn, not like conventional synthetic polymers, which rely on reserves of oil and gas. The monomer used to manufacture PLA is obtained from renewable crops and compostable. Research on textile applications of PLA polymer has recently been reported by several researchers. It has been shown that the PLA fibre has significant commercial potential as textile fibre due to its superior physical and structure properties. Both filament and spun yarns from PLA fibres have been commercialised [6, 7].

Sodium alginate can form a hydrophilic gel when in the presence of divalent cations such as copper (Cu^{2+}) via a unique ion exchange mechanism whereby the sodium ions attached to the carboxyl groups on the uronic acid monomers are exchanged by the copper ions, which subsequently cross-links the alginate chains together, forming a crystalline structure [8]. A number of studies have shown that the ultrasonic energy has many advantages over traditional treatment methods such as superior cleaning, a reduction in the textile processing time, and reduced energy and chemicals [9 – 11].

Thermophysiological comfort has been described as the ability of garment to keep the wearer dry whilst maintaining body temperature even when the wearer is subject to varying surrounding temperatures and humidity.

The comfort has been defined by many; the most popular definitions are "the absence of displeasure or discomfort" and "a neutral state compared to the more active state of pleasure". The comforts of the garment mainly depend on its thermal properties, water vapour permeability and air permeability [12, 13]. The themophysiological comfort properties of fabrics depend on fibre types (natural, synthetic), yarn production method (ring, open-end) and properties (count, twist), fabric structures (woven, knitted, nonwoven) and physical features (thickness, warp-weft number) and also textile finishing process (bleaching, dyeing) [14 – 16].

There are three fundamental ways by which heat energy can be transferred through the porous materials such as knitted fabrics conduction, convection, and radiation. Depending on the fibre's specific thermal conductivities, the size and configuration of the space between the fibres in the knitted specimen, heat transfer mechanisms – conductive, radiative, and convective – will provide very different contributions to the overall heat transfer throughout the specimens. Very complex interactions and contributions of various heat transfer

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mechanisms in the overall thermal properties of knitted fabrics makes the direct instrumental measurement of the thermal conductivity [22].

In this study, PLA, cotton and PLA/cotton knitted fabrics were treated by sodium alginate and copper. Ultrasonic energy was also employed during treatment process. It is aimed to treat the fabrics with copper to render antimicrobial activity. The fabrics were produced with 100 % PLA, 100 % cotton, and 50/50 % cotton/PLA yarns. Untreated (control) and treated fabrics were tested and analysed in terms of thermo physiological (Alambeta and Permetest instruments) properties including thermal conductivity, thermal resistance, thermal absorbtivity, water vapour permeability, and heat loss.

2. EXPERIMENTAL

Materials. Unbleached staple PLA, cotton and cotton/PLA blended ring-spun yarns were procured from the UK market and the yarn counts were determined in accordance with TS 244 EN ISO 2060: 1999. The count of the yarns was found to be Ne 30/2 ±2. Sodium alginate, MANUCOL ® DH, was obtained from Ashland Ltd. (formerly ISP) (SA, medium viscosity (40 – 90 mPas) (1 %), M : G ratio 61/39). Copper (II) sulphate, pentahydrate was obtained from Fisher Bioreagents Ltd., UK.

Manufacturing of knitted fabrics. Single pique (commercially known as Lacoste®) structures were knitted by using laboratory-type of weft circular knitting equipment. The single pique structure is shown in Figure 1 and the technical details of the pique fabrics is explained elsewhere [17].

Copper / alginate treatment. 30 cm × 30 cm fabric specimens were prepared and the specimens were fully immersed into the sodium alginate solution (2.5 % w/v) for 24 hours and then they were rinsed thoroughly with distilled water. After rinsing, the fabrics were then bathed in the copper sulphate solutions of different concentrations, (5 % and 10 % (w/v)) for two hours. Ultrasonic energy was applied to the fabrics under a 25 ºC bathing temperature at 20 minutes. For the ultrasonic application, the ultrasonic bath (Bamdelim Sonorex Digital 10P, 220 volt and 205 watt) was employed using a 10×10 % power. The treated fabrics were rinsed three times in distilled water and finally, the fabrics were left to dry at room temperature for 24 hours.

Thermophysiological comfort. The thermophysiological properties of the untreated (control) and copper treated knitted fabrics were determined by using the Alambeta and Permetest instruments (Sensora Instruments, Czech Republic). The Alambeta instrument provides values for thermal conductivity, thermal resistance (insulation), thermal absorptivity (warmth-to-touch), fabric thickness and thermal diffusivity. The test instrument was used to analyse the transient and steady state thermophysical properties of the fabrics. The specimens of 20 cm × 20 cm were prepared and placed in between two plates. With the two plates the heat flow through the fabric due to the different temperature of the bottom measuring plate (at ambient temperature) and the top measuring plate which is heated to 40 ºC. The thermal absorptivity of the textile structure is a measure of the amount of heat conducted away from structure's surface per unit time. The test was performed on the dry and wet states of the knitted fabrics, which were wetted with 0.2 ml of distilled water in the centre of the fabrics and allowed 4 minutes before retesting, in order to allow for the thermal recovery of the fabric. All tests were carried out on both faces of each specimen and the mean values calculated [18 – 20].

Prior to all the testing, the test specimens were conditioned for 48 hours in 65 % ±2 % relative humidity and 20 °C ±2 °C atmosphere. For each test method, 15 measurements were carried out and the mean values were calculated together, with their standard deviations.

Water vapour permeability and the resistance to evaporative heat loss of the fabrics were tested by using the Permetest Instrument. This instrument is based on the skin model, which simulates dry and wet human skin surface in terms of its moisture, water vapour and evaporative heat permeation.

The instrument uses the same principle as specified in ISO 11092 developed by Hohenstein Institute, whereby a heated porous membrane is used to simulate the sweating skin. The heat required for the water to evaporate from the membrane, with and without a fabric covering, is measured [21].

The workings of Alambeta instrument is shown in Figure 2. The ultra thin heat flow sensor 5 is attached to a metal block 2 with constant temperature which differs from the sample temperature. When the measurement begins, the measuring head 1 containing the mentioned heat flow sensor traverse down and touches the planar measuring sample placed on 4, which is located on the instrument base 3 under the measuring head. In this moment, the surface temperature of the sample suddenly changes and the instrument computer registers the heat flow course.

3. RESULTS AND DISCUSSION

The dimensional properties of the knitted fabrics are given in Table 1. The dimensional properties of fabrics have to be similar due to the Alambeta and Permetest instruments operating systems. Both bulk density and thickness of any tested fabric have a significant influence on results of tested parameters. As seen in Table 1, the differences between the fabrics are negligible.

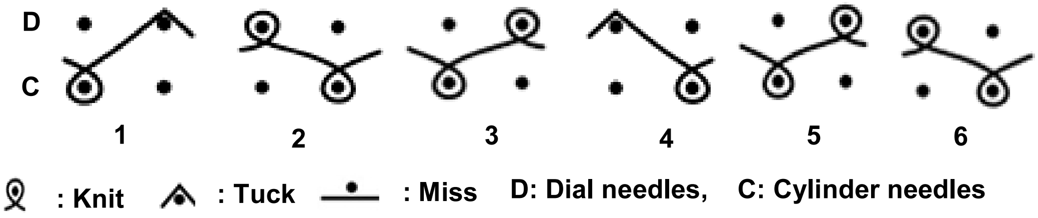

Fig. 1. Single pique knit structure [17]

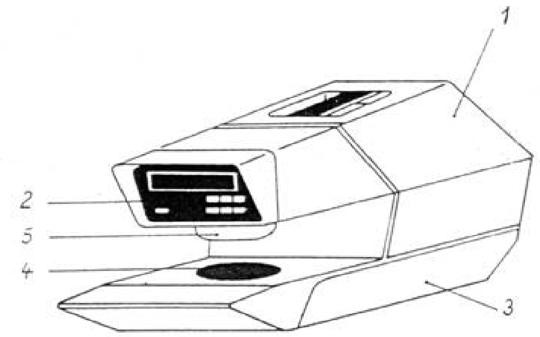

Fig. 2. Schematics of Alambeta Instrument by Sensora, Czech Republic

Table 1. Dimensional properties of knitted fabrics

	Fabric weight (gm^{-2})	Thickness (mm)	Bulk density (gm^{-3})
100 % PLA	284	1.33	0.213
100 % Cotton	291	1.30	0.223
50/50 % Cotton/PLA	261	1.30	0.201

The cotton fabric is found to be slightly bulkier than the other fabrics. The 100 % PLA fabric has higher thicknesses. Besides the PLA/cotton blended fabric has the lowest fabric weight and highest bulkiness. It is also important to mention that the treatment process did not affect the dimensional properties of fabrics tested.

Thermal conductivity of knitted fabrics in dry and wet state. The thermal conductivity of the fabrics was measured by using the Alambeta instrument. It basically gives the amount of heat, which passes from 1 m^2 area of tested structure through the distance 1 m within 1 s and create the temperature difference 1 K. The thermal conductivity can be calculated by using the following expression [23, 24].

$$\lambda = Q/ F\tau\times\Delta T/\sigma, \text{ in } Wm^{-1} K^{-1}, \quad (1)$$

where Q is the amount of conducted heat, F is the area through which the heat is conducted, τ is the time of heat conducting, ΔT is the drop of temperature, σ is the fabric thickness.

The thermal conductivity results are presented in Table 2. Both dry and wet states of fabrics were investigated separately due to the importance of fabric application areas. The thermal conductivity ranged from 37.1 W/mK×10^{-3} to 43.3 W/mK×10^{-3} in the dry state and 55.1 W/mK×10^{-3} to 97.1 W/mK×10^{3} in the wet state. The cotton and PLA/cotton blended fabrics obtained had the highest thermal conductivity values in their dry and wet states for all test combinations. The thermal conductivity of fabric is found to be depending on the fibres into the structure. It has been clearly seen that the presence of cotton fibres within the fabrics increases the thermal conductivity of the structures.

In the wet state of the fabrics, which were wetted with 0.2 mL of distilled water in the centre of the fabrics and allowed 4 minutes before retesting, in order to allow for the thermal recovery of the fabrics, there was significant increase of the thermal conductivity of fabrics associated with the water. Generally, the thermal conductivity of PLA fabrics are found to be lower as compared 100 % cotton and 50/50 % PLA/cotton.

The copper treatment increase the thermal conductivity of the fabrics all cases; besides, the changes are at significant level in the dry and wet states. The cotton fabric which was treated with 10 % copper solution had the highest thermal conductivity as compared to the other combinations. Generally, the 10 % treated fabrics had a slightly higher thermal conductivity in comparison with the 5 % treated fabrics. This is perhaps due to the increase of copper particles on the fabric structures. Other possible reasons could be that due to the ultrasonic treatment and rinsing process as reported in the previous studies [10]. The results, as shown in Table 2, indicate that the thermal conductivities of fabrics were altered after treatment at 5 % and 10 % solutions.

Thermal resistance of knitted fabrics in dry and wet state. The most important characteristic for summer clothing is to keep the wearer drier and cooler and, due to this, the fabrics used to make the garments should have a relatively lower thermal resistance. A higher thermal resistance will cause the wearer to become uncomfortable and extremely warm. The thermal resistance property of the structures depends on the fabric thickness and thermal conductivity. The resistance is expressed by the following relationship.

$$R\ (m^2kW^{-1}) = h(m)/\lambda\ , \quad (2)$$

where h is the fabric thickness, λ is the thermal conductivity ($W^{-1}K\ m^2\times10^{-3}$).

The results obtained from the Alambeta analysis are presented in Table 3. The thermal resistance of the untreated fabrics ranged from 32.9 to 35.3 $W^{-1}\ K\,m^2\times10^{-3}$ for the dry state and from 18.5 to 21.1 $W^{-1}K\,m^2\times10^{-3}$ for the wet state. In the dry and wet states, the untreated cotton/PLA fabric had relatively lower thermal resistance value as compared to the other fabrics. It has been observed that when the fabrics were wetted, the thermal resistance of the fabrics decreased significantly.

The copper treatment influences the resistance properties of fabrics significantly. The treated fabrics had significantly higher thermal resistance than their untreated counterparts. It is interesting to note that in contrast to earlier findings on laundering and comfort relationships, however, it has been also found that the thermal resistance of treated fabrics increases, although the fabrics were washed and rinsed before the retesting [27].

Table 2. Thermal conductivity (λ) of control and treated knitted fabrics in dry and wet states (W/mK×10^{-3})

	Control		5 %		10 %	
	Dry	Wet	Dry	Wet	Dry	Wet
100 % PLA	37.1 ±0.3	55.1	38.5 ±0.3	65.5	38.6 ±0.1	68.4
100 % cotton	41.3 ±0.4	81.5	42.9 ±0.7	95.2	43.3 ±0.2	97.1
50/50 % cotton/PLA	39.2 ±0.7	75.5	41.5 ±0.2	84.6	42.0 ±0.4	86.9

Table 3. Thermal resistance (r) of control and treated knitted fabrics in dry and wet states ($W^{-1}K\ m^2 \times 10^{-3}$) and % recovery after 4 min wetting (%)

	Control		5 %		10 %		% Recovery*		
	Dry	Wet	Dry	Wet	Dry	Wet	Control	5%	10%
100 % PLA	35.3 ±1.5	21.1	69.1 ±2.2	35.1	77.7 ±1.8	40.1	59.8	50.8	51.6
100 % cotton	33.7 ±2.1	18.5	65.3 ±3.1	32.2	74.1 ±2.1	36.7	54.9	49.3	49.5
50/50 % cotton/PLA	32.9 ±0.9	19.1	66.6 ±1.0	34.1	75.6 ±3.2	38.2	58.1	51.2	50.5

* – % Recovery after 4 minutes of wetting = (1 – ((dry – wet)/dry × 100).

The most likely causes of this increase due to the deterioration of fibres' moisture regain because of the copper treatment. The moisture regain has a great influence on wear comfort of fabrics [25]. In general, there was a correlation between thermal resistance and copper concentrations. The differences are noteworthy and 10 % treated fabrics have higher thermal resistance as compared to 5 % treated fabrics. The results of this study indicate that the copper treatment influence the thermal resistance of fabrics, conversely. The untreated fabrics can give relatively drier and cooler feelings when in contact with the skin as compared to the treated fabrics. The findings of this study also suggest that the cotton/PLA blended fabric has superior effects on the fabrics thermal conductivity as compared to their single-fibre fabric forms.

The percentage (%) recoveries of the tested fabrics after 4 min of wetting are given in Table 3. The term % recovery has come to be used to refer to the ability to keep the wearer dry during varying levels of fluids such as sweat. It is assumed that any fabric which has a seventy-five percentages or higher recovery it can get dry quickly. It is obtained from the results that the untreated fabrics have higher percentage recovery values as compared to their treated forms. It was the expected outcome due to the thermal resistance results. The PLA fabric had higher % recovery than the other fabrics. The % recovery is an essential property for the next-to-skin garments and also particularly sports garments; however, the treated fabrics which are not expected to use next-to-skin applications. Rate of drying is one of the main parameters for comfort characteristics of the next-to-skin and sport fabrics. An experimental study on the PLA and PLA/cotton fabrics showed that the PLA fibre containing fabrics would have enhanced thermal comfort properties as compared to 100 % cotton and PES blended cotton fabrics. However, the findings of the current study do not support the previous research [26].

Thermal absorptivity of knitted fabrics in dry and wet state. "Warm-cool" feeling (thermal absorptivity) of fabric is one of the important characteristics for textile garments and this feature is first sensation that is felt when any customer touches the garments, this is a kind of heat transfer between the skin and the fabric surface. Pure fabric 'warm-cool' characteristic can be modified during the textile finishing processes. Lower thermal absorptivity causes a warm feeling and diametrically higher thermal absorptivity value tends to give a cooler feeling. The thermal absorptivity can be measured by an Alambeta instrument and the value and is calculated by the following equation.

$$b = \sqrt{\lambda \times \rho \times c} \text{ in } Ws^{1/2}\ m^{-2}\ K^{-1}, \quad (3)$$

where λ is the thermal conductivity; ρ is the fabric density; c is the specific heat of the fabric.

The thermal absobtivity of the fabrics are given in Table 5. The untreated PLA fabric was observed to have the lowest thermal absorbtivity. The cotton containing fabrics had better thermal absorbtivity. The thermal absorbtivity values of the untreated and treated fabrics in the wet state are significantly higher as compared to the dry state of the fabrics. For instance, the thermal absorbtivity of PLA fabric increase by about 300 % when it is wetted. It is apparent from this table that the thermal absorbtivity of treated fabrics are significantly lower as compared to the untreated fabrics. The difference between 5 % and 10 % treated fabrics are also found to be noteworthy. The 5 % treated cotton and cotton/PLA fabrics had higher thermal absorbtivity than the 10 % treated cotton and cotton/PLA fabrics. Surprisingly, the 5 % and 10 % treated PLA fabric had similar absorbtivity results.

Table 4 presents the results calculated from the dry and wet thermal absorbtivity of fabrics. The percentage loss in warmth-to-touch feeling (% loss) from dry to 4 min wetting values ranged from 160.2 % to 221.2 % for all the tested fabrics. The % loss of the fabrics was influenced in varied ways when treated with copper. The 5 % treated fabrics had a considerably lower thermal conductivity in comparison with the 10 % treated fabrics. The cotton/PLA fabric had significantly lower % loss than 100 % PLA and 100 % cotton fabrics. The higher % loss of fabric can give warm, clammy, and uncomfortable felling to the wearer irrespective of the type and level of activity performed by the wearer [18].

Percentage loss in warmth to touch feeling from dry to 4 min wetting was determined using the following equation:

% loss = (the absorbtivity value of wetted fabric – the absorbtivity value of dry fabric / the absorbtivity value of dry fabric) × 100. (4)

Table 4. Thermal absorbtivity (b) of control and treated knitted fabrics in dry and wet states ($W\ m^{-2}\ s^{0.5}\ K^{-1}$) and % loss in warmth-to-touch feeling from dry to 4 min wetting (%)

	Control		5 %		10 %		% loss		
	Dry	Wet	Dry	Wet	Dry	Wet	Control	5 %	10 %
100 % PLA	95 ±3	275	66 ±5	212	65 ±7	201	189.5	221.2	209.2
100 % cotton	131 ±9	363	98 ±6	255	89 ±2	233	177.1	160.2	161.8
50/50 % cotton/PLA	125 ±7	332	79 ±9	243	72 ±4	229	165.6	207.6	218.1

Table 5. Water vapour permeability (*WVP*) (%) and the resistance to evaporative heat loss *(REHL)* (m^2 Pa W^{-1})

	WVP			*REHL*		
	Control	5 %	10 %	Control	5 %	10 %
100 % PLA	52.1	50.0	49.9	4.7	6.4	7.2
100 % cotton	51.3	50.4	49.6	5.8	6.0	6.3
50/50 % cotton/PLA	52.5	49.4	48.2	5.3	6.0	6.6

Water vapour permeability and resistance to evaporative heat loss (Permetest). The water vapour permeability (*WVP*) depends on the water vapour resistance which indicates the amount of resistance against the transport of water through the fabric structure. The amount of water present in a garment (which has a crucial importance in the level of comfort) must to be a minimum. The relative *WVP* is expressed using the following formula:

$$WVR = Q_s / Q_0 \times 100, \text{ in } \%, \quad (5)$$

where Q_s is the the heat flow with the fabric specimen (Wm^{-2}); Q_0 is the the heat flow without the fabric specimen.

The *WVP* and resistance to evaporative heat loss (*REHL*) results are presented in Table 5. The study of *WVP* and *REHL* was performed by using Permetest instrument. The treated fabrics had lower *WVP* as compared to their untreated counterparts. It is clear from Table 5 that the copper concentrations have a significant effect on the *WVP* properties of the tested fabrics. This is perhaps due to the effect of treatment which could make the fabric structures more close and tight therefore the permeability of treated fabrics decrease drastically. It can be seen from the data in Table 5 that the *REHL* of the treated fabrics were reported significantly higher than the untreated fabrics. The cotton containing fabrics had increased *REHL* as compared to their untreated forms. It is also interesting to note that the untreated PLA fabric had lowest *REHL* value; besides, it had the highest *REHL* after the treatment.

4. CONCLUSIONS

Copper is considered as an antimicrobial agent with useful medical applications in order to develop protection against the risk of the bacteria, which occurs hospital environment. Recently, it has been noted that there are nearly 300 different antimicrobial copper alloys spanning a wide range of applications [26]. In this study, 100 % PLA, 100 % cotton and 50/50 % PLA/cotton fabrics were treated with sodium alginate via a copper sulphate interaction by making use of ultrasonic energy and then the thermal comfort properties of treated fabrics were tested and analysed. The findings from this study make several contributions to the current literature. First of all, the copper treatment by using alginate and ultrasonic energy has been established.

Secondly, the effect of treatment on thermophysiological comfort properties of selected fabrics have been tested and analysed in the dry and wet states. Thirdly, thermophysiological comfort properties of cotton and PLA fibre fabrics have been compared based on the findings.

The results demonstrate that the difference between the untreated (control) and the treated fabrics is significantly important in terms of the tested parameters. The untreated fabrics were found to provide relatively drier and cooler feelings when the fabrics in contact with the skin as compared to the treated fabrics. However, the treated fabrics which were studied in this paper are aimed to use as hospital textiles to protect patients and hospital stuffs against a number of bacteria. In general, the copper concentrations, 5 % and 10 % influence the thermophysiological comfort properties of fabrics drastically.

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