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Investigation on the Dynamic Water Absorption of Double-Layered Weft Knitted Fabrics

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Abstract
Investigations on the dynamic absorption processes of double-layered knitted fabrics enabled to anticipate the fabric's ability to absorb humidity, transmit it to the next layer and evaporate to the environment, as well as to find the best combination of raw materials and knitting structure of fabrics designed for clothing for active leisure and sport. The main goal of this work was to investigate the influence of knitting structure and raw materials on the dynamics of water absorption in double-layered weft knitted fabrics using the drop wicking/wetting method. It was found that liquid spot dynamics is influenced by the following factors: the raw material, the course and wale density of the fabric, and the fabric knitting structure, i.e. the type of floats between the loops and arrangement of synthetic and natural/man-made loops on the inner and outer sides. The knitted fabrics made of cotton and man-made bamboo yarns (outer layer) and synthetic Coolmax® threads (inner layer) came top, with the fastest water absorption. The knitted fabrics made with a combination of PP threads and cotton yarns (especially the ones with a higher loop density) showed the worst ability to absorb water in the inner layer and to transmit it to the outer layer.

Key words: *dynamic absorption, area of liquid spot, shrinkage, double-layered weft knitted fabric.*

Introduction

Clothing comfort includes three main considerations: thermo-physiological, sensorial and psychological comfort [1]. Thermo-physiological comfort has become an important parameter of clothing especially designed for active leisure. Factors affecting thermo-physiological comfort are numerous: heat exchange within clothing, air permeability, transfer and evaporation of moisture, among others. Clothing must assist the body's thermal control function under changing physical loads in such a way that the body's thermal and moisture management is balanced, and a microclimate is created next to the skin [2]. This physiological effect is extremely important, especially in the case of clothing for sports and active leisure. The human continuously produces heat inside his/her body during all his/her activities because of metabolic processes. With greater physical exertion, and thus a greater level of heat generated by the body itself, heat transfer through clothing is insufficient to compensate for the body's energy balance. As a result, we begin to sweat; the aim being to cool the body through evaporation of sweat on the skin [2, 3].

Natural and cellulose man-made fibres such as cotton, bamboo are hygroscopic and therefore characterised by high absorption levels [4]. The moisture absorbed is bound in strongly and only released slowly. However, cotton fabrics hold absorbed water, and their moisture transfer property is not especially high during activity. This retention of water may increase the weight of the garment as well as impair heat dissipation from the skin and post–activity evaporative cooling [3, 5]. Synthetic fibres such as polyester, polypropylene, polyamide are not hygroscopic and therefore only absorb a comparatively small amount of moisture. However, because of the hydrophilic fibre surface they have a high moisture transfer rate. Synthetic fibre yarns improve the dimensional stability of knitted fabric. A combination of natural and synthetic fibre yarns is an optimal solution to design wear for leisure sports.

Moisture absorption includes the ability of material to retain a liquid in its interstices and pores [6, 7]. Textiles with high liquid sorption qualities, which absorb dyes and chemical finishes, could be used for applications in direct contact with human skin in order to help cool the body by readily absorbing moisture or perspiration. Absorption and permeability properties as well as moisture transmission through textiles are important for textile design and especially relevant for the comfort of clothing [7]. The interaction of liquids with textile could involve some fundamental physical phenomena: wetting of the fibre surface, the transport of liquid into assemblies of fibres, the adsorption of the fibre surface, and the diffusion of liquid into the interior of the material [7 - 9]. Since capillary forces are caused by wetting, wicking is a result of spontaneous wetting in a capillary system [7, 8]. During wicking, flat continuous filament yarns show typical capillary liquid flow due to the number and length of the filaments running parallel to each other. The degree of hydrophility of towel material has already been investigated using the sinking test. It was found that the washing process appeared to be an important parameter in defining the sinking time – in washed fabrics it became lower than that of fabrics which did not undergo any washing procedure [7 - 10].

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Moisture transmission through textiles along with wetting and wicking play a significant role in maintaining thermo-physiological comfort. Scientific understanding of the processes involved in moisture transmission through textile materials, as well as factors affecting these processes and mathematical modelling are significant in the design of new textile systems. In many processing techniques and end-use characteristics, the surface wettability of textiles and technical fibres is a key factor. In dyeing, finishing or coating processes, the wetting properties affect the processing parameters and final qualities of textiles [8 - 11].

Different methods of measuring water absorption are used. The interaction of liquids and textiles depends on the wettability of the textile, its surface geometry, the capillary geometry of the fibrous assembly, external forces, as well as on the liquid amount and characteristics. On the basis of the relative amount of liquid and the mode of liquid-fabric contact, the behaviour of the contact between liquid and textile could be investigated using an infinite liquid reservoir or limited one, as exemplified by drop wicking/wetting into a fabric [12, 13].

The main goal of this work was to investigate the influence of knitting structure and raw materials on the dynamics of water absorption in double-layered weft knitted fabrics using the drop wicking/wetting method.

Object and methods of investigation

Investigations were carried out on double-layered fabrics knitted in a plain plating pattern, with two types of combined structure, on circular knitting machines in a gauge 22E from cotton or man-made bamboo yarns in the outer layer and PP, PA, PES and Coolmax® (tetra–channel fibres by DuPont) yarns in the inner layer. Characteristics of the knitted fabrics tested are presented in ***Table 1***, and the knitting structure – in ***Figures 1*** and ***2***.

All experiments were carried out in a standard atmosphere for testing according to the standard ISO 139:2002. Structure parameters of the knitted samples were analysed according to British Standard BS 5441:1998.

The experiments were performed using a SMZ 800 Nicon Stereoscopic Microscope and Coolpix 4500 Digital Camera; 7.0 PE-Live software was applied for analysis of video records [7]. The absorption process was filmed from the start moment until the last moment, i.e. from the moment when the drop of distilled water (of 1 µl) fell onto the surface of the knitted fabric until it was absolutely absorbed by it. The height of the fall was as minimal as possible, i.e. 1 cm (chosen so that the drop could not touch the dropper and surface of the knitted fabric at the same moment). The test instruments used in the experiments are presented in ***Figure 3***. Two experiments were performed: filming from the upper side of the knitted fabric (see ***Figure 3.a***) and filming from the underside of the knitted fabric (see ***Figure 3.b***). The areas of the liquid spots were measured by investigating pictures of video records, and changes in the spot's area over time were calculated.

Tests were carried out in accordance with ISO 8655 for a piston-stroke pipette with an air cushion, using a fine balance with a moisture trap approved by the standardisation authorities.

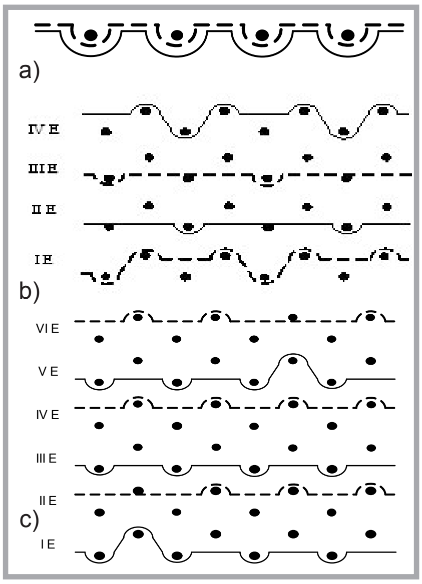

Figure 1. *Pattern of knitted fabrics investigated: a) plain plated single jersey, b) combined I (piqué), c) combined II; —— cotton C or bamboo B yarn, - - - PP, PA, PES, or Coolmax yarn.*

Changes in the dimensions of the knitted fabrics tested after washing and drying were calculated according to the standard ISO 26330:1993.

Table 1. *Characteristics of knitted fabrics tested.*

Sample code	Pattern	Linear density of yarns and percentage composition	Course density A, cm^{-1}	Wale density B, cm^{-1}	Loop length, l, mm	Shrinkage in longitudinal direction, λi, %	Shrinkage in transverse direction, λs, %
LSI–1	Plain plating	Cotton, 20 tex, 71%	24.5	12.5	2.84	1.75±3.04	-21.69±1.23
		PA, 7.8; 29%					
LSI–2	Plain plating	Cotton, 20 tex, 71%	24.5	12.5	2.79	0.56±2.09	-17.81±0.67
		Coolmax, 7.8; 29%					
LSI–3	Plain plating	Cotton, 20 tex, 71%	24.5	12.5	2.79	0.14±0.42	-15.88±2.36
		PES, 8.3; 29%					
LSI–4	Plain plating	Cotton, 20 tex, 71%	25	12	2.88	3.56±0.76	-19.44±1.23
		PP, 8.4; 29%					
LSII–1	Plain plating	Bamboo, 20 tex, 71%	24	12.5	2.85	-5.87±3.01	-17.25±3.56
		PA, 7.8; 29%					
LSII–2	Plain plating	Bamboo, 20 tex, 71%	24	12.5	2.81	-5.00±1.12	-17.81±4.92
		Coolmax, 7.8; 29%					
LSII–3	Plain plating	Bamboo, 20 tex, 71%	24	12.5	2.81	-5.38±2.10	-18.44±2.01
		PES, 8.3; 29%					
LSII–4	Plain plating	Bamboo, 20 tex, 71%	24.5	12	2.93	-1.37±2.0	-19.31±3.35
		PP, 8.4; 29%					
KI–1	Combined I (piquè)	Cotton, 20 tex, 71%	16	12	3.11	-13.75±3.37	-12.88±3.21
		PA, 7.8; 29%					
KI–2	Combined I (piquè)	Cotton, 20 tex, 71%	16	12	3.10	-14.88±1.38	-6.50±4.73
		Coolmax, 7.8; 29%					
KI–3	Combined I (piquè)	Cotton, 20 tex, 71%	16	12	3.10	-16.38±1.89	-4.69±3.62
		PES, 8.3; 29%					
KI–4	Combined I (piquè)	Cotton, 20 tex, 71%	16	11	3.21	-13,88±2.29	-6,37±0.56
		PP, 8.4; 29%					
KII–1	Combined II	Cotton, 20 tex, 76%	15	11.5	3.24	-19.75±2.68	-13.31±3.53
		PA, 7.8; 24%					
KII–2	Combined II	Cotton, 20 tex, 76%	15	11.5	3.26	-15.38±1.65	-7.69±3.53
		Coolmax, 7.8; 24%					
KII–3	Combined II	Cotton, 20 tex, 76%	15	11.5	3.26	-13.63±1.38	-8.56±1.23
		PES, 8.3; 24%					
KII–4	Combined II	Cotton, 20 tex, 76%	15	11	3.35	-15.38±1.38	-9.50±0.92
		PP, 8.4; 24%					

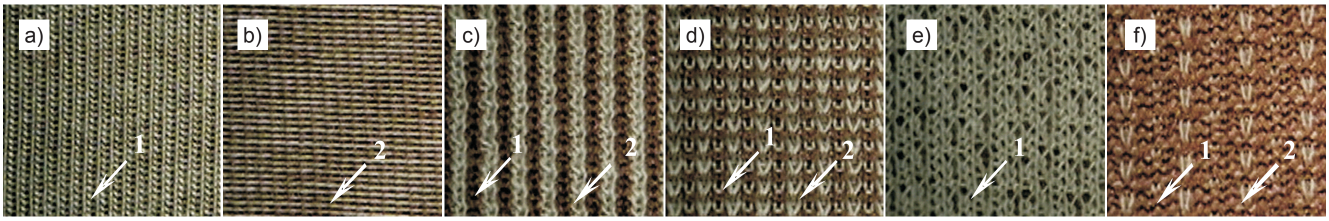

***Figure 2.** View of the surface of knitted fabrics investigated: a) right and b) left side of plain plated fabric, c) right and d) left side of combined I fabric, e) right and f) left side of combined II fabric, 1 - cotton C or bamboo B yarn, 2 - PP, PA, PES, or Coolmax thread.*

Results and discussion

Literature sources present scientific investigations analysing changes in water absorption dynamics in woven and nonwoven fabrics. However, there have been few investigations of the dynamic absorption processes of knitted fabric. In order to analyse the dynamics of a liquid spot on the plain plating designed (LS) and two types of combined structures (KI and KII) of weft knitted fabrics (***Figure 1***), research was carried out following the method presented above (***Figure 3***), where a liquid drop is applied to the inner side of the knitted fabric and the process of dynamic change in the liquid spot is monitored from both the upper side and underside. As soon as the drop is applied to the knitted fabric the monitoring process of the spot spread in the knitted fabric begins. The results revealed that the area of the liquid spot and speed of spreading depend on the knitting structure and raw material of the knitted fabric.

During the filming of weft knitted fabrics of plain plating pattern, it was determined that due to the cotton yarn (outer layer) and synthetic thread (inner layer) combination, the knitted fabric intensely absorbs water for the first 120 seconds, whereas for the knitted fabric made from a man-made bamboo yarn (outer layer) and synthetic thread (inner layer) combination, this occurred for the first 20 seconds. The results are presented in ***Figure 4.a, 4.b***. The process can be best described by logarithmic equations; which usually are chosen for description of relations depending on time. Hence, during the first moments, the moisture is clearly absorbed faster by bamboo knitted fabric; however, when the absorption process becomes slower, after approximately 2 minutes, the area of the spot on the cotton knitted fabric gets bigger. Furthermore, there is a tendency that knitted fabrics with the left side knitted from Coolmax® threads absorb water faster than those knitted from a combination of PA, PES and PP threads, which means that the surface of the Coolmax thread is wetted the most compared with the other synthetic threads investigated. Therefore moisture rapidly spreads in the surface of the knitted fabric and is transmitted to the next – outer layer. Comparing the results of the absorption dynamics of washed and unwashed fabrics knitted in a plain plating pattern (LS), while filming the knitted fabric from above, after monitoring intervals of 5 and 40 seconds, the difference between the liquid spot areas became clearly visible. The monitoring of changes in the dynamics of the liquid spot revealed that fabrics of a cotton or bamboo yarn (outer layer) and Coolmax® thread (inner layer) combination knitted in a plain plating pattern transport water most intensely during the time period of 40 - 180 seconds. Therefore, it is proved that special profile PES fibre Coolmax® strand threads remove moisture from the body surface most effectively.

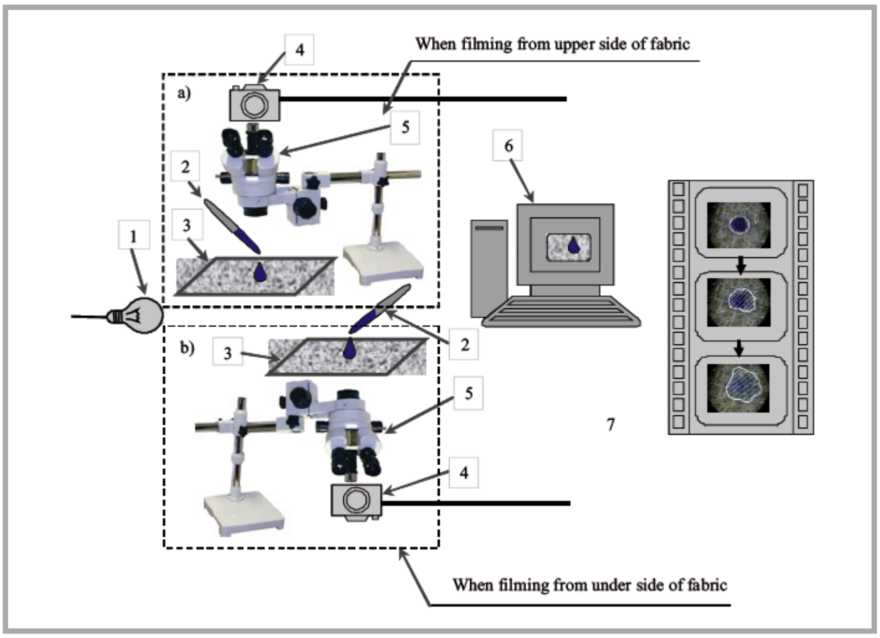

***Figure 3.** Test instruments used in the experiment: 1 - light source, 2 - pipette, 3 - knitted fabric, 4 – digital camera, 5 – stereoscopic microscope, 6 – computer, 7 – pictures of video record.*

After washing, the plain plated knitted fabrics analysed shrank in a transverse direction (approx. 20%), which indicated that the density of loops in the fabrics had increased. It influenced the spreading speed of the liquid spot in the first moments: in the beginning the spot area was clearly bigger than that of the spot on the unwashed fabric, i.e. looser knitted fabric. However, after a minute of monitoring, the liquid spot area had become similar to that on the unwashed knitted fabric (***Figure 4.c, 4.d***). Meanwhile, the washed fabrics knitted from a PP thread combination behaved in a different manner. During the monitoring period, a water drop applied to the fabric knitted of a cotton yarn and PP thread combination was not absorbed by it. Since the loop structure density is greater, the drop stayed on the PP threads without moisturising them and penetrating to the cotton layer. Slower absorption dynamics were also distinguished in washed knitted fabric of a bamboo yarn and PP thread combination. In the first moment (just after the application of the water drop) the spot area was approximately two times small-

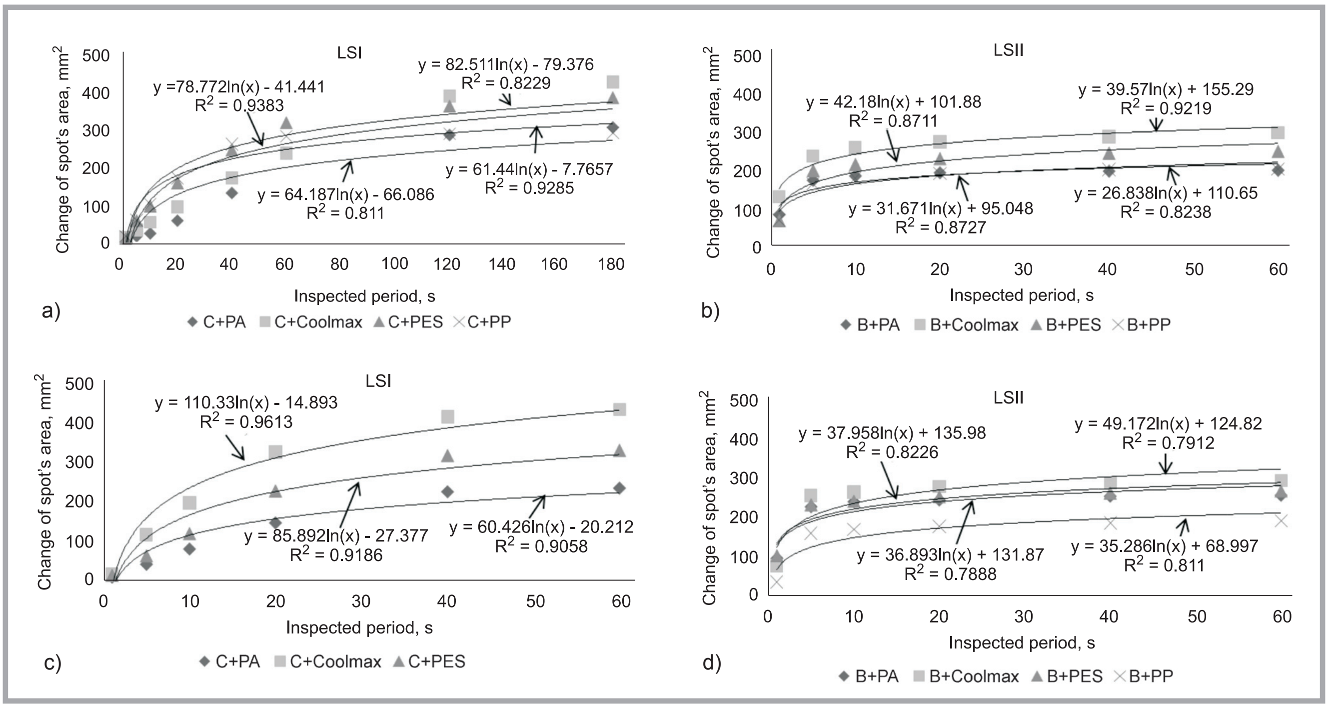

Figure 4. *Dynamic of the liquid spot area of plain plated knitted fabrics obtained by filming from the upperside: a, b – unwashed knitted fabrics, c, d – washed knitted fabrics.*

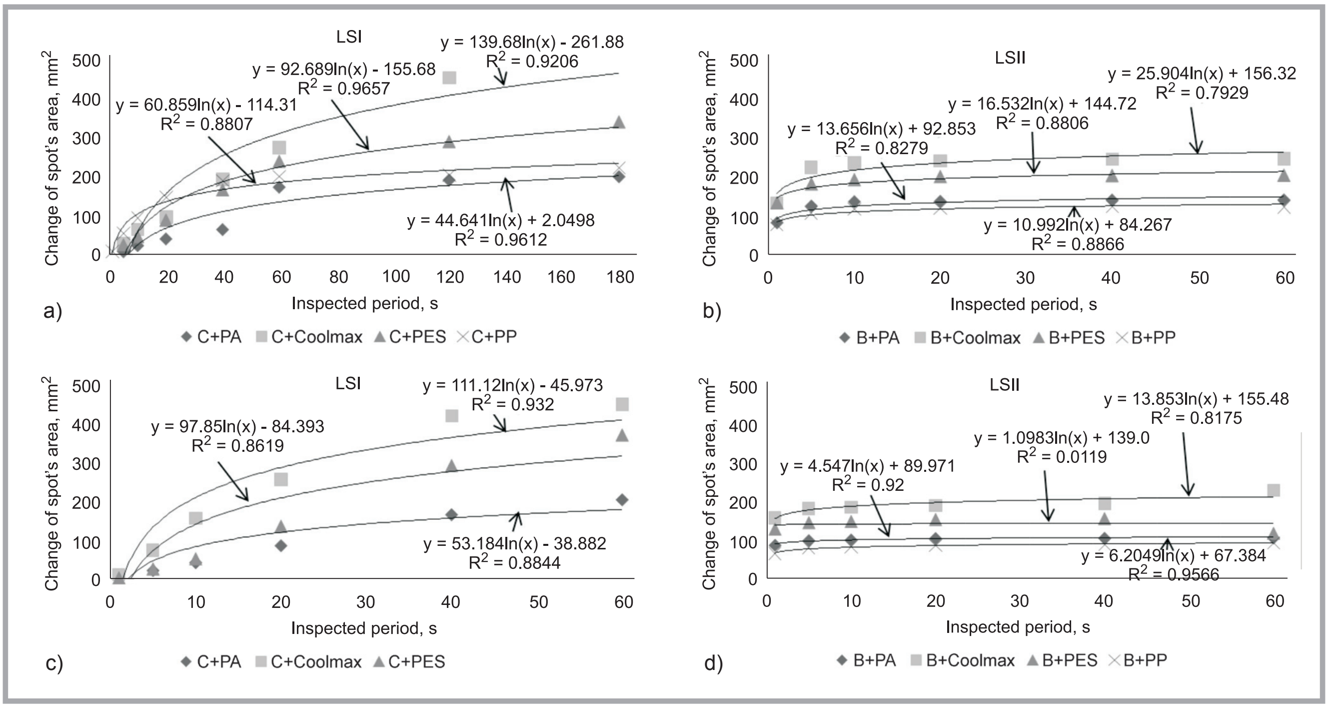

Figure 5. *Dynamic of the liquid spot area of plain plated knitted fabrics obtained by filming from the underside: a, b – unwashed knitted fabrics, c, d – washed knitted fabrics.*

er than on the unwashed one. However, after 5 seconds the sizes of the spot areas on both the washed and unwashed knitted fabrics were only slightly different.

Interesting results were obtained while monitoring the plain plated knitted fabrics from the underside, i.e. assessing the time needed for the liquid spot to appear on the other side of the fabric and the speed of spreading. The results presented in ***Figure 5.a*** show that a water drop soaks through fabric knitted of a cotton yarn and synthetic thread combination in 1 - 2 seconds, with the spot on the surface gradually expanding. ***Figure 5.b*** presents results showing that a water drop soaks through fabric knitted of a bamboo yarn and synthetic thread combination at once and rapidly spreads through the surface. The water soaks extremely fast through fabric knitted of a Coolmax® thread combination. Therefore with a garment sewn from such knitted fabric, the human body feels most dry. Moreover, the largest area of the liquid spot on the outer layer of the

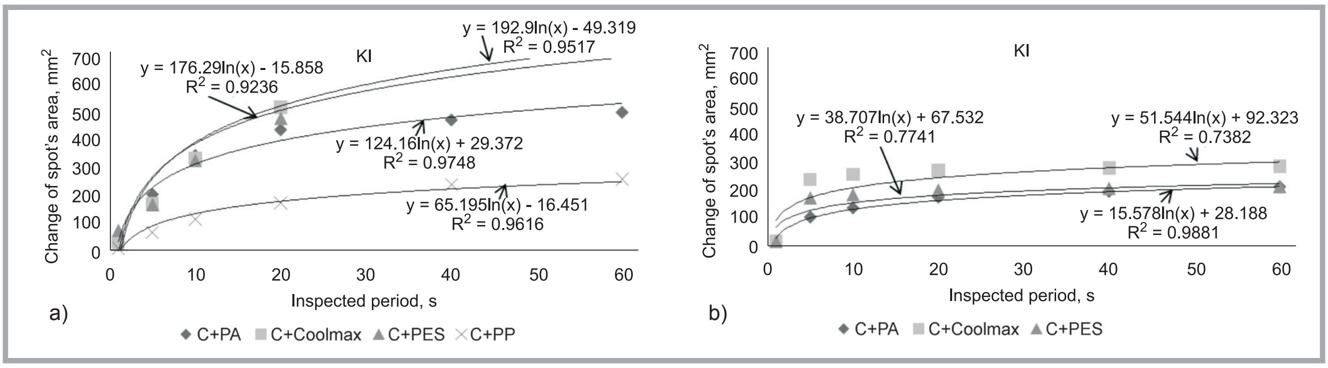

Figure 6. *Dynamic of the liquid spot area of combined (KI) knitted fabrics obtained by filming from the upperside: a – unwashed knitted fabrics, b – washed knitted fabrics.*

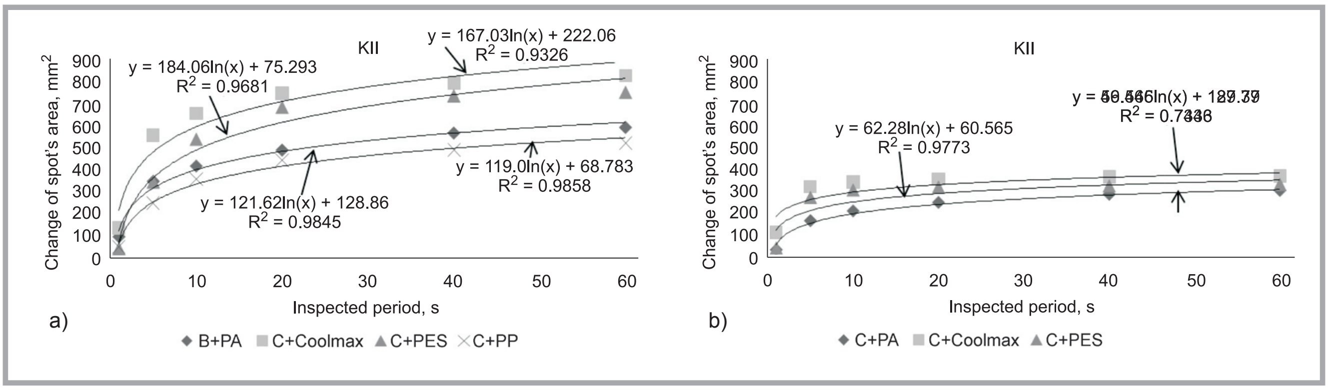

Figure 7. *Dynamic of the liquid spot area of combined (KII) knitted fabrics obtained by filming from the upperside: a – unwashed knitted fabrics, b – washed knitted fabrics.*

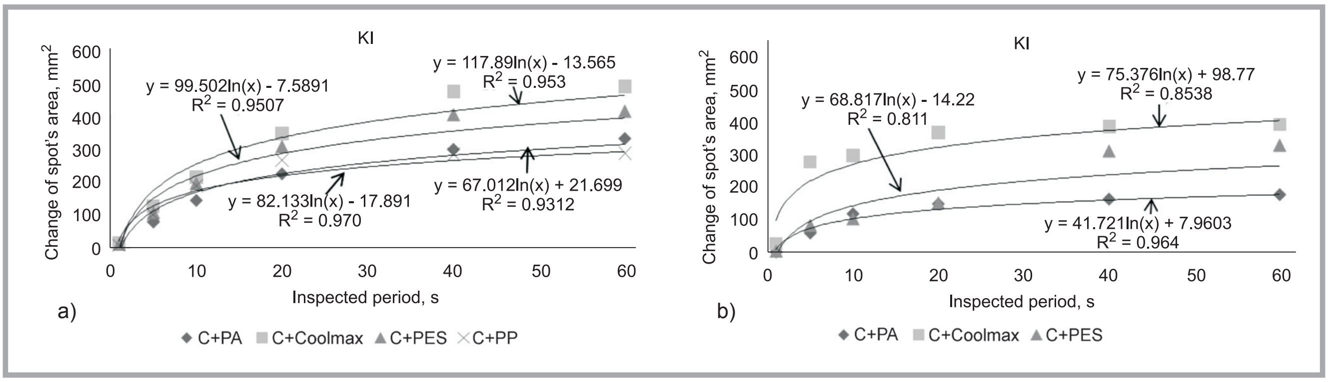

Figure 8. *Dynamic of the liquid spot area of combined (KI) knitted fabrics obtained by filming from the underside: a – unwashed knitted fabrics, b – washed knitted fabrics.*

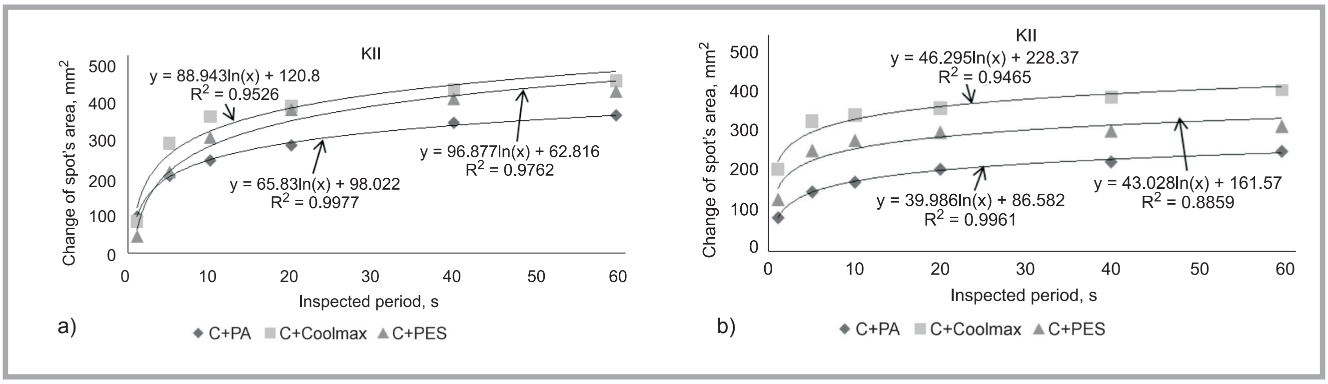

Figure 9. *Dynamic of the liquid spot area of combined (KII) knitted fabrics obtained by filming from the underside: a – unwashed knitted fabrics, b – washed knitted fabrics.*

fabric means that moisture will vapour out most rapidly.

Shrinkage (increased density of loops) has no visible effect on the drop soaking through the knitted fabric at the beginning; however, it affects the dynamics of the change in the spot area over time (***Figure 5.c, 5.d***). In this case, the influence of the raw material of the outer layer on the dynamics of the spot area comes to the forefront. A liquid drop applied to the knitted fabric comes into contact with single strands or naps and penetrates into interstices between them (in the case of the wetting of the surface). When natural fibres are wetted, liquid also penetrates into them, i.e. the fibre swells. The area of the spot on the outer side of fabrics knitted from a cotton yarn and synthetic thread combination rapidly increases for approximately one minute, after which the spreading speed decreases significantly. Meanwhile, the initial area of the spot spread on the outer side of fabrics knitted from a bamboo yarn and synthetic thread combination does not change significantly over time. It is commonly known that bamboo fibre absorbs moisture faster and in greater quantities than cotton fibre. This research has revealed that because of the better hygroscopic features of bamboo fibre, moister penetrates from the inner layer to the outer layer of double-layered weft knitted fabrics of a bamboo yarn and synthetic thread combination faster and at the same time shaping a smaller spot than knitted fabrics of a cotton yarn and synthetic thread combination. Of all the synthetic threads, the most distinctive ones are tetra-channel profile Coolmax threads, transporting moisture from the inner layer to the outer layer at the greatest speed, and PP threads, which are the most hydrophobic of all those investigated in this work. When a water drop is applied to the more dense knitted fabric of a cotton yarn and PP thread combination (***Figure 4.c***), during the monitoring period (2 minutes) the shape of the drop remained the same. In other words, since the wetting degree of PP fibre is very low, the surface tension force of the drop maintains its shape, the surface is not moistened by water and there are no possibilities of transporting moisture to the outer layer, where it would be absorbed by the natural fibre. Therefore, PP fibre thread is not very suitable for the production of clothing for active leisure and sports.

The left side of weft knitted fabrics of combined structure is composed of loops formed of synthetic threads and cotton yarns. Therefore, the structure of the left (inner) side of these knitted fabrics differs from the plain plated weft knitted fabrics (***Figure 2.d, 2.f***). Moreover, the inner and outer layers of this kind of knitted fabric are separate and linked only in a few wales. The results presented in ***Figure 6.a*** and ***Figure 7.a*** show that the dynamics of a liquid spot on weft knitted fabrics of combined structure are faster than in the case of plain plated weft knitted fabrics. In the first moment (10 seconds past the application of a water drop) the area of the liquid spot on the inner side of the combined KI weft knitted fabrics was 3 ÷ 6 times bigger and even 8 ÷ 10 bigger on the combined KII weft knitted fabrics than on the plain plated weft knitted fabric. The dynamics of the spot were different as well: The area of the liquid spot on the weft knitted fabrics of combined structure became steady after approximately 1 minute and on the plain plated weft knitted fabrics (***Figure 4.a***) – after approximately 3 minutes. The area of the final spot on the weft knitted fabrics of combined structure was approximately 2 times bigger than that of the spot on the plain plated knitted fabrics, which was because of the cotton yarn loops formed in the repeat of the weft of the inner layer.

After washing, the weft knitted fabrics of combined structure shrank in both the transverse and longitudinal directions (***Table 1***), and shrinkage in the longitudinal direction was about twice as much as in the transverse direction. It was noted that as the density of the knitted fabrics gets higher, the area of the liquid spot both in the initial period and after the dynamic period is more than two times smaller than that of the spot on the unwashed knitted fabrics (***Figure 6.b***, and ***Figure 7.b***). However, the surface of the washed knitted fabrics of a cotton yarn and PP thread combination was not moistened during the whole monitoring period (2 minutes).

The monitoring of liquid spreading on the outer side of the knitted fabrics (***Figure 8*** and ***Figure 9***) revealed that the area of the liquid spot spread on the surface of weft knitted fabrics of combined structure is similar in size to the spot on plain plated weft knitted fabrics, with the only difference being the speed of the spreading of the spot on the surface. The area of the liquid spot on the outer layer of the unwashed (more loose) plain plated weft knitted fabric became steady after approx. 3 minutes and on the outer surface of the washed (more dense) knitted fabric - after approx. 1 minute. The area of the liquid spot on the outer layer of the unwashed (more loose) combined KI weft knitted fabric became steady after approx. 1 minute and on the outer surface of the washed (more dense) knitted fabric – after approx. 20 seconds. The area of the liquid spot on the outer layer of the unwashed (more loose) combined KII weft knitted fabric became steady after approx. 40 seconds and on the outer surface of the washed (more dense) knitted fabric – after approx. 10 seconds. Obviously the research results were affected by the inter-arrangement of structural elements, i.e. the formation principle of two layers of knitted fabric, presented in ***Figure 2***. The higher dynamics of liquid moving between the layers of fabrics of combined structure were also the result of the presence of ribbed floats. That is, liquid was moving not only between the surfaces of the fibres but also by the longitudinal capillaries of the fibre. All loops of plain plated knitted fabric are set in one row, but every loop is composed of two threads.

The analysis of the results also shows that after the dynamics of the liquid spot area become steady, the area of the spot on both the inner and outer sides of plain plated weft knitted fabric is similar. Meanwhile, the spot area on the inner side of weft knitted fabrics of combined structure is almost two times bigger than on the outer side. Therefore, a body wearing a product made of plain plated weft knitted fabric feels drier than when wearing a product made of weft knitted fabrics of combined structure (when cotton loops are also formed in the inner layer). The areas of the spots in all the weft knitted fabrics analysed are very similar, as well as their possibilities for drying.

Conclusions

- Liquid spot dynamics are influenced by the following factors: the raw material, the course and wale density of the fabric, and the fabric knitting structure, i.e. the type of floats between loops and the arrangement of synthetic and natural/man-made loops in the inner and outer sides. It was found thatIn plain plated weft knitted fabrics with the outer layer made of man-made bamboo yarns, the liquid spot spreads instantaneously and the dynamics of the spot area become steady in approx. 20 seconds, whereas in knitted fabrics with the outer layer made of cotton yarns, the liquid spot spreads gradually, and the dynamics of the spot area become steady in approx. 1-3 minutes, subject to course and wale densities in the fabric.

- When the dynamics of the spot area become steady, the area of the liquid spot on the inner and outer surfaces of fabrics knitted from a cotton yarn and synthetic thread combination is greater than in the case of fabrics knitted from a man-made bamboo yarn and synthetic thread combination. The greater area of the liquid spot means this fabric will dry more rapidly.

- The fabrics knitted from cotton and, bamboo yarns (outer layer), as well as synthetic Coolmax threads (inner layer) came top, with the fastest water absorption. The fabrics knitted from a PP thread and cotton yarn combination (especially the ones with a higher loop density) showed the worst ability to absorb water.

- When the dynamics of the liquid spot area become steady, the area of the spot on both the inner and outer sides of plain plated weft knitted fabric is similar. Meanwhile, the spot area of weft knitted fabrics of combined structure with loops of synthetic threads and cotton yarns on the inner side is almost two times greater than on the outer side. Thus, the sensation of dryness is better when wearing a product made of weft knitted fabrics of plain plated pattern.

- When the dynamics of the liquid spot area become steady, the spot areas in the outer layer of all the weft knitted fabrics (for all corresponding raw materials) analysed are very similar, thus their drying conditions are similar as well.

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