

Ričardas Čiukas
Jovita Abramavičiūtė
*Paulius Kerpauskas

Kaunas University of Technology,
Department of Textile Technology,
Studentų 56, LT-51424 Kaunas, Lithuania
E-mail: Ricardas.Ciukas@ktu.lt
jovita.abramaviciute@stud.ktu.lt

* Lithuanian University of Agriculture
Department of Heat
and Biotechnology Engineering
Studentų 15, LT – 53362 Akademija, Kauno r.
Lithuania
E-mail: paulius.kerpauskas@lzuu.lt

Investigation of the Thermal Properties of Socks Knitted from Yarns with Peculiar Properties. Part I. Thermal Conductivity Coefficient of Socks Knitted from Natural and Synthetic Textured Yarns

Abstract

This study comprised an experimental investigation to determine the thermal properties of socks manufactured using not only traditional cotton yarns but also yarns of new kinds of fibres such as bamboo and soybean protein fibres, as well as blended yarns such as cotton/seacells and bamboo/flax. The influence of different fibres of the socks mentioned on the thermal conductivity coefficient of plain knits and plated plane knits with textured polyamide (PA) or elastane (Lycra) wrapped with textured polyamide thread was investigated. It was determined that a higher thermal conductivity coefficient is characteristic for knits with textured polyamide (PA) thread: lower – for knits with Lycra thread and those from pure yarns. The variation in thermal conductivity depending on the area density, linear density and thickness of plain and plated plain knits was discussed.

Key words: cotton, bamboo, soybean protein fibres, cotton/seacells, bamboo/flax, knitted socks, plated knits, thermal properties, thermal conductivity coefficient.

Introduction

Knitted fabrics not only possess stretch and provide freedom of movement, but they also have good handle and comfort. That is why knitted fabrics are commonly preferred for sportswear, casual wear, underwear and socks. The comfort provided by clothing depends on several factors, one of them being thermal comfort. It is known that fibre type, yarn properties, fabric structure, finishing treatments and clothing conditions are the main factors affecting thermo-physiological comfort [1].

The term comfort is a subjective concept which is only recognised by the person experiencing it. It can be defined as ‘the absence of displeasure or discomfort’ or ‘a neutral state compared to the more active state of pleasure’. A state of comfort can only be achieved when the most complex interactions between a range of physiological, psychological and physical factors have taken place in a satisfactory manner [2]. Hence, the comfort provided by clothing depends on such factors as softness, flexibility, moisture, diffusion, air permeability, thermal comfort, etc.

Human thermal comfort depends on a combination of clothing, climate, and physical activity [3]. The warmth of a fabric is due to insulation provided by air trapped between fibres and yarns. Fabrics from straight filament yarns remove heat rapidly by conduction when

placed next to the skin and in such a way produce a so-called cool feel or handle. This phenomenon occurs just for a moment because the skin adapts rapidly to mild stimulations. Fabrics from hairy yarns feel warm on contact with the skin due to the insulating air held between the fabric fibres and the skin [4]. With the aim of making comfortable socks, we not only used cotton yarns but also a new industrial method of making yarns of soy, bamboo, seacells and their blends with traditional fibres such as cotton and flax. These fibres have a good influence on humans because they are naturally antibacterial and biodegradable, have a high moisture absorption capacity, softness, brightness UV protective properties, good mechanical and physical performances, and antiphlogistic, antiallergic properties [5, - 7].

There have been some researches [8, 9] on the thermal comfort of various fabrics. They all noted that the wickability, air permeability and heat transfer influence the thermal comfort of a garment. Nida Oglakcioglu et al [1] compared the thermal comfort of single jersey, 1×1 rib and interlock structures. The general conclusion of these studies was that 1×1 rib and interlock fabrics, due to their high thermal insulation values, should be preferred for winter garments in order to protect from the cold. Comparing 1×1 rib and interlock fabrics, it would be better to use 1×1 rib fabrics for a warmer feeling on first contact. On the other hand,

single jersey structures should be chosen for active sports or summer garments.

The thermal properties of 1×1, 2×2 and 3×3 rib knit fabrics were compared by Ucar and Yilmaz [10]. They noted that a decrease in the rib number leads to a decrease in heat loss, which may be due to an increase in air entrapped in the fabric, i.e. a bulkier structure. If the structure between the rib knit stitches (front and back stitch) has a flat shape, the use of 1×1 rib and a tight structure would provide better thermal insulation against cold weather.

The thermal contact feeling of fleecy knitted fabrics in four different compositions were investigated by S. Gunesoglu et al [11]. They found that the thermal contact feeling of fleecy fabrics is strongly affected by the raising treatment, which is the final process of making typical fleecy fabrics. The yarn type and fibre blend (pure cotton and PET/cotton) is less important.

However, there have been no investigations on the thermal properties of plain or blended knits for socks from natural yarns and plated knitted socks with textured polyamide (PA) and elastane (Lycra) wrapped with textured polyamide thread in articles. In this paper, not only knitted socks from cotton yarns were investigated but also those from other new 21st century pure yarns such as bamboo and soybean protein fibres, and blended yarns such as cotton/seacells.

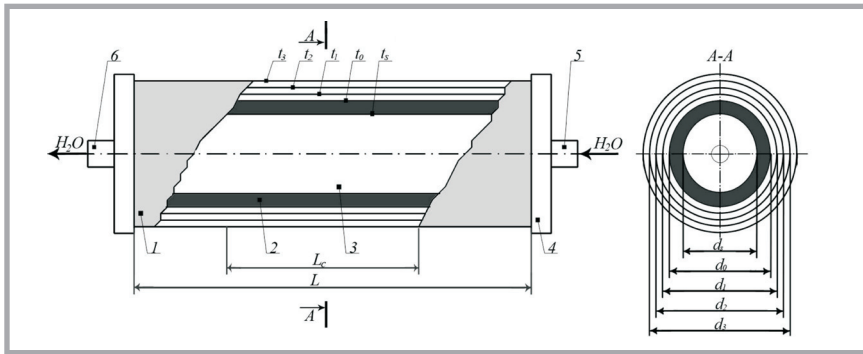


Figure 1. Principle scheme of the temperature measurement device: 1 – multilayer fabric, 2 – glass tube, 3 – distilled water, 4 – thermo insulation material, 5, 6 – incoming and outgoing water pipes, L – width of sample, L_c – part of constant temperature of glass tube, t_s – temperature of inner layer of glass tube, t_0 – temperature of inner layer of fabric, t_1 – temperature of first layer of fabric, t_2 – temperature of middle layer of fabric, t_3 – temperature of outer layer of fabric, $A-A$ – cross-section of glass tube and three layers of samples: d_s – diameter of inner layer of glass tube, d_0 – diameter of inner layer of fabric, d_1 – diameter of first layer of fabric, d_2 – diameter of middle layer of fabric, d_3 – diameter of outer layer of fabric.

Table 1. Results of measurements.

Indication of knitted sample variant		Total linear density, tex	Thickness b, mm	Thermal conductivity coefficient λ , W/mK	Relative error, %
CL	Cotton 14 tex + Lycra 10 tex	24	0.71	0.0344	13.2
BL	Bamboo 14 tex + Lycra 10 tex	24	0.89	0.0390	12.1
SL	Soy 14 tex + Lycra 10 tex	24	0.92	0.0229	4.8
CSL	Cotton + Seacell 19 tex + Lycra 10 tex	29	0.71	0.0232	8.1
BFL	Bamboo + flax 24 tex + Lycra 10 tex	34	0.88	0.0255	9.4
CC	Cotton 14 tex + Cotton 14 tex	28	0.39	0.0329	4.2
BB	Bamboo 14 tex + Bamboo 14 tex	28	0.38	0.0228	10.2
SS	Soy 14 tex + Soy 14 tex	28	0.39	0.0269	5.1
CSCS	Cotton+Seacell 19 tex + Cotton+Seacell 19 tex	38	0.48	0.0293	2.7
BFBF	Bamboo+flax 24 tex + Bamboo+flax 24 tex	48	0.48	0.0296	4.2
CPA	Cotton 14 tex + PA 20	34	0.81	0.0424	4.0
BPA	Bamboo 14 tex + PA 20 tex	34	0.77	0.0559	2.6
SPA	Soy 14 tex + PA 20 tex	34	0.75	0.0509	7.1
CSPA	Cotton+Seacell 19 tex + PA 20 tex	39	0.85	0.0644	1.8
BFPA	Bamboo+flax 24 tex + PA 20 tex	44	0.83	0.0545	7.6
CCL	Cotton 14 tex + Cotton 14 tex + Lycra 10 tex	38	0.79	0.0386	13.1
BBL	Bamboo 14 tex + Bamboo 14 tex + Lycra 10 tex	38	0.92	0.0429	3.3
SSL	Soy 14 tex + Soy 14 tex + Lycra 10 tex	38	0.94	0.0309	2.8
CSCSL	Cotton+Seacell 19 tex + Cotton+Seacell 19 tex + Lycra 10 tex	48	0.97	0.0374	13.1
BFBFL	Bamboo+flax 24 tex + Bamboo+flax 24 tex + Lycra 10 tex	58	0.92	0.0370	4.5
CCC	Cotton 14 tex + Cotton 14 tex + Cotton 14 tex	42	0.55	0.0321	6.9
BBB	Bamboo 14 tex + Bamboo 14 tex + Bamboo 14 tex	42	0.52	0.0336	2.8
SSS	Soy 14 tex + Soy 14 tex + Soy 14 tex	42	0.54	0.0277	3.8
CSCSCS	Cotton+Seacell 19 tex + Cotton+Seacell 19 tex + Cotton+Seacell 19 tex	57	0.69	0.0503	3.5
BFBFBF	Bamboo+flax 24 tex + Bamboo+flax 24 tex + Bamboo+flax 24 tex	72	0.68	0.0380	1.8
CCPA	Cotton 14 tex + Cotton 14 tex + PA 20 tex	48	0.88	0.0604	4.1
BBPA	Bamboo 14 tex + Bamboo 14 tex + PA 20 tex	48	0.90	0.0591	2.3
SSPA	Soy 14 tex + Soy 14 tex + PA 20 tex	48	0.89	0.0492	7.6
CSCSPA	Cotton+Seacell 19 tex + Cotton+Seacell 19 tex + PA 20 tex	58	0.91	0.0448	4.0
BFBFPA	Bamboo+flax 24 tex + Bamboo+flax 24 tex + PA 20 tex	68	0.94	0.0524	4.6

The thermal properties of bamboo/flax were also studied.

Object of investigation

The objects of investigation were the same knits as those described in previous research [5], where the air permeability of pure and plated cotton, bamboo, soy and blended yarns of cotton/seacell, bamboo/flax fibre and their structural parameters (area density, loop length and tightness factor) were reported. For plated knits, textured polyamide PA and elastane (Lycra) wrapped with textured polyamide thread were used. **Table 1** shows the linear density, thickness, and thermal conductivity coefficient of the knits, as well as the relative error of the thermal conductivity coefficient.

All the variants of knits were produced with the same (cotton, bamboo, soy) yarns with a linear density of 14 tex. Combining two or three yarns with PA and Lycra thread allows to obtain knits with the same linear density but of different fibres, and from the same fibre but with a different linear density.

Knits from blended cotton/seacell fibre yarns (19 tex) and bamboo/flax fibre yarns (24 tex) were investigated. As was mentioned before, the same variants of knits from pure yarns, knits plated with elastane Lycra and knits plated with textured polyamide PA thread were manufactured.

Methods of testing and calculation

Thermal conductivity was determined with a measuring device described in [12]. A basic scheme of this device is presented in **Figure 1**. The principal element of this device is glass tube 2, whose ends are insulated with a thermo-insulation material so that the temperature field created by the device would remain unaffected. Inside the glass tube distilled water of 40 °C temperature flows. The temperature of the water is accurately maintained by an impulse thermostat. Sample 1 was wound on the glass tube in three layers. Temperature measurements were then carried out with thermocouples, which were located in five places – on the inside and outside of the glass tube and between every layer of the sample i.e. at points t_s , t_0 , t_1 , t_2 , t_3 . The thermocouples were located according to

methodology of temperature measurement [13]. When the temperature became constant, measurement was registered. Temperatures were registered using an ALMEMO 2590-9 device with micro-processor data processing and accumulation systems. The resolving power of the device is 0.1 °C. The variation coefficient of the temperature measurements did not exceed 3.68 %.

The thermal conductivity of the fabric (λ in W/mK) can be found using the following equation [12]:

$$\lambda = \lambda_s \frac{(t_s - t_0) h \left(\frac{d_3}{d_0} \right)}{(t_0 - t_3) h \left(\frac{d_0}{d_s} \right)} \quad (1)$$

where:

- λ_s - thermal conductivity coefficient of the glass tube,
- t_s - temperature of the inner layer of the glass tube in °C,
- t_0 - temperature of the inner layer of the sample in °C,
- t_1 - temperature of the first layer of the sample in °C,
- t_2 - temperature of the middle layer of the sample in °C,
- t_3 - temperature of the outer layer of the sample in °C,
- d_s - diameter of the inner layer of the glass tube in m,
- d_0 - diameter of the inner layer of the sample in m,
- d_1 - diameter of the first layer of the sample in m,
- d_2 - diameter of the middle layer of the sample in m,
- d_3 - diameter of the outer layer of the sample in m.

By using an indirect method of determining the thermal conductivity coefficient, it is possible to calculate the thermal conductivity coefficient of separate layers of multilayer fabric when the thermal conductivity coefficient of the first layer $\lambda_i = \lambda_s$ is known (determined by equation 1). In this case, the thermal conductivity coefficient of any layer of the fabric (λ_i) is found from the equation 2 [12]:

$$\lambda_i = \lambda_{i-1} \frac{(t_{i-1} - t_i) h \left(\frac{d_{i+1}}{d_i} \right)}{(t_i - t_{i+1}) h \left(\frac{d_i}{d_{i-1}} \right)} \quad (2)$$

where:
i = 2, ..., n.

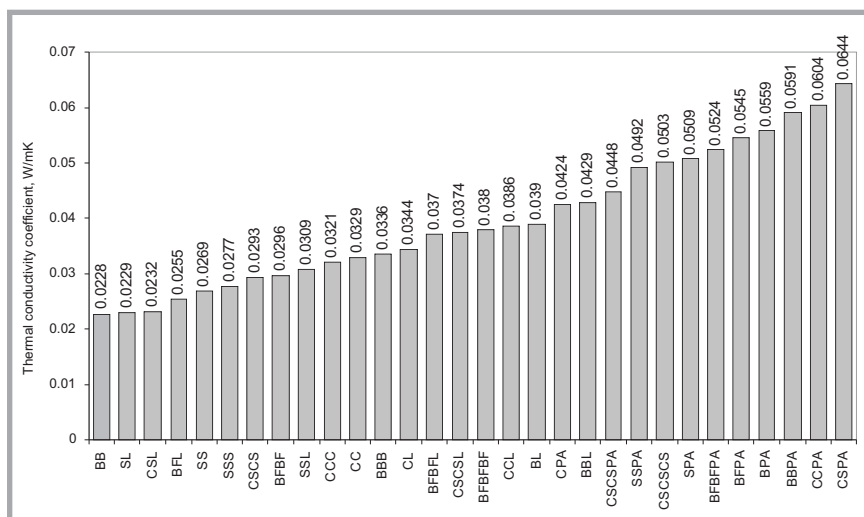


Figure 2. Thermal conductivity coefficient samples of knitted socks.

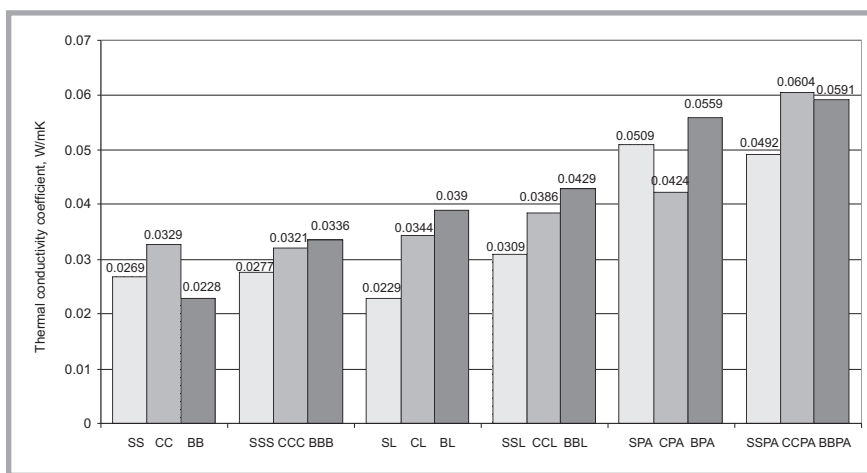


Figure 3. Thermal conductivity coefficient of knits manufactured from soy, cotton, bamboo (linear density XX-28 tex, XXX-42 tex) and their combination with Lycra (XL-24 tex, XXL-38 tex) and textured PA (XPA-34tex, XXPA-48 tex) threads

Experimental results

In this work the thermal conductivity coefficient of socks manufactured from various yarns such as pure, blended and with a combination of textured polyamide or Lycra thread was investigated. Measurements were repeated 6 times at randomly chosen parts of the samples, the average values of which are presented in Table 1 and Figure 2. Relative error values of the thermal conductivity coefficient were calculated and found to range from 1.8 – 13.2 %.

Regarding the thermal conductivity coefficient, the range of values obtained is significant, ranging from 0.0228 to 0.0644 W/mK. As can be seen from Figure 2, knits with textured polyamide thread PA have the highest values (ranging from 0.0424 to 0.0644 W/mK). Lower values have knits manufactured from

pure and blended yarns and their combination with Lycra thread.

Influence of natural fibre yarns on the thermal conductivity coefficient

In Figure 3 we can see the results for knits from pure soy, cotton and bamboo yarns, which are the sixth group with the same linear density of yarns. The first group of knits is (XX – SS, CC, BB) from 28 tex yarns, the second (XXX – SSS, CCC, BBB) – 42 tex, the third (XL – SL, CL, BL) – 24 tex, the fourth (XXL – SSL, CCL, BBL) – 38 tex, the fifth (XPA – SPA, CPA, BPA) – 34 tex, the sixth (XXPA – SSPA, CCPA, BBPA) – 48 tex. From Figure 3 we can see that samples from soy yarns have a lower thermal conductivity coefficient than bamboo, except pure yarns from the first group, where there is a converse variant, and the fifth group (SPA, CPA, BPA), where the ther-

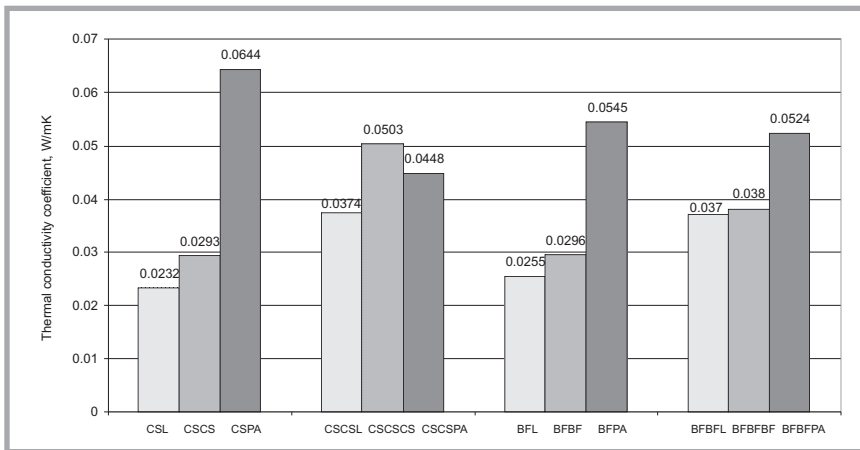


Figure 4. Thermal conductivity coefficient of knits manufactured from Cotton/seacell (CSCS-38 tex, CSCSCS-57 tex), their combination with Lycra (CSL-29 tex, CSCSL-48 tex) and textured PA (CSPA-39 tex, CSCSPA-58tex); Bamboo/flax (BFBF-48 tex, BFBFBF-72 tex), and their combination with Lycra (BFL-34 tex, BFBFL-58 tex) and textured PA (BFPA-44 tex, BFBFPA-68 tex) threads.

mal conductivity coefficient of soy and bamboo yarns are higher than that of cotton yarns. An explanation could be that PA thread (in the structure of pure yarns and those plated with PA thread) comprises more than 50% of all the linear density; such a structure differs from the those of samples from pure thread and that plated with Lycra. The thickness of CPA (0.81 mm) differs from that of SPA (0.75 mm) and BPA (0.77 mm). Comparing the average thickness of all the knit groups, we can see that there are differences between them (I – 0.39 mm, II – 0.54 mm, III – 0.84 mm, IV – 0.88 mm, V – 0.78 mm, VI – 0.88 mm).

In **Figure 4** we can see the results for samples from blended cotton/seacell and bamboo/flax yarns and their combination with Lycra and PA thread. Comparing the thermal conductivity coefficient of knits manufactured from pure CSCS yarns, we can see that it is similar to that of pure CC yarns; however, it increases when the linear density rises. Knits with Lycra thread have a lower thermal conductivity coefficient than those from pure yarns. PA thread greatly increases the thermal conductivity coefficient. Moreover, knits with PA thread – CSPA have the highest thermal conductivity coefficient, which decreases when the linear density increases (CSCSPA – 48 tex). The linear density does not have an influence on the thermal conductivity coefficient of knits from blended and pure yarns; mostly it depends on changes in structure when plated thread is used.

Knits manufactured from bamboo/flax yarns behave like knits from cotton/sea-

cell. The thermal conductivity coefficient of knits with Lycra is lower than that of knits from pure yarns. On the other hand, BFBF knits have a higher thermal conductivity coefficient than those from BB; it increases for plated knits with PA and reaches the highest values in variants of knits from cotton/seacell yarns when the linear density is small (BFPA 34 tex). The thermal conductivity coefficient marginally decreases when the linear density greatly increases (BFBFPA of 68 tex).

On the other hand, the thermal conductivity coefficient does not depend on the linear density but on the structure of the knit, which is dependent on the plated yarns. Samples from pure yarns CSCS – 0.48 mm and BFBF – 0.48 mm have a very distinctive thickness compared with plated knits with a similar thermal conductivity coefficient: CSCSPA – 0.91 mm, CSL – 0.71 mm, BFBFPA – 0.94 mm, and BFL – 0.88 mm, which means that Lycra and PA thread changes the thickness, area density, porosity and thermal conductivity coefficient of knitted samples.

Verification of the correlation between the thermal conductivity coefficient of the samples from pure or blended yarns and their combination with Lycra and textured polyamide PA thread and the area density and thickness was performed. The correlation coefficient for knits from natural yarns and plated knits with textured polyamide (PA) and Lycra thread was calculated. There is a correlation only between the thermal conductivity coefficient, area density ($r = 0.88$) and thickness ($r = 0.83$) of knits manu-

factured from three pure yarns. Besides this, no correlation was found between the thermal conductivity coefficient and factors mentioned when knits from pure yarns plated with Lycra or PA thread were used. This could be explained by the fact that Lycra or textured PA thread change the size and density of the loop.

Conclusion

It was determined that knits manufactured from pure cotton, soy, bamboo yarns and plated knits with Lycra thread have a lower thermal conductivity coefficient. All knit variants with PA thread have the highest thermal conductivity coefficients. As a result, the maximum thermal conductivity coefficient is higher by about 200%, meaning that the thermal conductivity coefficient increases by about 100% for one third of all knit variants with pure and plated with Lycra thread (BBL), whereas the remaining 100% comprises knits plated with textured PA thread.

The thermal conductivity coefficient of blended yarns (CS, BF) changes differently than that of knits from cotton, bamboo or soy yarns. The highest thermal conductivity coefficient was found for knits plated with PA, the lowest – for knits from pure yarns and those plated with Lycra thread. There is a stable tendency of the thermal conductivity coefficient of all variants to increase when there is more PA or Lycra thread in the sample.

The most important influence on the thermal conductivity coefficient is the structure of knits. PA thread increases the thickness of samples, but the area density does not rise; therefore, it is different with Lycra thread. Knits have little thickness, but the area density of the knitted sample increases more. Because of the reversible deformation of elastane, the course and wale density of samples decreases; therefore the knitted sock becomes thicker, and the thermal conductivity decreases as well. The thermal conductivity coefficient could be controlled by changing the raw material composition and linear density of yarns.

Comparing socks knitted from different fibres (cotton, bamboo, soy), the most comfortable socks for a warm season would be those knitted from a combination of yarn with PA thread, as these are characterised by a higher thermal

conductivity coefficient, and the person would feel more comfortable wearing such socks. Socks plated with (Lycra) should be used for a cold season, as these are characterised by a lower thermal conductivity coefficient.

For summer, socks knitted from pure yarns of cotton/seacell or bamboo/flax blends and their combination with textured polyamide could be used. For winter the most comfortable would be socks knitted from a combination of cotton/seacell or bamboo/flax blends with Lycra thread.



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University of Bielsko-Biała
Faculty of Materials and Environmental Sciences
Institute of Textile Engineering and Polymer Materials
ul. Willowa 2, 43-309 Bielsko-Biała, Poland