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Application of Microtomography in Textile Metrology
Uporaba mikrotomografije za merjenje v tekstilstvu

Original Scientific Paper/*Izvirni znanstveni članek*
Received/*Prispelo* 12-2013 • Accepted/*Sprejeto* 01-2014

Abstract
Porosity represents one of the parameters of knitted fabrics, which significantly affects their air permeability and thus the overall physiological comfort of knitted clothes. X-ray computed microtomography (µCT) is a relatively new but not yet widely used method for studying textile porosity. The paper discusses the use of a 3D image of the textile structure obtained by applying µCT in the textile metrology. Specifically, it deals with the analysis of options for determining the 3D porosity of knitted fabric by µCT and subsequent analysis of the relationship of porosity versus the fabric permeability to air. The first part of the article was aimed to analyse the suitability of application of µCT to determine the 3D porosity of textile materials and determination of appropriate measurement conditions. Obtained porosity data measured by the 3D device SkyScan 1174 was compared to the porosity calculated by the standard mathematical model. The research results show that µCT system is suitable alternative method for 3D porosity measurement. There is very small difference (about 6%) between the percentage of the air volume of the examined knitted fabric obtained by µCT (64.6%) and porosity expressed through the volume fraction by standard mathematical model (70.6%). The last part analyses the dependent relationship between porosity of the knitted structures obtained by using µCT SkyScan 1174 and air permeability measured on FX device 3300 according to EN ISO 9237. Analysis between air permeability and measured porosity of others knitted structures verified correctness of suggested measurement process of 3D porosity.

Keywords: micro CT, 3D porosity, knitted fabric, air permeability, 3D model of knitted fabric

Izvleček
Poroznost je eden od parametrov pletiv, ki znatno vplivajo na njihovo zračno prepustnost ter posledično na splošno fiziološko udobje izdelanih pletenin. Rentgenska računalniška mikrotomografija (µCT) je razmeroma nova, še ne splošno uporabljena metoda za proučevanje poroznosti tekstilij. V članku je proučena raba 3D slik tekstilnih struktur, pridobljenih z µCT, v tekstilni metrologiji. Podrobneje je podana analiza možnosti določanja 3D poroznosti pletiv z µCT in poznejšo analizo razmerja med poroznostjo in zračno prepustnostjo pletiva. Prvi del članka je namenjen predstavitvi analize ustreznosti uporabe µCT za določanje 3D poroznosti tekstilnih materialov in določitvi ustreznih razmer za merjenje. Vrednosti poroznosti, pridobljene s 3D napravo SkyScan 1174, so bile primerjane s poroznostjo, izračunano s standardnim matematičnim modelom. Rezultati raziskave prikazujejo, da je sistem µCT ustrezna alternativna metoda za merjenje 3D poroznosti. Razlika med odstotkom volumna zraka preizkušanega pletiva, pridobljenega z µCT (64,6 %), ter poroznostjo, izraženo z volumsko frakcijo s standardnim matematičnim modelom (70,6 %), je zelo majhna, in sicer znaša približno šest odstotkov. V zadnjem delu članka je podana analiza razmerja med poroznostjo pletenih struktur, ki so bile pridobljene s pomočjo µCT SkyScan 1174, ter zračno prepustnostjo, izmerjeno na napravi FX 3300 v skladu s standardom EN ISO 9237. Analiza med zračno prepustnostjo in izmerjeno poroznostjo drugih pletenih struktur je potrdila pravilnost predlaganega postopka merjenja 3D poroznosti.

Ključne besede: mikrotomografija, 3D poroznost, pletivo, zračna prepustnost, 3D model pletiva

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*Tekstilec 2014, **57**(1), 4−11*
DOI: 10.14502/Tekstilec2014.57.4−11

1 Introduction

Many scientists have been studying knitted fabrics for years, mainly the single structure, and its basic element – the knitted loop. Supported by new expertise, modern testing and measuring techniques, e.g. electron microscopy and computer picture analysis, they enable the specification of the loop shape and size in dependence on the geometrical parameters of the loop [1]. Anyway, there is a new advanced method to analyse the 3D structure and physiological properties of knitted fabrics using μ CT [1].

Air permeability is an important factor which affects the comfort of the textile product [2]. Air permeability is actually a function of the porosity of the material; therefore an indication about the porosity is valuable information. Currently, there are several methods to determine the porosity of textile materials. The two main theoretical approaches are unit cube analysis and mass technique, porosity determination from the material density or from the surface cover of the fabric, modified surface porosity. However, there are other theoretical calculations that are based on similar concepts but with tiny variations, which would include Archimedes method, liquid displacement technique and others. Experimental techniques include, for example, SEM, Gas adsorption [3], image analysis system [4, 5] and finally the measurement of porosity using μ CT [3].

X-ray computed microtomography (μCT) represents the most recent method of textile porosity examination. When it comes to analysis of textile structure [6], the characterization of variability in 3D textile architecture [7], or various studies of the distribution and transport of moisture in textiles [8], μCT approach is an advanced and accurate technique.

Textile porosity is a key parameter which affects its permeability. The air permeability of a fabric is defined as the amount of air passed through a surface under a certain pressure difference in a unit time. It was found that the structural characteristics of knitted fabrics (loop length, structure compactness and structure type) have an important influence on the air permeability of the knitted fabrics [9].

From the very structure of the knitted fabric it is clear that it has much more pores than woven fabrics, therefore, in general, the air permeability of knitted fabrics is higher than woven fabric permeability (woven fabrics of the same weight). It is very important to carry out tests of air permeability because they define fabric attributes of warmth, wind protection and "breathability" of knitted material. Air permeability is an important factor that affects comfort by transporting moisture vapour from the skin to the outside atmosphere [10]. This transport of the moisture (in the case of a clothed body) takes place in several ways, namely the capillary, migration, diffusion and sorption ways. Diffuse transport of the moisture is carried out through the pores of the knitted fabric thanks to their size and "obliquity" that participates in the capillary outflow.

The main objective of this work is to conduct 3D analysis of porosity within a chosen textile material by μCT, compare the results with a standard calculated porosity based on the mathematical model, and to determine both the feasibility and advantages of this new alternative method for analysing the physiological properties of textiles. Subsequently the dependency between 3D porosity of the material and air permeability of the fabric is evaluated.

2 Methodology

2.1 Materials

Within this experiment, a set of 4 materials was tested. The basic parameters of the tested knits are shown in Table 1.

Table 1: The basic characteristics of tested knitted materials

Fabric	Raw materials	Weight [gm^{-2}]	Pattern	Thickness [mm]	Density course/wale [dm^{-1}]
1	85% aramide (Nomex) 15% aramide (Kevlar)	415	single jersey	3.07	42/35
2	100% cotton	350	single jersey	2.80	33/32
3	100% cotton	660	single jersey	3.78	46/33.5
4	53% wool 24% acrylic 23% nylon 6.6	277	single jersey	3.70	33/25

2.2 Methods

The first part of the experiment aimed to analyse the suitability of application of μCT to determine the 3D porosity of textile materials. In this section we investigated material No. 1, used for the production of heat-resistant gloves. The acquisition of 3D images of the tested knits was performed by microtomography SkyScan 1174. Industrial tomographs offered on the market mostly have a similar construction. Between the X-ray source and detector (Figure 1), which converts radiation into an electrical signal (the information), the measured specimen rotates about a vertical axis. During this rotation 2D images (slices) are taken in many steps.

From these (often hundreds of) images, reconstruction software creates a 3D model of the real specimen in the form of cloud points. These points called voxels (derived from the concept of spatial point – volume pixel) are points ordered in space that are associated with information about the absorption properties of the real object in this position [11].

While evaluating of the porosity using μCT scanning is necessary to note some fundamental differences compared with other methods. Using μCT imaging not only are the pores between yarns evaluated, but also the pores (voids) inside a yarn, which is not possible using the theoretical methods. That is a sum of closed and open pores leading to total porosity. A closed pore in 3D is a connected assemblage of space (black) voxels that is fully surrounded on all sides in 3D space by solid (white) voxels. An open pore is defined as any space located within a solid object or between solid objects, which has no connection in 3D to the space outside the object or objects [12]. In the case of knits we can say that the space between the yarns will be the open pore space and some voids inside a yarn (if fully surrounded by yarn material) will be defined as closed porosity. So we expect a low percentage of closed porosity and a high percentage of open porosity as an outcome for porosity calculations.

3D analysis of the knitted fabric itself requires the completion of a number of important tasks, respectively setting the best conditions for scanning the textile materials:

- setting a suitable fixation of the textile samples,
- setting an appropriate ROI (region of interest at which the analysis is performed),
- setting the optimal threshold,
- analysis of the porosity.

Detailed description of measurement process by μCT SkyScan 1174 and setting of optimal measurement condition is carried out in chapter 3.1. Final measurements are taken under the following settings: large pixel camera, rotation step: 0.7°, rotation degrees: 360°, averaging 20, exposure: 3300 ms, voltage source: 25 kV.

The second part was focused on the porosity calculation by the mathematical model and comparing these results with porosity by μCT. There is a detailed description of above mentioned in chapter 3.2.

The porosity of a fabric is connected with certain of its important features, such as air permeability, water permeability, dyeing properties etc. [10]. The third part investigates the relationship between 3D porosity of the knitted fabric (measured by μCT), and the air permeability of knits (R [m/s]) determined by the standardized method according to Standard EN ISO 9237:1995. Air permeability was investigated using a pressure of 100 Pa. Analysis between air permeability and measured porosity of others knitted structures verified correctness of suggested measurement process by μCT.

3 Results and discussion

3.1 Evaluation of 3D fabric porosity by microtomography method

Fixation of the textile samples

When scanning textile materials (unlike other solid materials such as bone, metal parts etc.), there is already a problem in the actual scanning. Custom fixation of the specimen scanned with universal tomograph is conducted using a simple plate with plasticine. Due to inhomogeneity of the fabric, it's viscoelasticity, low stiffness, deformations caused by textile's gravity and twisting of the edges, it was necessary to design an appropriate specimen fixation which would stabilize the shape of the knits throughout the scanning process, without causing their deformation, or deterioration of the external and internal structure of the specimen.

Attaching the tested fabric with double-sided adhesive tape horizontally on a cylindrical stand base (Figure 2) appeared to be an optimal method of fixation. In this horizontal way of fixation we obtain fewer cuts than in the vertical location of the sample, but also a completely different view on the cuts in the evaluation program, which in this case helped to facilitate the threshold and ROI definition as well as the definition of a unit cell of the knitted fabric.

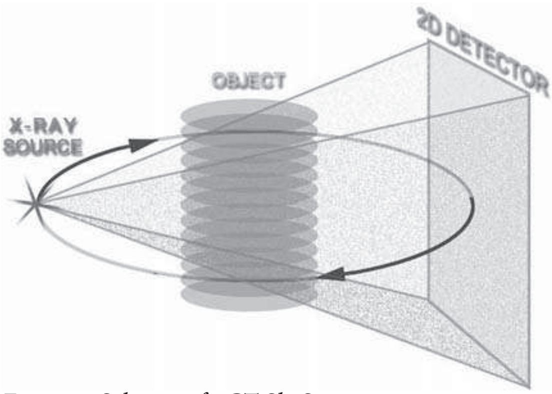

Figure 1: Schema of μCT SkyScan1174

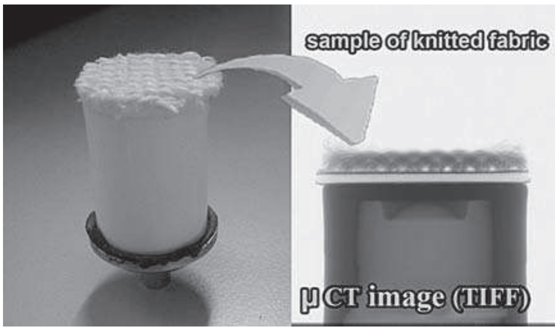

Figure 2: Fixation of the knitted fabric specimen

Setting of ROI, evaluation process of data from the μCT Scan

When scanning is completed the reconstruction of the obtained cuts follows. After opening the scanned cuts of the fabric (Figure 4) the next step is to set ROI and VOI – the volume of interest is the sum of all ROI in all selected layers (Figure 3). Then analysis is made only from the active selected sections [12].

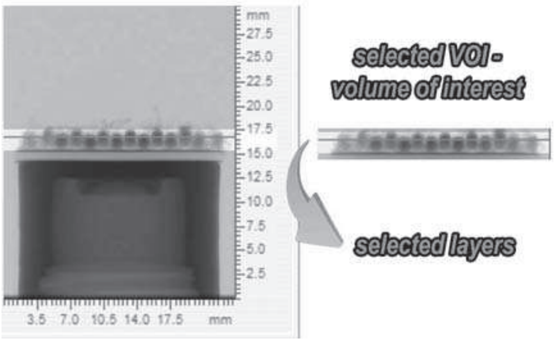

Figure 3: VOI – Volume of Interest

We chose the first active top and last bottom layer from the selection (Figure 4), taking into consideration the fact that some of the wales and courses of knitted fabric sticks up above the level of others, therefore it is necessary to choose a certain mean value.

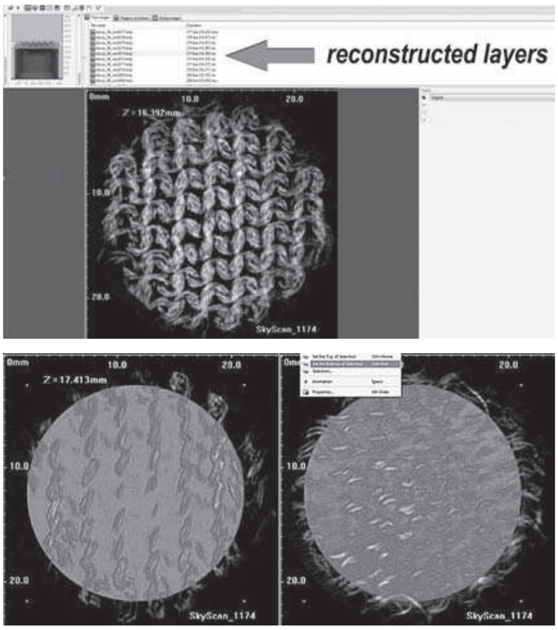

Figure 4: Reconstructed layers of the knitted fabric and the view of the first and last active knit's layer

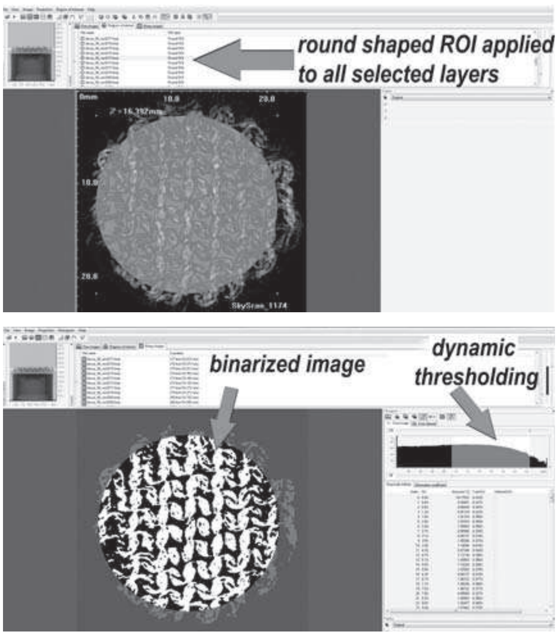

Figure 5: Round shaped ROI applied to all selected layers and the thresholding of the image

For this measurement a circular ROI without the edges of the sample (Figure 5) was chosen. Then, ROI was copied to all the selected layers. The next step was the thresholding of the images. In Figure 5 we can see a table with a histogram which can be used to edit the value of threshold. This creates a binary image, in which the mass is shown in white and air voids are shown in black.
Image thresholding is a crucial step that has to be executed very precisely as bad determination of this value may result in an incorrect outcome. Therefore the binarized image was carefully visually compared with the "raw" image in different layers (Figure 6). The next step after thresholding is 3D analysis (Figure 6) where we choose the parameters that we want to analyse. In this case we selected the parameter "porosity" respectively the "number of objects".

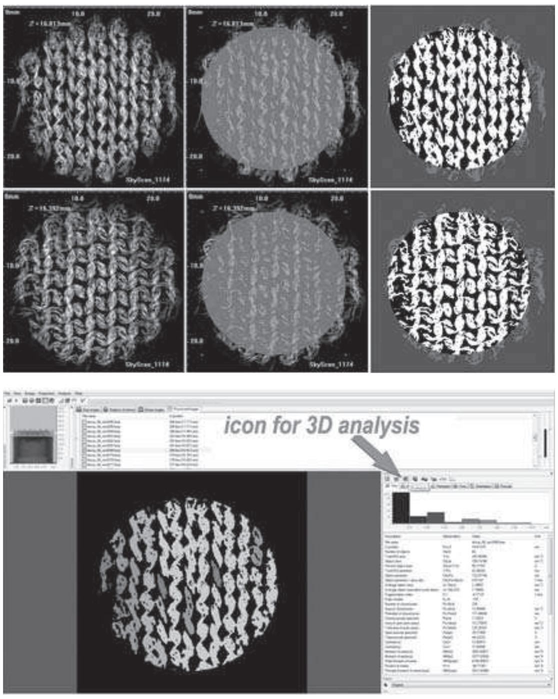

Figure 6: Comparison of the "raw" and binarized images (left), icon for 3D analysis (right)

Porosity results of μCT analysis
The scan was carried out on 3 samples cut out from different places of the knitted fabric. Three types of ROI (Figure 7) were examined on each sample but in the end the round-shaped ROI was chosen as the best option. Each sample was evaluated under the same conditions: scanning parameters, same number of selected layers (31) and same threshold values: low threshold = 112, upper threshold = 250.

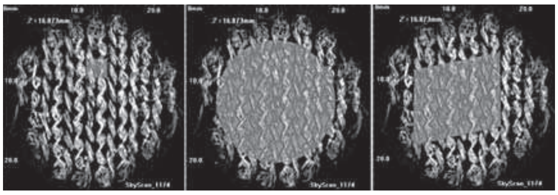

Figure 7: Three types of ROI

Table 2: Final porosity results – specimen of knitted fabric No. 1

Properties	Porosity [%]		
Type of ROI	Sample 1	Sample 2	Sample 3
1 unit cell	60.21	67.14	66.32
Round shaped ROI	60.56	68.00	65.26
Polygonal ROI	60.92	68.07	65.19
Mean	60.56	67.74	65.59
Standard deviation	0.36	0.52	0.63

The overall average porosity of the knitted fabric examined by μCT is 64.6%, the coefficient of variation represents 5.7% and the confidence interval is within <60.4, 68.9>.

3.2 Evaluation of fabric porosity by mathematical model

Porosity of the knitted fabric is formulated by volume fraction μ, which is the ratio of fibre material volume V to the unit cell cube volume V_c [13]. In the case of the knitted fabric, Vc can be defined as a cuboid of dimensions: $a \times b \times T_0$ (Figure 8) where a is course spacing, $\boldsymbol{b}$ is wale spacing, T_0 is thickness of the fabric.

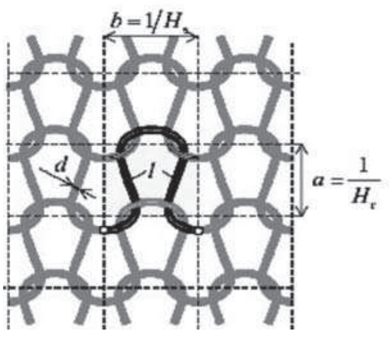

Figure 8: Basic unit cell cube of the knitted fabric

Volume of the fibres, respectively of the yarn V (Equation 1) in one basic unit cell (dark grey rectangle) can be expressed as the product of the loop length l in the unit cell and it's cross section area Sp.

$$V = \frac{l \cdot \pi d^2}{4} \quad (1)$$

Then we can formulate the volume fraction as the ratio of V and V_c (Equation 2).

$$\mu = \frac{V}{V_c} \quad (2)$$

Porosity of the knitted fabric ψ_p can be expressed by equations 3–4, as a supplement to the volume fraction:

$$\psi_p = 1 - \frac{V_{yarn}}{V_{total}} \quad (3)$$

$$\psi_p = 1 - \mu \quad (4)$$

where V_{total} is volume of one basic unit cell of knit.

In order to express the fabric's porosity, respectively volume fraction by standard calculations based on the mathematical model, the following measurements of the knitted fabrics were made by KES system, namely measurement of the of fabric's thickness (T_0), and by image analysis Nis-Elements, namely number of wales and courses per cm, dimensions of 1 basic unit cell, effective diameter of the yarn, loop length (Figure 9).

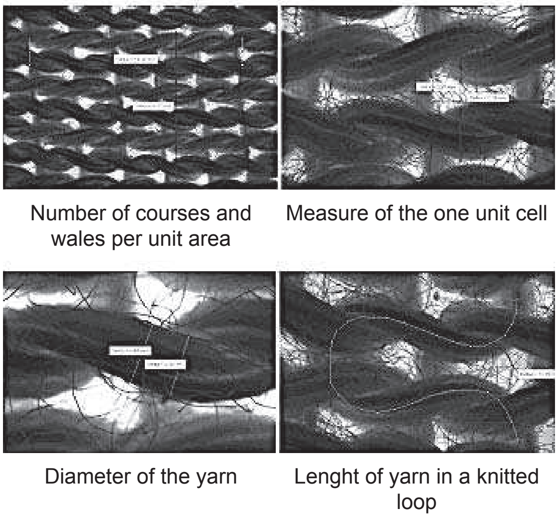

Figure 9: Dimension measurements of the knitted fabric by using image analysis Nis – Elements

Table 3 shows the knit's parameters measured by image analysis system Nis – Elements.

Table 3: Values for porosity calculation

Properties	Values
Mean thickness T_0 of the measured knitted fabric by using KES system	3.067 m
Number of courses per cm (Hr)	4.127 cm^{-1}
Number of wales per cm (Hs)	3.490 cm^{-1}
Mean loop length l (experimentally measured)	1.137 cm
Mean value of effective diameter of the yarn d	0.842 mm
Mean value of dimension a	0.240 cm
Mean value of dimension b	0.292 cm
Mean area of 1 basic unit cell of the knitted structure	0.070 cm^2

Because of the clearer picture of the measured knitted fabric – the density coefficient was calculated. The density coefficient of basic single knitted fabrics is usually C = 0.7–0.9 depending on the fabric structure. According to Dalidovič, the theoretical density coefficient of the ideal basic single knitted structure is C = 0.865 [14]. In our case the density coefficient is C = 0.82. The density coefficient, paradoxically, does not directly describe the porosity/compactness of the knitted structure. It only defines the ratio between the loop width and loop height, or the ratio between the horizontal and vertical density of the knitted structure (Equation 5) [14, 9].

$$V = \frac{a}{b} \approx \frac{Hs}{Hr} = 0.85 \quad (5)$$

where Hs is number of courses per cm and Hr is number of wales per cm.

Volume fraction μ was calculated from the experimentally measured values and it equals. Porosity of the knitted structure was calculated as that which represents the resulting value of the porosity 70.6%. Finally the difference between porosity measured by μCT and porosity calculated from the mathematical model is only about 6%, therefore it can be stated that the μCT method is suitable for measuring the porosity of knitted fabrics.

3.3 Porosity by microtomography and air permeability

The following experiment analyses the dependent relationship between porosity of the knitted structures obtained by using μCT SkyScan 1174 and air permeability measured on FX device 3300 according to EN ISO 9237. This analysis was carried out to verify correctness of suggested process of 3D porosity measurement. Therefore the group of three knitted structures (Table 1) were investigated by the same way as knits No. 1. Table 4 shows measured values of the porosity and air permeability.

Table 4: Results of porosity measurement, air permeability measurement of tested materials

Fabric	Statistical characteristics	Porosity [%] by μCT	Air permeability [ms^{-1}] by FX 3300
1	mean	64.63	1.26
	standard deviation	3.22	0.11
2	mean	58.54	1.15
	standard deviation	1.74	0.04
3	mean	54.81	0.37
	standard deviation	1.92	0.03
4	mean	70.52	2.5
	standard deviation	2.38	0.11

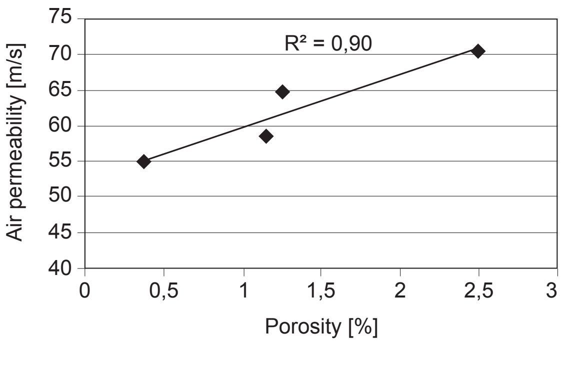

Figure 10: Chart of air permeability of tested materials on their porosity

Graph 1 (Figure 10) shows a near positive linear relationship between pore size and air permeability values ($R^2 = 0.9$), hence it could be assumed as the high value of the correlation. The abovementioned results affirm suitability of microtomography application for 3D porosity measurement.

4 Conclusions

This work has confirmed the suitability of μCT for textile materials, respectively for analysis of the physiological properties in textile metrology. Dependent property of the porosity – air permeability – was evaluated by conventional standard methods. Based on the obtained 3D image of the knitted fabric structure, an analysis of the relationship between 3D porosity & air permeability was subsequently made. Obtained porosity data measured by the 3D device SkyScan 1174 was compared to the porosity calculated from the standard mathematical model.

The percentage of the air volume in the examined knitted fabric obtained by μCT is 64.63%. Porosity expressed through the volume fraction has a value of 5.97% higher than by μCT approach, which is 70.6%. Due to the variability of architecture of the knitted structures, this result is considered as very satisfactory. Furthermore, the assumption of a strong relationship between air permeability and porosity of the knitted structures was confirmed, where $R^2 = 0.9$, which represents a near positive linear relationship.

The benefit of this work is as a more accurate method for evaluating porosity of knitted structures which is less laborious and less time consuming than traditional ways of porosity determination. Moreover, in more complicated knitted structures than the single jersey it is very difficult to obtain a mathematical model, so the μCT approach can significantly simplify the determination of porosity.

Another benefit is the possibility of processing 3D images in different programs, for example further mathematical analysis, rendering of the textile structures or graphical output in the form of images and animations. These programs also allow "insight" into the internal structure of the investigated specimen.

An interesting possible outcome of μCT approach is also storing the 3D model format stl which is designated for 3D printing (RP). Based on the spatial information obtained from this stl format the 3D model of the knitted structure was printed.

3D analysis of knitted structure's porosity was proven to be a suitable method and relatively accurate, and therefore the results from the 3D analysis made by µCT can be considered as an alternative method for determining porosity of textile materials. Since porosity is a function of air permeability, we consider µCT analysis a new evaluation method of physiological textile properties.

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