Liquid transfer properties of textile fabrics as a function of moisture content

Milada S. Novaković[1,2], Jovana Milanović[1], Dragana Grujić[3] and Snežana B. Stanković[1]

[1]*University of Belgrade, Faculty of Technology and Metallurgy, Belgrade, Serbia*
[2]*High Technical College of Professional Studies, Zrenjanin, Serbia*
[3]*University of Banja Luka, Faculty of Technology, Banja Luka, Bosnia and Herzegovina*

Abstract

Liquid transport in textile fabrics determines thermal comfort during high physical activity of a person when liquid perspiration is produced and needs to be transferred away from the skin to keep the thermal balance. In this investigation, an attempt was made to get some indications of how the combination of the fabric composition, geometry and dimensional stability, and the moisture content influences liquid transfer properties of plain weft knitted fabrics. Therefore, the knitted fabrics made from pure hydrophilic (hemp fibres), pure hydrophobic (acrylic fibres) and a hydrophilic/hydrophobic (hemp/acrylic) fibre blend underwent a trial wear and care period. The Malden Mills water distribution test was performed for the knitted fabrics with different moisture contents (0-30 %) in order to evaluate the effect on liquid transfer properties. Water transfer ability and water holding capacity of the knitted fabrics were also determined after undergoing the wear trial test. The obtained results were analysed with respect to macro and micro scales of porosity of knitted fabrics. It has been shown that the geometric configuration of the complex porous network in knitted fabrics influenced their liquid transfer properties in the whole moisture content range regardless of the composition. Despite the reconfiguration of the pore system in the knits during the trial period, their liquid transfer properties were still dependent on the pore size and distribution.

Keywords: water distribution test, knitted fabric; hemp; acrylic; transplanar wicking; porosity

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1. INTRODUCTION

Liquid transport in textile fabrics is a critical factor that affects wet treatments of fabrics (dyeing and finishing), filtration properties of medical and industrial textiles, and thermophysiological comfort of apparel. For clothing particularly intended for next-to-skin applications (intimate apparel, sportswear, footwear), it is of crucial importance to achieve the fabric's ability to help in maintaining the heat balance of the human body by creating an adequate microclimate next to the skin even if the physical activity or environmental conditions change. When the core temperature of the human body exceeds 37 °C, sweat (liquid perspiration) is produced covering the skin, and needs to be released away from the skin to reduce the body temperature [1]. The clothing material should transmit, and release sweat to the atmosphere, otherwise skin wetness will increase, leading to the worsening of the overall comfort. The liquid moisture flow through textile fabrics is governed by two sequential processes - wetting and wicking. Wetting is the initial process of liquid migration over the fabric surface toward thermodynamic equilibrium, where the fibre-liquid interface replaces the fibre-air interface. As a result of the entry of water into the capillary system (capillary spaces between fibres), the capillary pressure is generated initiating the wicking process - a spontaneous transport of liquid through capillary channels [2]. During the transfer of liquid through textile fabrics, the wicking process can be accompanied by simultaneous diffusion of water into fibres (water absorption) depending on the fibre hydrophilicity.

Corresponding author: Snežana B. Stanković, Faculty of Technology and Metallurgy, Karnegijeva 4, Belgrade, Serbia
E-mail: stankovic@tmf.bg.ac.rs
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Natural fibres such as cellulosic fibres (cotton, flax, hemp) and wool are hydrophilic, which means that they have bonding sites for water molecules. As a consequence, water absorption by the fibres competes with the capillary action. This may add to dampness, buffering or chilling actions when wearing the garment produced of these fabrics, making it uncomfortable [3]. On the other hand, synthetic fibres such as polyester, acrylic and polyamide being hydrophobic, have low ability to get wet (to take up water from the skin), but good moisture transportation and release [4]. Since neither natural nor synthetic fibres can perform well in the moisture absorption and moisture transmission through the fabric at the same time, various approaches in the research on this subject were attempted to achieve good moisture management properties. One of the approaches is the finishing treatment of textile fabrics for improving moisture management properties [5-6]. To achieve improved moisture absorption and release properties of polyester fabrics, profiled polyester fibres have been developed [7-9] Good performance of textile fabrics in absorbing, transferring and dissipating moisture can be also achieved by blending hydrophilic and hydrophobic fibres. Combination of hydrophilic and hydrophobic fibre types in textile fabrics has been performed by using blended [10-12] or composite yarns [13] or by combining yarns when producing the fabric [14]. Zhu and Takatera [15] investigated the effect of hydrophobic yarns on liquid migration in woven fabrics produced from two different yarns, one being hydrophilic and the second one made of hydrophobic fibre or of a mixture of fibres (cotton/polyester). The possibility of combining different properties such as hydrophilic and hydrophobic by producing two-layer woven [16] or knitted [17-18] fabrics has already been accepted in practice. Two distinct layers (face and back side) of knitted fabrics can be obtained by producing a plated structure – a specially designed structure with different fibre types in each layer. In our investigation, the combination of hydrophilic and hydrophobic yarns was achieved by simultaneous formation of the loops from two yarns [19]. This is similar to the plating technique, but unlike the plated structure, in our knitted fabrics two different yarns are randomly arranged on the face or back of the knit. For the hydrophilic component, the hemp yarn was chosen as a more eco-friendly alternative to cotton with very good predispositions for production of comfortable, high-added value products [19-23]. Hemp has been a source of fibre for technical and clothing textiles for centuries, however, due to the large-scale cultivation of cotton and the advent of synthetic fibres the hemp cultivation declined. Today's trend for searching alternative renewable and biodegradable fibre sources has attracted considerable interest in hemp as eco-friendly and healthy fibres [24]. Acrylic yarn was chosen for combining with the hemp one due to a low moisture regain of acrylic fibres (1.5 – 2.5 %) [25] and fast drying ability [26]. There are other synthetic fibres with the ability to dry faster than acrylic ones, but acrylic fibres were confirmed to offer some good comfort performance to textile materials due to their porosity, softness and good liquid management properties [27-28]. There are a very limited number of studies on the liquid management properties of hemp [29-31] and acrylic [10,28,32-33] textile fabrics, and this is the first investigation dealing with the liquid transfer properties of hemp/acrylic blended textile fabrics. Since clothing textile materials are intended for repeated use and care cycles, they should retain the ability to transfer liquid during subsequent uses. Although the importance of this issue was recognized by the scientists, there have been a very limited number of investigations on the effect of repeated laundering on the liquid management properties of textile fabrics [34-37]. Given that knitted fabrics are very prone to structural changes not only due to laundering but also as a consequence of the mechanical stresses during wearing, the effects of repeated wear and care cycles of knitted fabrics on their liquid transfer properties have been the subject of this study.

In transient (non steady-state) wear conditions when liquid perspiration occurs and have to be rapidly managed by the fabric, the process of wicking competes with the process of liquid absorption by hydrophilic fibres or spreading of the liquid if the fabric is hydrophobic. Competition between these two phenomena continues until the steady-state rate of liquid regain and liquid transfer is achieved. Duration of the non steady-state behaviour is dependent on the fibre type and moisture transfer ability of the fabric [38]. According to the literature [39], hemp fibres can absorb up to 30 % of water. In addition, it has been reported that textile fabrics can absorb up to 30 % of water under real wearing conditions (absorbed liquid sweat or moisture originating from the humid air) [1].

It has been shown that moisture accumulation within textile fabric strongly affects its thermal comfort sensation [40-41]. Various investigations indicated that the thermal insulation and water vapour permeability of textile fabrics were influenced by moisture content in the fabric [42-49]. Bearing this in mind, it seems reasonable to expect that moisture content in the fabric affects its liquid transfer properties. Therefore, in this study an attempt was made to investigate the liquid transfer properties of knitted fabrics having up to 30 % moisture accumulated.

2. EXPERIMENTAL

During the transient period, the liquid transfer process interacts with the moisture which has been already accumulated within the fabric as free water in the pores or absorbed by the fibres. To analyse this, the Malden Mills (Polartec® LLC, USA) water distribution test [50], with some modifications, was chosen to use in this study. This is the transplanar wicking test which is more realistic as compared to the longitudinal wicking ("strip") test, since water transport in clothing is generally transplanar to the fabric plane. The liquid transfer properties of knitted fabrics were expressed by two parameters: water transfer ability and water holding capacity. The experimental approach included a trial period (repeated wear and care cycles) of the knitted fabrics and the evaluation of their liquid transfer properties after a period of usage.

The plain weft knitted fabrics used in this research were produced from hemp (Linificio Canapificio Nazionale, Italy) and acrylic, PAN (poly(1-acrylonitrile)), (Pirotex, Serbia) yarns both having linear density of 50 tex (mass of the yarn in grams per 1000 m) and 400 m^{-1} twist (turns per 1 m of the yarn). Geometry of the yarns is presented in Table 1. Diameter of the hemp and acrylic yarns, as well as those unravelled from the wet relaxed knits, was measured by using a Nikon SMZ800 stereomicroscope (Nikon Instruments Inc., USA). The average diameter values were calculated from 50 readings. The bulk density of the yarns was calculated according to the following equation:

$$\rho_{\mathrm{y}} = \frac{4T}{d^2 10^3 \pi} \tag{1}$$

where T / tex is the yarn linear density, and d / mm is the yarn diameter. By knowing the bulk density of the yarns, their packing density was calculated as the ratio of the yarn's bulk density and the fibre density (1.5 g cm^{-3} for hemp and 1.2 g cm^{-3} for acrylic). Hairiness of the yarns was measured by using an SDL 103 hairiness monitor device (Shirley Developments Ltd., UK). The hairiness was registered on the traveling yarn in 5 s intervals and later was reduced to 1 m of the yarn length. Thirty readings were taken for both yarns and the average values of the hairiness were calculated.

Table 1. Geometry parameters of the hemp and PAN yarns

Parameter	Hemp	PAN
Diameter (SD)[a], mm	0.22 (0.02)	0.28 (0.03)
Bulk density, g cm^{-3}	1.258	0.791
Packing density	0.84	0.66
Hairiness (SD), m^{-1}	3.4 (1.1)	63.5 (5.5)

[a] standard deviation for experimentally tested parameters

To obtain a blended knitted fabric, the hemp and PAN yarns were assembled (joined together) on a knitting machine (F-W F & P, Germany) so as to obtain 50 % hemp / 50 % PAN knit. Pure (100 %) hemp and PAN knitted fabrics were obtained by knitting two hemp and two PAN yarns, respectively, under the same knitting settings. The knitted fabrics were dry relaxed by keeping them flat under standard atmospheric conditions (20 ± 2°C, 65 ± 2 % R.H.) for 72 h. The pieces of the knitted fabrics were rinsed with warm water (40 °C) and dried flat at room temperature to relax their structure. Construction characteristics of the wet relaxed knits are shown in Table 2.

Table 2. Construction characteristics of the wet relaxed knitted fabrics

Parameter	Hemp	Hemp/PAN	PAN
Course density (SD)[a], cm^{-1}	13.6 (0.5)	12 (0.3)	10.4 (0.5)
Wale density (SD), cm^{-1}	6.2 (0.2)	6.1 (0.2)	6.9 (0.1)
Stitch density, cm^{-2}	84.3	73.2	71.8
Thickness (SD), mm	0.957 (0.032)	1.022 (0.038)	1.092 (0.037)
Areal density (SD), g m^{-2}	415 (20.2)	376 (6.2)	378 (4.8)

[a] standard deviation for experimentally tested parameters

A plain weft knitted fabric is formed by a matrix of the same loops (stitches). Course density is determined by the number of courses (rows of loops) in a unit length of fabric. The number of wales (columns of loops) in the unit width of fabric is the wale density. The product of the course and wale densities yields the number of loops per unit area of the fabric giving the loops or stitch density. Thickness of the knitted fabrics was determined according to the standard ISO 5084 [51]. Areal density (mass per unit area) of the knits was obtained by weighing 10 $\times$ 10 cm sample on a torsion balance calibrated in g m^{-2}. Ten specimens of each knit were taken for the test. To assess the geometry of the knitted fabrics, the porosity, open porosity, planar and volume stitch moduli were calculated. Then porosity of the knits P / % can be calculated as

$$P = 100 - \frac{\rho_k}{\rho_f}100 \tag{2}$$

where ρ_f is the fibre density, and ρ_k is the bulk density of the knit. Open porosity O / % of the knits was calculated by the following equation:

$$O = 100 - \frac{\rho_k}{\rho_y}100 \tag{3}$$

The planar stitch modulus (σ_P), which shows the ratio of the surface of a stitch and the surface occupied by the yarn forming the stitch, and the volume stitch modulus (σ_V), which indicates the ratio of the volume of a stitch and the volume occupied by the yarn, which forms the stitch, were determined by the following equations [52].

$$\sigma_P = \frac{AB\sqrt{\pi\rho_Y}}{2l\sqrt{T}} \tag{4}$$

$$\sigma_V = \frac{4ABt}{\pi d^2 l} \tag{5}$$

where A / mm is the width of the stitch, B / mm is the height of the stitch, l / mm is the yarn length in the stitch, and t / mm is the thickness of the knit.

To measure the liquid water transfer ability of the knitted fabrics while varying their moisture content, the knit samples were pre-processed before conducting the measurement. The samples (5 $\times$ 5 cm) were dried by a moisture analyser (MA 50.R, readout accuracy 0.001 %, RADWAG, Poland) in order to remove all moisture, and each sample was soaked in distilled water (20 $\pm$ 1 °C) for 2 h. The sample was considered wet-out at the condition when air bubbles were not produced upon squeezing the sample under water. The wetted sample was laid flat between dry paper towels until water stopped dropping out of them. Then the sample was kept flat under standard atmospheric conditions and dried for some time (15 min) to reduce the moisture content but not less than 30 %. The measurement of liquid transfer through each knit was performed while the moisture content in the sample was varied in 5 % steps starting from 30 % to the ultra-dry state or 0 % of moisture (in dry or normal state all textile fabrics contain some amount of moisture). The various stages of sample wetness were achieved using the moisture analyser. To ensure reliable results an effort was made to perform the liquid transfer measurement as quickly as possible in order to keep the moisture content in the wet sample approximately constant. The Malden Mills water distribution test enabled measurements within a few minutes for every moisture level. According to the procedure, a 5 $\times$ 5 cm square fabric sample was placed horizontally on a piece of filter paper (F2040 grade quantitative ashless, Chmlab Group, Spain), which was previously weighed and placed with the absorbent side up on an impermeable flat surface. The fabric sample was placed with the left side (technical back) up because this side is most often in contact with the skin in clothing. After 2 ml of water was delivered uniformly by a pipette over the sample surface, and left for 2 min to stabilize, the sample was covered by another previously weighed filter paper with the absorbent side down to be in contact with the sample surface. A piece of plexiglass was placed over the paper-sample-paper sandwich, and 500 g metal weight was centred on top of it. After 1 min, the weight and plexiglass were removed, and masses of the filter papers were recorded. The short manipulation time made it possible to minimize the error of measured filter papers (±0.0002 g). The difference between masses of the wet and dry filter papers indicated the mass of water absorbed by each filter paper. In fact, the mass of water absorbed by the lower filter paper was an indication of the water transferred through the sample. Therefore, the ratio of the transferred water mass (water absorbed by the lower paper) to the total water absorbed by both filter papers was defined as the water distribution value, which indicates the water transfer ability. The higher the water distribution value, the higher the water transfer ability. The experiments were done in triplicate. The ability of the knitted fabrics to pick up moisture during the Malden Mills test and retain it within the structure was determined as the mass of water kept by the sample or the water holding capacity. This parameter was calculated by subtracting the total mass of water absorbed by both filter papers from the total mass of water applied to the sample.

From wet relaxed pieces of the knitted fabrics three undershirts (sleeveless shirts) were sewn to be used in the wear trial tests in which ten volunteers participated. The volunteers were wearing each undershirt (pure hemp, hemp/PAN and pure PAN) for five days in real life situations. Before each trial, the undershirts were washed in warm water (40 °C) using a commercially available detergent Perwoll Wool & Delicates (Henkel GmbH, Austria), line-dried and ironed by an electric iron (120 °C). Every undershirt underwent ten wearing (by ten volunteers) and care cycles. One cycle involved wearing the undershirt for five days (5 h a day), washing, drying and ironing. The diameter and bulk density of the yarns as well as the construction and geometric parameters of the knitted fabrics after undergoing the wear trial tests were determined as described above. The Malden Mills water distribution test was repeated on the knits after the trial period. The specimens of the knitted fabrics were cut from the back of the shirts.

2. 1. Statistical analysis

Paired t-test was performed to evaluate the significance of the effects of the wear and care process on the liquid transfer properties of the knitted fabrics. When the t-value falls within the critical region defined by the critical t-value ($t > t_{crit}$), provided the p-value (probability value) is less than α = 0.05 (confidence level 95 %), a change in the measured characteristic after the treatment (wear trial tests) is considered statistically significant. Analysis of variance (ANOVA) with a confidence level of 95 % was performed to obtain the *F* (*F*-distribution) and p values for all samples. $p < 0.05$ was considered significant for the statistical evaluation of the results. The null hypothesis for this test (that the means are equal) can be rejected when $F > F_{crit}$.

3. RESULTS AND DISCUSSION

Although it is generally accepted that knitted fabrics undergo major dimensional changes during wet relaxation, it has been proved that the structure is modified over up to seven washing cycles [53]. On the other hand, Heap *et al.* [54] have shown in their project that the shrinkage of knitted fabrics throughout wearing is noticeably lower as compared to the shrinkage measured during the laboratory washing procedure. This is to be expected as a consequence of repeated stretching of the knitted fabric during periods of wearing the garment. Bearing this in mind, it seems reasonable to expect that for the wear trial test, ten cycles are sufficient not only to reach the dimensional stability of the knitted fabrics, but also to evaluate changes in the behaviour of the knits regarding the liquid transfer ability.

3. 1. Structural characteristics of the knitted fabrics

Construction characteristics of the knitted fabrics after the wear trial test, presented in Table 3, indicated that hemp-containing knitted fabrics underwent some changes – an increase in the surface stitch density, thickness and areal density. Supposing that in the wet relaxation procedure the yarns were released from tension, which was imposed on them during knitting [54], changes in construction characteristics of the knitted fabrics exposed to the wear trial test can be attributed to two simultaneous but opposing processes occurring in the course of the wear and care cycles. One of the processes is consolidation of the knit structure due to yarn swelling (described latter in the text) and the lubricating effect of water during washing. This water lubricating effect results in a reduction in frictional forces at the interlacing points in the knitted fabrics, which is additionally promoted by extra energy supplied by mechanical action during laundering. The other process, opposing the first one, is the reconfiguration of loops resulting from the mechanical deformation (extension, bending, compression, and shear) of the knitted fabrics during wearing. Described processes counteract each other in all repeated wear and care cycles. Bearing this in mind, unchanged both stitch and areal densities of the PAN knitted fabric after the wear trial test can be explained by the balance between the consolidation (shrinkage) and reconfiguration (re-stretching) processes. Thickness of the PAN knit exposed to the wear trial test was reduced, which could be attributed to its compression during laundering and ironing cycles. As a consequence of being made of hydrophilic fibres, the hemp yarn underwent significant changes (swelling and contraction) during washing the hemp-containing knitted fabrics due to which their loops were distorted. This migration shrinkage of the hemp-containing knitted fabrics was manifested by an increase in their stitch density and thickness (Table 3). The increased stitch density of these knits resulted in the increased areal density.

Table 3. Construction characteristics of the knitted fabrics after the wear trial test

Parameter		Hemp	Hemp/PAN	PAN
Stitch density	Course (SD), cm^{-1}	12* (0.4)	12 (0.3)	11 (0.3)
	Wale (SD), cm^{-1}	8* (0.2)	7* (0.2)	6.5 (0.1)
	Stitch density, cm^{-2}	96	84	71.5
Thickness (SD), mm		1.042* (0.038)	1.055* (0.032)	1.056 (0.054)
Areal density (SD), g m^{-2}		477*(9.6)	438* (5.5)	376 (4.5)

*statistically significant regarding the values of the wet relaxed knitted fabrics

Not only did the knitted fabrics undergo changes during the period of wearing and care of the undershirts, but also the hemp and acrylic yarns underwent changes in their geometry. As can be seen in Table 4, diameters of both yarns increased, and bulk densities decreased after the wear trial test, which resulted in lower fibre packing densities (lower fibre volume fraction in a unit volume of the yarn). An increase in the hemp yarn diameter, and hemp fibre rearrangement, can be expected due to repeated swelling of the yarn during care treatments. On the other hand, due to hydrophobic characters of the acrylic fibre, swelling of the PAN yarn was unlikely to happen, and therefore the increase in the PAN yarn diameter may be the result of soft acrylic fibres that were initially protruding from the yarn surface, while during the wear trial test adhered to the yarn body. This is illustrated by SEM micrographs in Figure 1. The projecting PAN fibres are less apparent on the surface of the knit after the wear trial test. Bearing in mind that during wearing and washing processes the loss of fibres from fabrics can be expected, some fall-out of fibres has probably occurred during the trial period and some fibre ends can be seen on the micrograph (Fig. 1b). However, the same micrograph also illustrates partial closing of open pores in the knit (in the middle of the micrograph) caused by the PAN fibres which were reoriented in the plane of the knit after the test. If the softness of PAN fibres is taken into consideration, it seems reasonable to believe that most of the fibres have rearranged in the plane of the knit. This hypothesis also arose from the increased compressibility of the acrylic knit that was repeatedly exposed to wear and care cycles [55]. In the case of the hemp yarn, only a small amount of the fibre fall-out is believed to occur due to extremely reduced hairiness of the yarn (Table 1).

Table 4. Geometry of the yarns after wet relaxation and the wear trial test of the knits

Parameter		Hemp	PAN
Diameter (SD), mm	Wet relaxed	0.23 (0.04)	0.28 (0.04)
	After the wear trial test	0.24 (0.03)	0.30 (0.04)
Bulk density, g cm^{-3}	Wet relaxed	1.151	0.791
	After the wear trial test	1.014	0.689
Packing density	Wet relaxed	0.77	0.66
	After the wear trial test	0.68	0.57

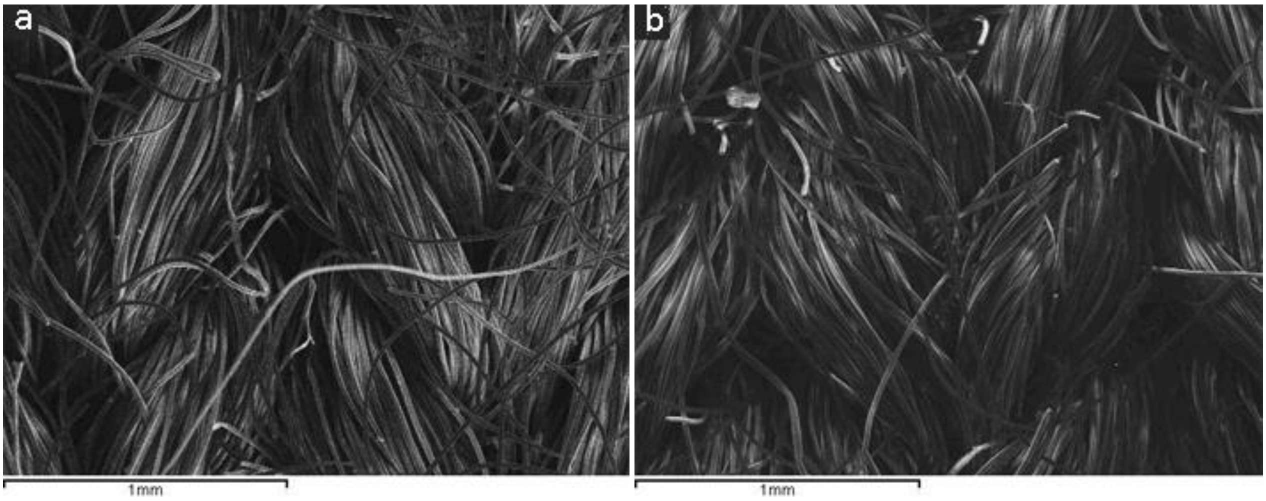

Figure 1. SEM micrographs of the PAN knitted fabric: a) wet relaxed and b) after the wear trial test

Since liquid transmission through textile fabrics essentially occurs through void spaces within the fabric, it is important to assess changes in pore distribution within the knitted fabrics. These changes have to be expected due to the reconfiguration of loops as well as described changes in the geometry of the yarns. The porosity values presented in Table 5 express the total porosity of the knitted fabrics including macro-pores between interlacing yarn segments (open pores) and micro- pores (closed pores) between fibres in the yarns. The open porosity values indicate the total amount of macro-pores in the knitted fabric. After undergoing the wear trial test, porosities of the knitted fabrics were a bit reduced (1.3 % for PAN, 2.3 % for hemp and 5 % for hemp/PAN). Open porosities were also reduced but to a greater extent (14.2 % for PAN, 12.2 % for hemp and 17.4 % for hemp/PAN) as compared to the changes in the total porosity of the knits. Since the open porosity does not quantify the size (surface area and depth) of individual open pores in a knit, the stitch surface and stitch volume coefficients were calculated (Table 5). A lower value of the stitch surface coefficient indicates a reduced surface area of the open pores. It can be seen in Table 5 that the area of open pores was reduced after the wear trial test for all the knitted fabrics. In addition, it seems that the PAN knit has undergone the lowest change in the size of the cross-section of open pores. Although having the lowest surface area of open pores before the wear trial test, the PAN knit was characterized by the highest value of the volume stitch coefficient (the highest surface area of the pores) after the trial period. The lower the value of the volume stitch coefficient, the lower the volume of open pores in a stitch. According to the results (Table 5), the volume of voids in the knitted fabrics was reduced after the wear trial test.

Table 5. Indicators of pore distribution in the knitted fabrics

Parameter		Hemp	Hemp/PAN	PAN
Porosity, %	Wet relaxed	71.1	72.8	71.2
	After the wear trial test	69.5	69.2	70.3
Open porosity, %	Wet relaxed	62.4	62.1	56.3
	After the wear trial test	54.8	51.3	48.3
Stitch surface coefficient	Wet relaxed	0.69	0.72	0.65
	Worn	0.57	0.58	0.6
Stitch volume coefficient	Wet relaxed	1.43	1.28	1.02
	Worn	1.24	1.15	0.96

3. 2. Liquid transfer properties of the knitted fabrics

Prior to assessment of the liquid transfer ability of the knitted fabrics, it is useful to analyse the moisture content in the samples immediately before the water distribution test is conducted. The range of moisture contents in the knitted samples was varied from 0 to 30 %, even though 0 % moisture in textile fabrics (ultra-dry state) is not a natural state, since all textile fibres contain a certain amount of water depending on the ambient conditions (temperature and air humidity). In their dry state (under standard atmospheric conditions), hemp and acrylic fibres contain 8-12 % and 1.5-2.5 % moisture, respectively. Additional liquid in fabric may be free water in the fabric pore system or absorbed by the fibres. It was reasonable to expect that excess water in the hemp knitted fabrics had been absorbed by the hydrophilic hemp fibres. This absorption is followed by fibre swelling when the fibre macromolecules are pushed apart by absorbed water molecules, which reduced the pore size between fibres (micro-pores) and yarns (macro-pores). Therefore, the size of the hemp knit macro-pores quantified by the stitch surface and stitch volume coefficients can account for the moisture content of up to 10 %. The yarn geometry (diameter) in the wet sample (moisture content above 10 %) is difficult to determine because this should be performed in a very short time keeping the sample moisture content at the constant level, in order to ensure reliable results. However, values of the coefficients must decrease when the sample contains a higher amount of water because of the increase in the yarn diameter. In other words, although we did not quantify the change in the macro-pore size, it certainly happened. The geometric configuration of the micro-porous system in yarn is very complex, and difficult to quantify, since these interfibre spaces are channels with a wide shape and size distribution, interconnected or not. However, the yarn porosity can be assessed by its bulk density and the packing density. As can be seen in Table 4, the hemp yarn (from the wet relaxed knit) was characterized by a higher bulk density and higher packing density as compared to the values determined for the PAN yarn despite their same linear densities and twist. This is attributed to differences in geometry and deformation behaviour of hemp and acrylic fibres. Values of the bulk density and packing density of the hemp yarn correspond to those assessed for the knit sample having up to 10 % moisture content. When the moisture content in the hemp knit is higher, some portion of the original free space (in dry sample) must be filled by swollen fibres.

Bearing in mind hydrophobicity of the acrylic fibre, the excess moisture (moisture above the equilibrium moisture content) can be expected to be in the pores of the PAN knit. This means that its pore system (both macro- and micro-pores) is partially filled with water. In the hemp/PAN knitted fabric in which the hemp and PAN yarns were combined, it seems reasonable to expect that some amount of water is absorbed by the hemp fibres inducing a change to some extent in the size of micro-pores in the hemp component, as well as the size of the macro-pores in the hemp/PAN knit. Some water may be in capillaries in the PAN yarn. Therefore, the macro-pore size determined by the stitch surface and volume coefficients for the hemp/PAN knit may be reduced for the samples having excess moisture.

In the Malden Mills water distribution test, water transfers through a textile fabric transversally (transplanar wicking) and radially (in-plane wicking). At the beginning of the water-fabric contact, water travels through macro-pores outward since the liquid spreads along the path of the least resistance. When macro-pores become saturated, they serve as reservoirs for micro-pores to wick the liquid [56]. Results of the water distribution test conducted are presented in Figure 2. Concerning the results for knitted fabrics before the wear trial test, two zones can be distinguished. In the first zone (close to 10 % moisture content), the lowest water transfer ability was exhibited by the hemp knitted fabric which can be expected due to the hydrophilic nature of hemp fibres. The PAN knitted fabric was characterised by the highest water transfer, which could be attributed to high wicking capacities of both macro- and micro-pores. The water transfer ability of the ultra/dry sample of the hemp/PAN knit was similar to that of the hemp counterpart while becoming similar to the PAN knit with an increase in the moisture content. However, the calculated mass of water retained in the sample (presented in Fig. 3) showed that the hemp knit kept the least amount of water as compared to the other ones. To explain this result, we should refer to the geometry of the knits (Table 5). The largest volume of macro-pores is in the hemp knit, followed by the hemp/PAN and PAN knits. It has been already shown by Birrfelder et al. [57] that macro-pores of relatively large diameters fill up relatively slowly. This can be a valid explanation for the results obtained. Smaller macro-pores in the PAN knitted fabric were filled faster transporting the liquid transplanar accompanied with the in-plane wicking by capillary action in micro-pores. In addition, the larger diameter and lower bulk and packing densities of the PAN yarn (Table 4) indicate its higher porosity as compared to the hemp yarn, which provides it with the higher capacity for holding water. Since the hemp/PAN knitted fabric was produced by combining one hemp and one acrylic yarn, the total volume of micro- pores would be between those of the hemp and PAN knits. This, along with the smaller size of macro-pores in the hemp/PAN knit (comparing to the hemp knit), promoted radial wicking and increased the water holding capacity.

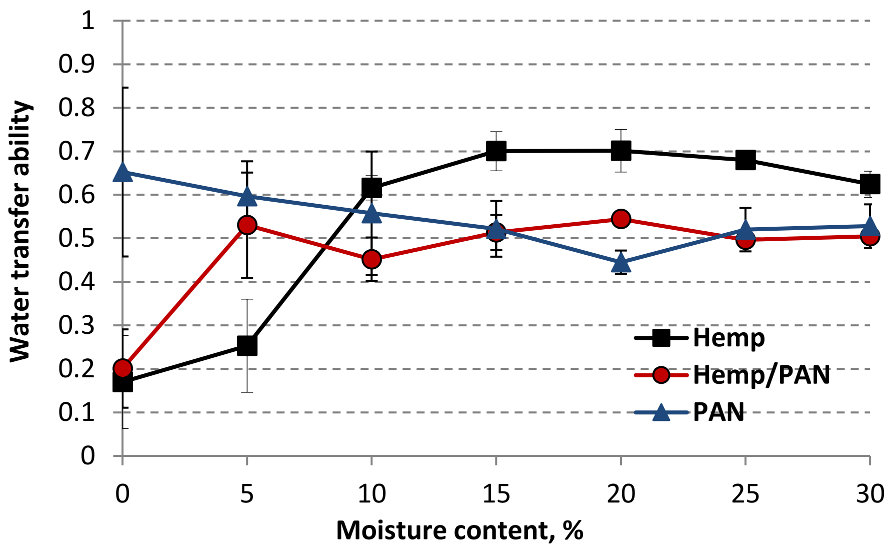

Figure 2. Water transfer ability of the knitted fabrics before the wear trial test

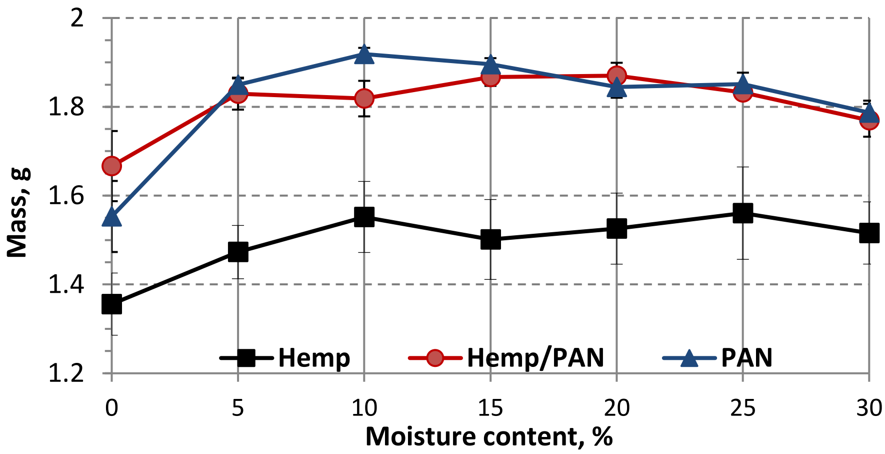

Figure 3. Water holding capacity of the knitted fabrics before the wear trial test

In the second moisture content region (above 10 %), the hemp knitted fabric became the most permeable to liquid, as could be observed in Figure 2. This can be attributed to previously described changes in both knit and hemp yarn geometries caused by the fibre and yarn swelling. A reduction in the size of macro- pores in the hemp knit may have accelerated the transversal wicking. A decrease in the radius of micro channels between fibres in the yarn accelerates horizontal wicking in the radial direction (spreading of the liquid), since smaller pore sizes produce higher capillary pressures, which enhance liquid spreading distance [56]. Statistical analysis showed that water transfer abilities of the PAN ($F(0.41)<F_{crit}(2.85)$ for $p(0.86)>\alpha(0.05)$) and hemp/PAN ($F(0.16)<F_{crit}(2.85)$ for $p(0.97)>\alpha(0.05)$) knitted fabrics did not change with various moisture contents in the sample. In addition, these two knits behaved similar in respect to the ability to transfer liquid outward. Moreover, results of the statistical analysis indicated that these knitted fabrics have similar water holding capacities over the moisture content range investigated, unlike the hemp knit which exhibited statistically lower liquid holding capacity in the whole moisture content range (Fig. 3). The statistical analysis also indicated that the liquid holding capacity of the hemp knit remained practically constant in the whole moisture content range ($F(0.84)<F_{crit}(2.37)$ for $p(0.55)>\alpha(0.05)$). The reason for this result is the constant amount of bonding sites for water molecules. The water holding capacity of the PAN knit was proved to be dependent on the moisture content ($F(28.24) >F_{crit}(2.37)$ for $p(4.89\times10^{-12})< \alpha(0.05)$). The hemp/PAN knitted fabric exhibited the water holding capacity similar to that of the PAN knit, but it was insensitive to changes in the moisture content ($F(1.41)<F_{crit}(2.37)$ for $p(0.25)>\alpha(0.05)$), similarly as for the hemp knit.

Since the hemp knitted fabric underwent some changes in structure (Table 3) and geometry (Table 5) after the wear trial test, it was reasonable to expect certain changes in the liquid management properties, too. Figure 4 indicates the increased water transfer ability of the hemp knit after the trial period in the lower moisture content range (0 – 15 %), which can be attributed to reduction in the macro-pore size (stitch surface and stitch volume coefficient reduction), due to which the transplanar wicking was enhanced. However, the water transfer ability of the hemp knit negligibly changed in the higher moisture content range (20 – 30 %), which could be explained by macro-pores saturation. It seems that the promotion of radial wicking is questionable due to changes in the hemp yarn geometry (decrease in the bulk and packing densities, Table 4) during the wear trial test. As can be noted in the Figure 5, and was statistically proved for the whole tested moisture content range, the water transfer ability of the PAN knit did not change after the wear trial test. This result is expected considering the low extent of changes in the pore size after the test (Table 5). In addition, a decrease in the bulk and packing densities of the PAN yarn caused the micro-pore (capillary) size to increase and consequently a delay in radial wicking. The water transfer ability of the hemp/PAN knitted fabric was increased in the whole moisture content range after the wear trial test (Fig 6), as a consequence of the reduced pore size in the knit (Table 5). Statistical analysis showed that after the trial period, water transfer abilities of all knitted fabrics were independent on moisture content regardless of the composition ($F(0.84) < F_{crit}(2.85)$ for $p(0.56) > \alpha(0.05)$; $F(0.185) < F_{crit}(2.85)$ for $p(0.98) > \alpha(0.05)$; and $F(1.13) < F_{crit}(2.85)$ for $p(0.39) > \alpha(0.05)$ for the hemp, hemp/PAN and PAN knitted fabrics, respectively).

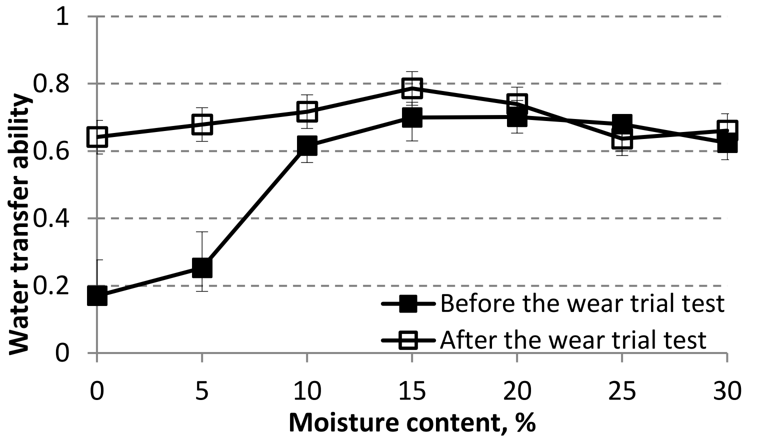

Figure 4. Water transfer ability of the hemp knitted fabrics before and after the wear trial test

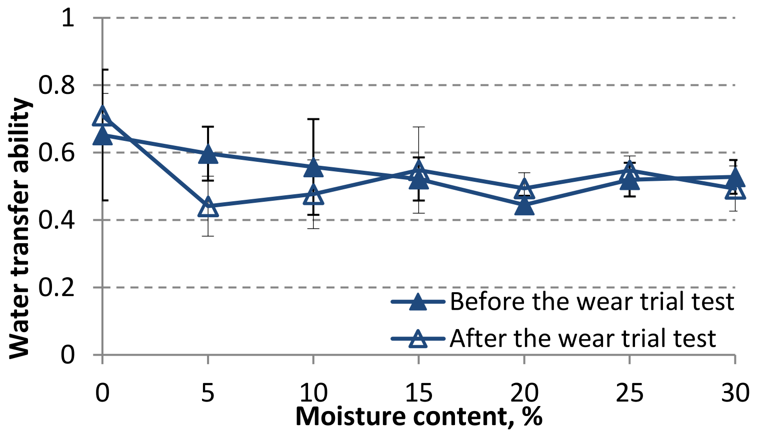

Figure 5. Water transfer ability of the PAN knitted fabrics before and after the wear trial test

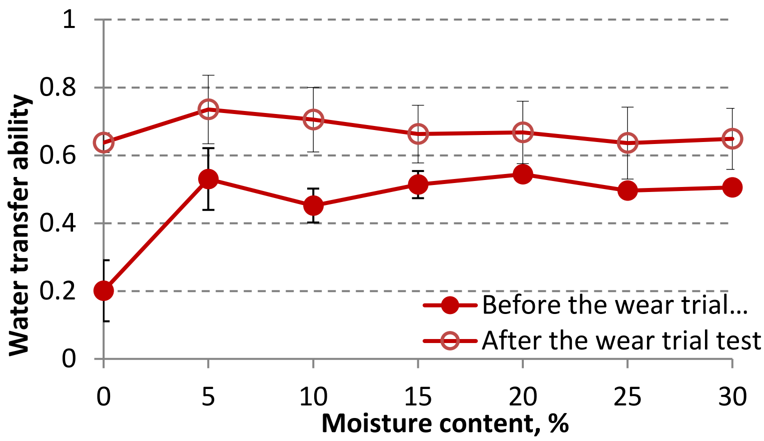

Figure 6. Water transfer ability of the hemp/PAN knitted fabrics before and after the wear trial test

Water holding capacities of the knitted fabrics after the wear trial test is presented in Figure 7. Statistical analysis confirmed that water holding capacities for all the investigated knitted fabrics after the wear and care cycles were statistically same over the whole range of moisture contents. This result was due to the fact that the water holding capacity of the hemp knit, which differed from the other ones before the wear trial test, increased after the test. The increase in the areal density of the hemp knit after the wear trial test (Tables 2 and 3) accounts for the increased water absorption, since higher density of fibres per unit area of the knit means more bonding sites (hydroxyl and other oxygen containing groups) for water molecules. The amount of bonding sites was also increased in the hemp/PAN knit after the wear trial test, but did not contribute significantly to the increase in the water holding capacity. The water holding capacity of the PAN knit stayed at the same level after undergoing wear and care cycles. This was confirmed by paired t-test results presented in Table 6.

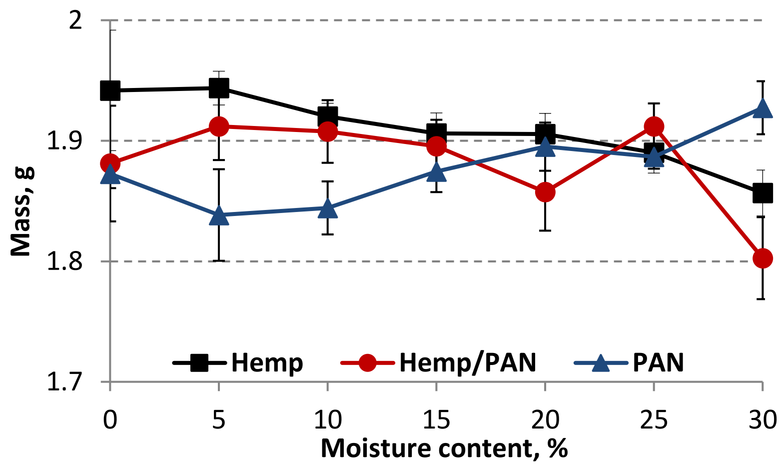

Figure 7. Water holding capacity of the knitted fabrics after the wear trial test

Table 6. p-values of the paired t-test (the null hypothesis: the means of water holding capacity before and after the test are equal)

Fibre	Moisture content, %						
	0	5	10	15	20	25	30
	p-value						
Hemp	0.003*	0.001*	0.008*	0.008*	0.014*	0.034*	0.009*
Hemp/PAN	0.027*	0.182	0.088	0.176	0.651	0.379	0.359
PAN	0.031*	0.494	0.604	0.431	1	0.666	0.596

*statistically significant: $p < \alpha$ (0.05)

Sensitivity of the water holding capacity of each knit to different moisture contents, presented in Figure 7 was investigated by applying the ANOVA statistics. Similarly as for the initial knitted fabrics (before the trial period), water holding capacities of hemp and hemp/PAN knitted fabrics after the wear trial test were independent on the moisture content (($F(1.25) < F_{crit}(2.37)$ for $p(0.31) > \alpha(0.05)$ and ($F(1.37) < F_{crit}(2.37)$ for $p(0.25) > \alpha(0.05)$, respectively). On the contrary, the water holding capacity of the PAN knit was again a function of its moisture content ($F(3.36) > F_{crit}(2.37)$ for $p(0.01) < \alpha(0.05)$). However, it should be noted that there were two moisture content sections with similar water holding capacity of the PAN knit. As illustrated in a smaller graph in Figure 7, the first section was in the moisture content range 0 to 15 % (($F(1.12) < F_{crit}(3.09)$ for $p(0.36) > \alpha(0.05)$, and the second one was in the range of 15 to 35 % moisture content (($F(1.50) < F_{crit}(3.68)$ for $p(0.25) > \alpha(0.05)$. The water holding capacity of the PAN knit increased with an increase in the moisture content above 15 %.

4. CONCLUSION

In this study, liquid transfer properties of plain weft knitted fabrics were determined by two parameters – water transfer ability and water holding capacity. Experimental variables were the composition, geometry, and moisture content of the knitted fabrics. In addition, liquid transfer properties were determined for the knitted fabrics after undergoing a trial period (wear and care cycles). The results obtained showed that the geometric configuration of the complex porous network in knitted fabrics influenced the water transfer ability and water holding capacity in the whole moisture content range regardless of the composition. On the other hand, changes in the geometry of the porous system are determined by complex fibre-water interactions. The statistical analysis gave the clear indication that the water holding capacity was influenced by the moisture content in the hydrophobic (PAN) knitted fabric. In addition, the statistical analysis confirmed that changes in the knit geometry during the wear trial test increased the water holding capacity only for the hydrophilic (hemp) knitted fabric. It is hypothesised that consequential changes in the geometry of the hemp and PAN yarns during the trial period (increase in the micro-pore size) may be the reason why improvements in the water transfer ability were not seen either for the PAN or the hemp knit in the higher moisture content range, after the wear trial test. However, the positive effect of blending hemp (hydrophilic) and PAN (hydrophobic) fibres on the liquid transfer ability of the knitted fabrics in the exploitation stage is confirmed, which is particularly important from the point of thermal comfort sensation. Although the results obtained cannot be explicitly extrapolated to textile materials other than those investigated in this study, they may be the basis for further investigations of interactions of the experimental variables (fibre type, geometric configuration, moisture content) in a number of different fabrics in order to establish useful design guidelines for textile materials with adequate liquid transfer properties.

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SAŽETAK

Karakteristike prenosa tečnosti u tekstilnim materijalima pri različitom sadržaju vlage

Milada S. Novaković[1,2], Jovana Milanović[1], Dragana Grujić[3] i Snežana B. Stanković[1]

[1]*Univerzitet u Beogradu, Tehnološko-metalurški fakultet, Beograd, Srbija*
[2]*Visoka tehnička škola strukovnih studija, Zrenjanin, Srbija*
[3]*Univerzitet u Banjoj Luci,Tehnološki fakultet, Banja Luka, Bosna i Hercegovina*

(Naučni rad)

U uslovima veće fizičke aktivnosti kada se osoba intenzivno znoji, potrebno je da se tečni znoj što pre odvede sa površine kože kako bi se održala toplotna ravnoteža organizma. U tom smislu, sposobnost tekstilnog materijala da upije i oslobodi tečnost u okruženje ima presudnu ulogu u obezbeđivanju toplotnog komfora. U ovom istraživanju je ispitivan kombinovani uticaj vrste vlakana, geometrije i dimenzione stabilnosti pletenina, kao i sadržaja vlage, na njihovu sposobnost prenošenja tečnosti. Stoga su pletenine od konoplje (hidrofilna vlakna), akrila (hidrofobna vlakna) i njihove kombinacije (konoplja/akril) podvrgnute testu nege i nošenja. Malden Milsov (Malden Mills) test distribucije vode sproveden je pri različitom sadržaju vlage u ovim pleteninama, kako bi se ocenili efekti koje količina vlage u materijalu ima na sposobnost pletenina da upiju i da propuste tečnost. Na isti način su testirane i pletenine posle perioda nege i nošenja. Rezultati su pokazali da je geometrijska konfiguracija složene mreže pora (makro- i mikro-pora) u pleteninama odgovorna za njihova svojstva prenosa tečnosti u čitavom ispitivanom rasponu sadržaja vlage, bez obzira na sirovinski sastav. Nakon perioda nege i nošenja pletenina došlo je do preraspodele pora u pleteninama, ali je sposobnost upijanja i prenosa tečnosti i dalje uslovljena veličinom i distribucijom pora.

Ključne reči: test distribucije vode; pletenina; konoplja; akril; kapilarno kvašenje