

Investigation on the Air and Water Vapour Permeability of Double-Layered Weft Knitted Fabrics

Kaunas University of Technology,
Department of Textile Technology
Studentų 56, LT-51424 Kaunas, Lithuania
E-mail: asta.bivainyte@stud.ktu.lt

Abstract

During the investigation, double-layered weft knitted fabrics for leisure sports were designed with physiological and thermal comfort in mind. Physiological comfort is determined by the state of the organism during physical activity, and thermal comfort is determined by the feeling of warmth/coldness and damp/dryness, which depends on the air permeability and capability to absorb and evaporate sweat. The main goal of this study was to investigate the influence of knitting structure, fibre type, and yarn properties on the air and water vapour permeability of double-layered weft knitted fabrics. An investigation was carried out using fabrics knitted in plain plating and with combined structures on a circular knitting machine. One layer (outer) was made from cotton yarns or man-made bamboo yarns and the other one (inner) was from synthetic fibre yarns (polypropylene, polyester and polyamide). The study established that the fibre composition of yarn and knitting structure parameters, such as the loop length, area linear filling rate and pattern have a significant influence on the air permeability of double-layered weft knitted fabrics. The main influence on the water vapour permeability of double-layered knitted fabrics is the kind of raw material i.e. the wetting and wicking properties of fibres.

Key words: air permeability, water vapour permeability, double-layered fabric, weft knitted fabric.

■ Introduction

Clothing designed for leisure sports is worn not only for aesthetic reasons but also for special control functions of the human body. Clothing comfort includes three main considerations: thermo-physiological, sensorial and psychological comfort [1, 2]. Thermo-physiological comfort has become an important parameter of clothing especially designed for active leisure. Factors affecting thermo-physiological comfort are numerous, including heat exchange within clothing, air permeability, the 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 that a microclimate is created next to the skin [3]. This physiological effect is extremely important, especially

in the case of clothing for sports and active leisure. Items of clothing with poor thermo-physiological wear characteristics not only detract from the well-being of the human but also impair his/her physical performance and may even act as a health hazard.

The human produces heat continuously 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. In this case, we begin to sweat, the aim being to cool the body through evaporation of sweat on the skin [3]. Naturally, the prerequisite for cooling is that this sweat can actually evaporate. Therefore, clothing must always ensure a high level of moisture transmission and evaporation.

The air in the microclimate between individual items of clothing also has a physiological function. When the body is at rest, this air in the microclimate contributes up to approximately 50% of the effective thermal insulation properties of the clothing. When the body is in motion, approximately 30% of the heat and moisture can be removed by air convection in the microclimate and air exchange via the clothing [3]. Air permeability, being a biophysical feature of textiles, determines the ability of air to flow through the fabric. Airflow through textiles is mainly af-

ected by the pore characteristics of fabrics. The pore dimension and distribution in a fabric is a function of fabric geometry. The yarn diameter, knitting structure, course and wale density, and yarn linear density are the main factors affecting the porosity of knitted fabrics [4, 5]. Air permeability also depends on the finishing treatment [6 – 8]. In sportswear, high air permeability is desirable.

Water vapour permeability is the ability to transmit vapour from the body. The ability of clothing to transport water vapour is an important determinant of physiological comfort [9, 10]. Sweat should be removed from the surface of skin to the that of the fabric of the next-to-skin clothing. After the body has stopped sweating, the textile fabric should release the vapour held in the atmosphere in order to reduce the humidity on the surface of the skin.

Clothing for the leisure sports is difficult to design as far as physiological requirements are concerned since these are often contradictory because of the differing climatic and activity conditions. It is not a simple task to optimise sportswear as regards thermo-physiological and sensorial comfort. On the other hand, leisure sports are characterised by the fact that maximum physical performance is not always achieved and that active phases are interspersed with rest phases [11 – 13]. In addition, a leisure sportsperson often wears his/her clothing for several hours.

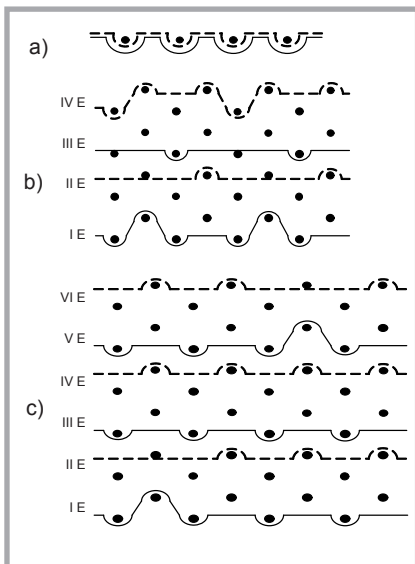


Figure 1. Pattern of the knitted fabrics investigated: a) plain plated single jersey, b) combined I (pique), c) combined II; — cotton C or bamboo B yarn, - - - PP, PA, PES, or Coolmax yarn.

During the investigation, double-layered weft knitted fabrics for leisure sports were designed physiological and thermal comfort in mind. The typical double-layered construction of knitted fabrics includes the following elements [14]:

- One layer of knitted fabric made of conductive and diffusive yarns, which directly adjoins the body. Its role is to remove and transport sweat from the body in liquid and vapour forms.
- Another layer of knitted fabric made of absorptive yarn, which is not in direct contact with the skin. The role of this layer is to keep the humidity far from the body and vaporise it to the environment.

Natural fibres such as cotton, bamboo and wool are hygroscopic and, therefore, characterised by high absorption levels [15]. The moisture absorbed is bound in strongly and only released slowly. Cotton fabrics, on the other hand, 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 [16]. Synthetic fibres such as polyester, polypropylene and acrylic are not hygroscopic and, therefore, only absorb a comparatively small amount of moisture. However, because of their 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 when designing wear for leisure sports.

The main goal of this work was to investigate the influence of knitting structure parameters and raw materials on the air and water vapour permeability of double-layered knits used for leisure sports.

Object and methods of investigation

Investigations were carried out on double-layered fabrics knitted with a plain plating pattern and two types of combined structure on a circular knitting machines with an E 22 gauge. The materials used were cotton and regenerated bamboo yarns¹⁾ for the outer layer and PP, PA, PES, and Coolmax (tetra-channel fibres by DuPont) yarns for the inner layer. Overall, 16 particular variants of knits were investigated. Characteristics of the knitted fabrics tested are presented

Table 1. Characteristics of the knitted fabrics tested. Note: the relative error δ of all counts presented in Table 1 is less than 6%.

Pattern	Sample code	Linear density of yarns and composition percentage	Course density P_v , cm^{-1}	Wale density P_h , cm^{-1}	Loop length l , mm	Area linear filling rate E	Air permeability, $\text{dm}^3/(\text{m}^2\cdot\text{s})$	Water vapour permeability, $\text{mg}/(\text{m}^2\cdot\text{h})$
Plain plating	LSI-1	Cotton, 20 tex, 71% PA, 7.8; 29%	24.5	12.5	2.84	1.817	860	3562
	LSI-2	Cotton, 20 tex, 71% Coolmax, 7.8; 29%	24.5	12.5	2.79	1.701	852	4058
	LSI-3	Cotton, 20 tex, 71% PES, 8.3; 29%	24.5	12.5	2.79	1.701	855	3693
	LSI-4	Cotton, 20 tex, 71% PP, 8.4; 29%	25	12	2.88	2.045	899	3560
	LSII-1	Bamboo, 20 tex, 71% PA, 7.8; 29%	24	12.5	2.85	1.696	896	4141
	LSII-2	Bamboo, 20 tex, 71% Coolmax, 7.8; 29%	24	12.5	2.81	1.589	871	4773
	LSII-3	Bamboo, 20 tex, 71% PES, 8.3; 29%	24	12.5	2.81	1.589	881	4274
	LSII-4	Bamboo, 20 tex, 71% PP, 8.4; 29%	24.5	12	2.93	2.016	927	4008
Combined (pique)	KI-1	Cotton, 20 tex, 71% PA, 7.8; 29%	16	12	3.11	1.753	863	3887
	KI-2	Cotton, 20 tex, 71% Coolmax, 7.8; 29%	16	12	3.10	1.867	882	4338
	KI-3	Cotton, 20 tex, 71% PES, 8.3; 29%	16	12	3.10	1.867	877	3905
	KI-4	Cotton, 20 tex, 71% PP, 8.4; 29%	16	11	3.21	1.820	920	3862
Combined	KII-1	Cotton, 20 tex, 76% PA, 7.8; 24%	15	11.5	3.24	1.688	788	3999
	KII-2	Cotton, 20 tex, 76% Coolmax, 7.8; 24%	15	11.5	3.26	1.566	779	4358
	KII-3	Cotton, 20 tex, 76% PES, 8.3; 24%	15	11.5	3.26	1.566	772	3888
	KII-4	Cotton, 20 tex, 76% PP, 8.4; 24%	15	11	3.35	1.758	876	3832

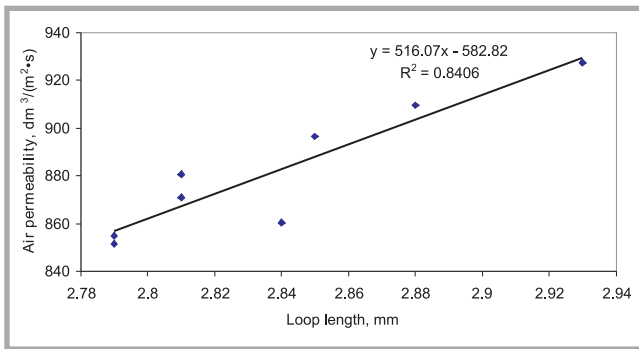


Figure 2. Influence of loop length on the air permeability of fabrics knitted with a plain plated LS pattern.

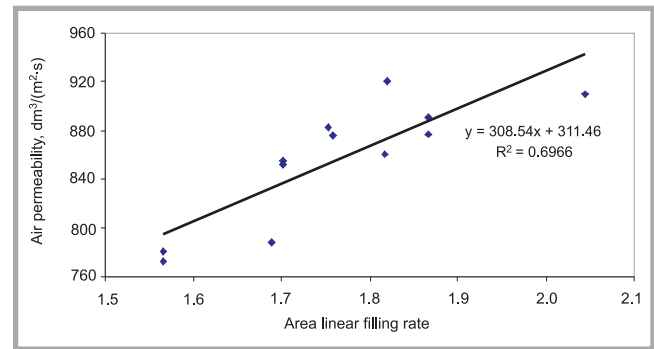


Figure 3. Influence of the area linear filling rate on the air permeability of all the knits investigated.

in **Table 1**, and the knitting structure is shown in **Figure 1**.

All experiments were carried out in a standard atmosphere according to Standard ISO 139. Structure parameters of the knitted samples were analysed according to British Standard BS 5441:1998. The area linear filling rate E was calculated according to the equation:

$$E = (l \cdot d)/(A \cdot B), \quad (1)$$

where l – loop length in mm; d – yarn diameter in mm; A – wale spacing in mm; B – course spacing in mm.

Air permeability tests of the double-layered knitted fabrics investigated were conducted according to Standard EN ISO 9237:1997 using a head area of 10 cm² and pressure difference of 100 Pa. 10 tests per sample were performed. The air permeability R was determined according to the following equation:

$$R = 167 D/A \text{ in } \text{dm}^3/(\text{m}^2\text{s}), \quad (2)$$

where D – average air flow rate in dm³/min; A – operative area of the sample equal to 10 cm².

The rate of moisture vapour transfer was measured using the cup method. Samples with a diameter of 10 cm were kept on a round cup containing water of 40 °C temperature in controlled conditions (an air temperature of 25 °C and relative humidity of 50%) for a duration of 1 hour. 5 tests per sample were performed. The water vapour permeability W was determined according to the following equation:

$$W = M_W/(A \cdot t) \text{ in } \text{mg}/(\text{m}^2\text{h}), \quad (3)$$

where M_W – mass of water evaporated from the cup in mg; A – operative area of the sample in m²; t – time of water mass, M_W , evaporation in h.

The relative error δ was calculated according to the equation:

$$\delta = \frac{t_n \cdot v}{\sqrt{n}}, \text{ in } \%, \quad (4)$$

where t_n – Student coefficient, v – coefficient of variation in %, n – number of tests.

Results and discussion

The influence of the fibre composition and structural parameters of knits on the air permeability of double-layered knits

The influence of the fibre composition and structural parameters of knits on the air permeability of double-layered knits for leisure sports was investigated. General investigations on the air permeability of knits were conducted with plain knitted fabrics. On the other hand, the air permeability of fabric depends on the number and size of pores through which most of the airflow permeates. Several methods of measuring the porosity of plain knitted fabrics are known. However, assessing the porosity of double-layered knitted fabrics is fraught. One of the goals of this investigation was to find structural parameters conducive to evaluate the porosity of double-layered knits with different patterns.

Loop length is one of the structural parameters that determine pore size in knitted fabric. The influence of loop length on the air permeability of the fabrics under investigation knitted in a plain plated single jersey (LS) pattern is shown in **Figure 2**. The results obtained show the dependence of air permeability on loop length. When the loop length increases, the air permeability also rises because of the increasing porosity of knitted fabrics, as was demonstrated in [4]. The coefficient of determination R^2 of the fabrics

under investigation knitted in a plain plated pattern is 0.8406. Similar tendencies were obtained for double-layered fabrics knitted with combined patterns *KI* and *KII* (see **Table 1**). However, this dependence is obtained only for fabrics knitted in the same pattern. In other words, the loop length cannot be used as the common rate for comparison of the air permeability of knitted fabrics with different patterns.

There is no dependence of the air permeability of double-layered knitted fabrics with different knitting patterns on the area density or thickness of the fabric used in this work.

The air permeability of double-layered knitted fabrics with different patterns can be predicted by the area linear filling rate E (**Figure 3**). The influence of this parameter on air permeability can be described by a linear equation with the coefficient of determination $R^2 = 0.6966$. By increasing the area linear filling rate, the air permeability of fabrics increases, which could also be explained by the fact that when the loop length increases, the course spacing and wale spacing increase as well i.e. it increases the size of pores through which the airflow permeates. Parameter E assesses the knitting pattern (i.e. the average loop length in the pattern and loop density of the fabric) as well as yarn characteristics (i.e. yarn linear density, and type of fibres).

The influence of the fibre composition and structure parameters of knits on the water vapour permeability of double-layered knits

The influence of the knitting structure and fibre composition of double-layered knits with various knitting patterns on water vapour permeability was investigated in this work.

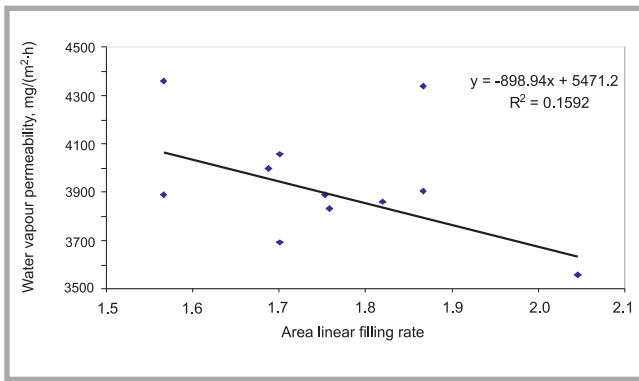


Figure 4. Influence of the area linear filling rate on the water vapour permeability of knits with all the structures investigated.

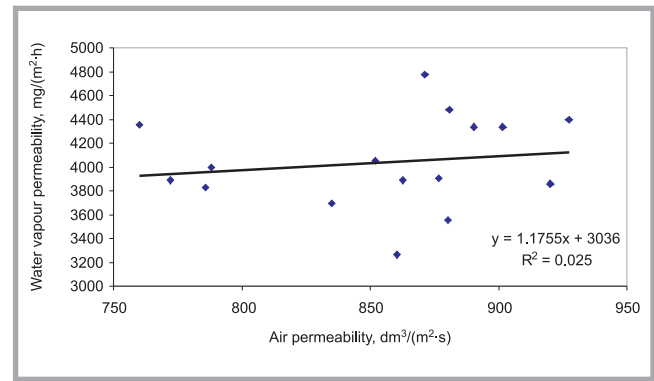


Figure 6. Correlation between the air permeability and water vapour permeability of knits.

The influence of the area linear filling rate E on the water vapour permeability of double-layered fabrics knitted from cotton, PP, PA, PES, and Coolmax yarns investigated herein is shown in **Figure 4**. From the results presented in this Figure, we can see that to predict water vapour permeability using the area linear filling rate is impossible; the coefficient of determination is very low ($R^2 = 0.1592$). The coefficient of determination of the dependence of water vapour permeability on loop length has an even lower value, which is due to the fact that hardly any of the humidity vapours away through pores of the knit. The rest of the humidity is absorbed by hydrophilic fibres and gradually evaporated. The quantity and rate of the humidity absorption of double-layered knits (of the type investigated) depend on the wicking and wetting angle of fibres.

The influence of fibre composition on the water vapour permeability of double-

layered fabrics knitted in various patterns is shown in **Figure 5**. The fabrics of all the structures knitted from cotton (or bamboo) and a Coolmax yarn blend investigated herein have the highest water vapour permeability values: $4058 \div 4358$ mg/(m²h) for cotton fabrics (depending on the knitting structure), and 4778 mg/(m²h) for bamboo fabric knitted with a plain plated structure. Fabrics knitted from a cotton (or bamboo) and PP yarn blend have the lowest water vapour permeability (in contrast to the air permeability of the fabrics investigated): $3560 \div 3830$ mg/(m²h) for cotton fabrics (depending on the knitting structure), and 4008 mg/(m²h) for bamboo fabric. As presented in **Figure 5**, fabrics knitted from a bamboo and synthetic yarn blend are generally characterised by a 700 – 800 mg/(m²h) higher water vapour permeability than those knitted from cotton and a suitable synthetic yarn blend (with the same knitting structure – plain plating single jersey). The following re-

sults demonstrate the apparent influence of fibre composition on the water vapour permeability of knitted fabrics.

The results presented in **Figure 6** show that there is no correlation between the water vapour permeability and air permeability of the double-layered knitted fabrics investigated. Therefore, the designing of knitted fabrics for active leisure with only air permeability or water vapour permeability in mind is not right, because water vapour permeability depends on the structure of knits in not the same order as air permeability.

Conclusions

The main conclusions drawn from the experiment performed are as follows:

- The air permeability of double-layered knitted fabrics with the same pattern depends on the loop length. However, the loop length cannot be used as the common rate for comparison of the air permeability of knitted fabrics with different patterns.
- The air permeability of double-layered knitted fabrics with different patterns can be predicted by the area linear filling rate. When this parameter increases, air permeability also rises.
- To predict water vapour permeability using the loop length or area linear filling rate is impossible; the coefficient of determination is $R^2 = 0.1592$.
- The main influence on the water vapour permeability of double-layered knitted fabrics is the kind of raw material i.e. fibre wetting and wicking properties.
- There is no correlation between water vapour permeability and the air permeability of the double-layered knit-

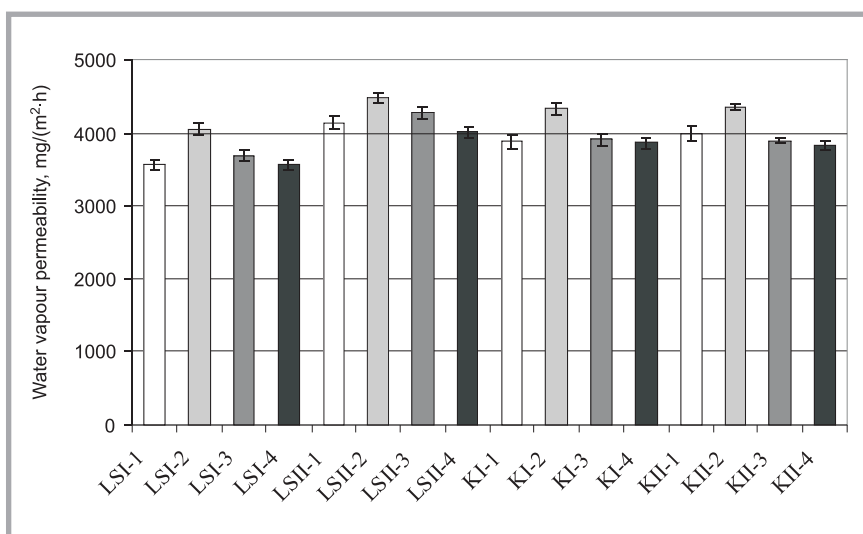


Figure 5. Influence of the knitting structure and fibre composition on the water vapour permeability of knits (marked as in Table 1).

ted fabrics investigated because water vapour permeability depends on the structure of knits in not the same order as air permeability.



Editorial note

- 1) "Regenerated bamboo yarns" are composed from cellulose man-made fibres manufactured from a bamboo pulp.

Acknowledgments

We would like to thank JSC "Omniteksas" and Vydas Damalakas for their technical support.

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Received 24.01.2011 Reviewed 23.02.2011



INSTITUTE OF BIOPOLYMERS AND CHEMICAL FIBRES

LABORATORY OF BIODEGRADATION

The Laboratory of Biodegradation operates within the structure of the Institute of Biopolymers and Chemical Fibres. It is a modern laboratory with a certificate of accreditation according to Standard PN-EN/ISO/IEC-17025: 2005 (a quality system) bestowed by the Polish Accreditation Centre (PCA). The laboratory works at a global level and can cooperate with many institutions that produce, process and investigate polymeric materials. Thanks to its modern equipment, the Laboratory of Biodegradation can maintain cooperation with Polish and foreign research centers as well as manufacturers and be helpful in assessing the biodegradability of polymeric materials and textiles.

The Laboratory of Biodegradation assesses the susceptibility of polymeric and textile materials to biological degradation caused by microorganisms occurring in the natural environment (soil, compost and water medium). The testing of biodegradation is carried out in oxygen using innovative methods like respirometric testing with the continuous reading of the CO₂ delivered. The laboratory's modern MICRO-OXYMAX RESPIROMETER is used for carrying out tests in accordance with International Standards.



The methodology of biodegradability testing has been prepared on the basis of the following standards:

- **testing in aqueous medium:** 'Determination of the ultimate aerobic biodegradability of plastic materials and textiles in an aqueous medium. A method of analysing the carbon dioxide evolved' (PN-EN ISO 14 852: 2007, and PN-EN ISO 8192: 2007)
- **testing in compost medium:** 'Determination of the degree of disintegration of plastic materials and textiles under simulated composting conditions in a laboratory-scale test. A method of determining the weight loss' (PN-EN ISO 20 200: 2007, PN-EN ISO 14 045: 2005, and PN-EN ISO 14 806: 2010)
- **testing in soil medium:** 'Determination of the degree of disintegration of plastic materials and textiles under simulated soil conditions in a laboratory-scale test. A method of determining the weight loss' (PN-EN ISO 11 266: 1997, PN-EN ISO 11 721-1: 2002, and PN-EN ISO 11 721-2: 2002).



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1997, PN-EN ISO 11 721-1: 2002, and PN-EN ISO 11 721-2: 2002).

The following methods are applied in the assessment of biodegradation: gel chromatography (GPC), infrared spectroscopy (IR), thermogravimetric analysis (TGA) and scanning electron microscopy (SEM).

Contact:

INSTITUTE OF BIOPOLYMERS AND CHEMICAL FIBRES
ul. M. Skłodowskiej-Curie 19/27, 90-570 Łódź, Poland
Agnieszka Gutowska Ph. D.,
tel. (+48 42) 638 03 31, e-mail: lab@ibwch.lodz.pl