# THE THERMAL AND POROUS PROPERTIES OF PROTECTIVE RUBBER BOOTS

**Marcela Kolinova**[1], **Martina Syrovatkova**[1], **Petra Komarkova**[2] **and Rudolf Tresnak**[2]

[1]*The Institute for Nanomaterials, Advanced Technology and Innovation, Technical University of Liberec, Czech Republic*
[2]*Department of Clothing, Technical University of Liberec, Czech Republic*
*marcela.kolinova@tul.cz, martina.syrovatkova@tul.cz, petra.komarkova@tul.cz, rudolf.tresnak@tul.cz*

**Abstract:** *Utilization of the space warp knitted fabric and their combination with different non-textile materials increases in many areas of life nowadays. These materials are highly porous with excellent thermal properties. This paper presents an experimental investigation on the thermal behaviour and porosity of the sandwich structures defined for the production of protective rubber boots. The coefficient of the thermal conductivity was measured by the heat flow meter and togmeter. The porosity was detected by the using non-destructive method by the microtomography. The paper also describes the influence of porosity on the thermal conductivity of the sandwich structures defined for the production of protective boots. The results show significant effect of sandwich structure porosity on their thermal conductivity. Finally the paper describes the sandwich structures by the using special software for analysis the porosity of structures, their connectivity and the pores size distribution inside structures. The results of this study indicate that the sandwich structure containing 3D knit show better thermal properties.*

**Keywords:** *thermal conductivity, porosity, pores size distribution, protective rubber boots, space warp knitted fabric.*

## 1 INTRODUCTION

It is well know that the porosity is important parameter for thermal properties. Thermal properties of the specific footwear have influence on the choice of material for their construction. Generally, low thermal conductivity of material is characterized by beneficial thermal properties [1]. The insulation characteristics of the specific footwear depend on the structure, material thickness, number of layers, humidity of the environment, etc. For this special protective footwear are required good porous and thermal properties. During summer, the thermal conductivity of materials should be low to resist heat transfer from outside to inside and in winter it is reverse (to protect heat transfer from inside to out). The porosity of the fabric is a key parameter for evaluating the permeability of the material. Air permeability is important factor influences the comfort of a textile product and is actually a function of the porosity of the material [4]. There are several methods to determine the porosity of the material [2]. One of the latest methods is the detection of this parameter using X-ray microtomography. There is a non-destructive analysis of any textile and non-textile structure. There are many methods and devices for measurement of thermal insulating properties of fabrics [3]. They differ in principle and applicability. For each device we have to evaluate the influences of various factors (different sample sizes, dissimilar pressure for testing samples, different types of sensors, measurement errors, etc.). For detecting the porosity of the textile structures exist methods (image analysis, bubble sort, ...) which are different methodology and applicability [10].

## 2 EXPERIMENTAL

### 2.1 *Materials*

In the present study four sandwich structures defined for the production of protective rubber boots are used for testing (Table 1). Material thickness measurement was performed as per ČSN EN ISO 5084.

**Table 1** The tested materials and their characteristics

| Sample No. | Fiber composition | | | | | | | Thickness [mm] | Mass per unit area [g/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|
| | *rubber* | *3D knitted* | *PU foam* | *brush. velour* | *adhez. layer* | *rubber foam* | *tricot* | | |
| C1 | ✓ | ✓ | ✓ | ✓ | - | - | - | 8.79 | 2680 |
| C2 | ✓ | ✓ | ✓ | ✓ | - | - | - | 10.72 | 2660 |
| C3 | ✓ | - | - | - | ✓ | ✓ | ✓ | 7.20 | 3640 |
| C4 | ✓ | ✓ | - | ✓ | ✓ | ✓ | - | 9.98 | 3690 |

### *2.2 Methods*

The paper shows 3D analysis of the sandwich structures. The resolution is porosity, connectivity, pore size distribution and 3D visualization of the samples. This study indicates experimental investigation of the effect of porosity on the thermal properties which are most frequently evaluated by the coefficient of thermal conductivity. Material properties were measured according to standards - EN ISO 5084 (800844) Textiles - Determination of thickness of textiles and textile products and EN ISO 12127 (800849) Textiles - Determination of mass per unit area using small samples. Thermal and porous properties of sandwich structures were experimentally verified by heat flow meter (Instrument was designed according to ASTM C518-04 - Standard Test Method for Steady - State Thermal Transmission Properties by Means of the Heat flow Meter Apparatus. Resulting values of thermal conductivity are calculated in accordance with ASTM C1045-01 - Standard Practise for Calculating Thermal Transmission Properties Under Steady - State Conditions.), togmeter (according to ISO 5085 - Determination of thermal resistance - Part 1: Low thermal resistance, Part 2: High thermal resistance) and microtomography (according to producer´s standards are not standardized). Finally an attempt has been made in this study to find the correlation between thermal conductivity and porous characteristics of the test samples.

*Coefficient of the thermal conductivity*

The measurement of the ability of a material to transfer heat [5]. Given two surfaces on either side of the material with a temperature difference between them, the thermal conductivity is the heat energy transported per unit time and per unit surface area, divided by the temperature difference. It is measured in watts per degree Kelvin [3].

*The instruments to measure coefficient of thermal conductivity*

The general principle of the heat flow meter instruments is based on one dimensional Fourier law. If a flat sample is placed between two flat isothermal plates maintained at two different temperatures, and a uniform one-dimensional temperature field has been stabilized, the temperature field in the sample should be uniform within all the sample's volume [4]. The temperature gradient can be determined by measurements of the difference between temperatures of the hot and cold plates and thickness of the sample. The lower plate was set at 35°C and the upper plate been continuously adjusted to temperatures -20, -10, 0, 10 and 20°C.

*The instrument to measure thermal resistance*

The principle of the device is that, so conductors in series with respect to the direction of heat flow, the ratio of the temperature drop across the conductors is equal to the ratio of their thermal resistance. Thus, if the temperature drop across a material of known thermal resistance and that across a test specimen in series with it are measured, the thermal resistance of the test specimen can be calculated. The specimen is tested in the horizontal plane [5]. The instrument is equipped temperature sensors. The heating element is controlled by a digital temperature controller. The device is placed in the casing where is controlled air flow. The samples of a circle are inserted on one plate of the unit or between the two plates of the device. Then turn on heating element and temperatures are read in each of the three thermoelectric points after steady state.

*Porosity, connectivity and pores distribution*

Microtomography can be used to visualization the internal structure of the materials by non-destructive way [8, 9]. There is important 2D or 3D analysis to obtain quantitative parameters of scanned dataset. Special software performs a picture analysis on selected pixels (white pixels = object and black pixels = pores). Connectivity determines which pixels are connected to other pixels (2D)/voxels (3D), it characterized mass and pores. A precondition for such an analysis is different X-ray absorption material components [8].

*The microtomography to 3D analysis of the structures*

Microtomography scans the object in the form of 2D images, which can be converted with the help of special reconstruction software to 3D object. The resolution of the device is up to 0.5 micron, the maximum size of a tested material 70 mm in diameter and in length [6].

## 3 RESULTS AND DISCUSSION

### *3.1 Measurements of thermal conductivity λ by using heat flow meter*

The influence of temperature of the upper plate device on the coefficient of thermal conductivity of the sandwich materials is shown in Figure 1. There is evident that the coefficient of thermal conductivity increases with increasing temperature of the upper plate unit from the Figure 1. All tested sandwich structure exhibit very acceptable thermal insulation properties for different temperature gradients. The graph shows the average value (5 measurements). The coefficient of variation has a very low mutual variety. The curve of sample C3 shows different dependence than other structures. This sample consists from rubber foam and does not contain spacer warp knitted fabric.

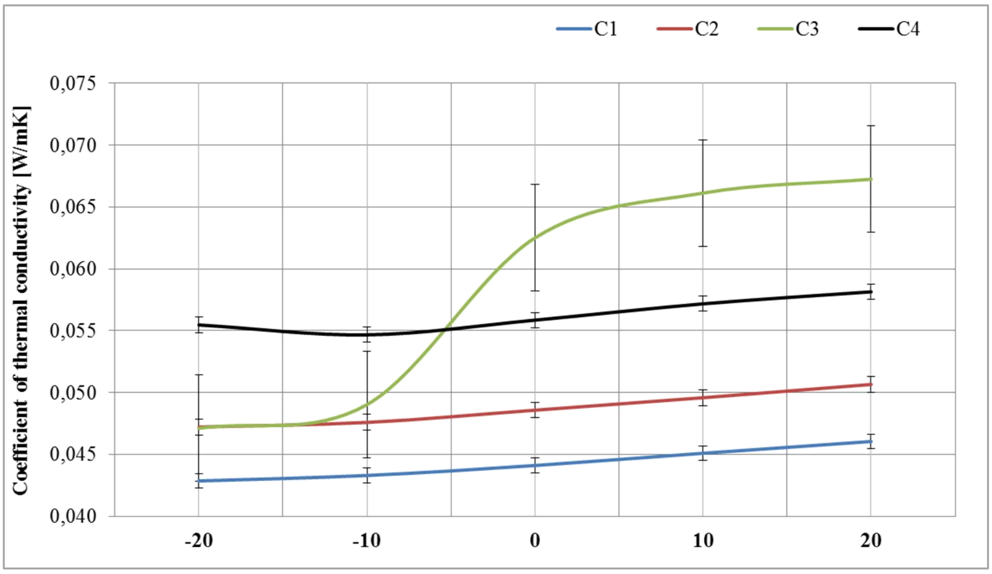

**Figure 1** The influence of temperature on the coefficient of the thermal conductivity

### 3.2 *Measurements of thermal resistance by using togmeter*

There was used method of measuring single-plate. The sample remained uncovered and after steady state temperatures were read in each of the three thermoelectric points. The result of measurement is shown in Figure 2.

The measurement the coefficient of thermal conductivity by this device shows a low value of this parameter. As in the previous experiment, the thermal insulating properties of the sandwich structures defined for the production of protective boots are very favourable. The sample C3 has higher coefficient of thermal conductivity. The graph shows the average value (5 measurements). The coefficient of variation has a very low mutual variety.

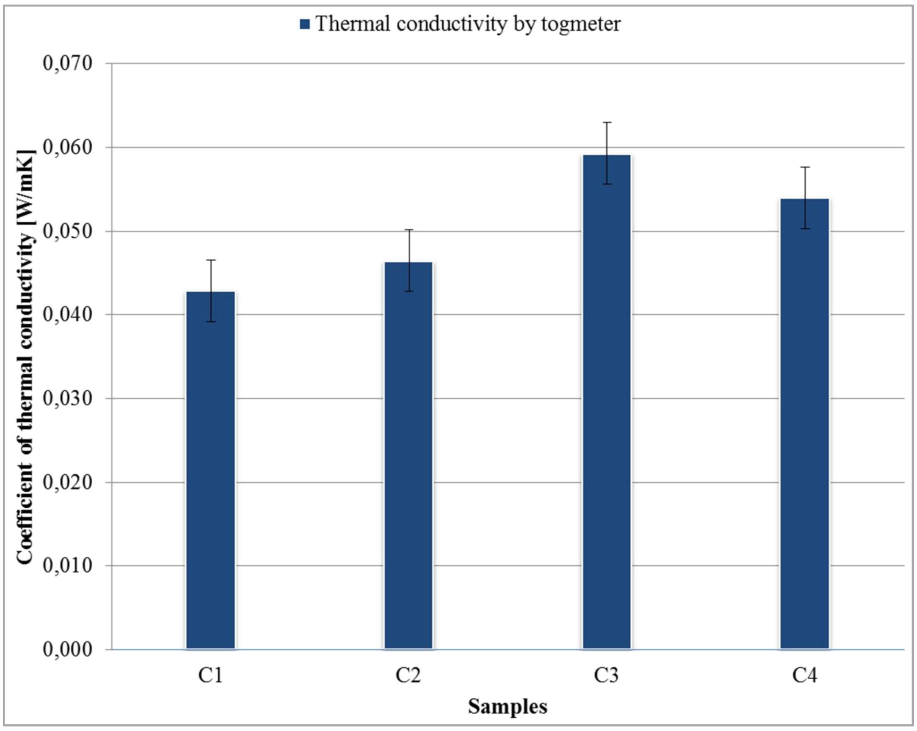

**Figure 2** The measurement of coefficient of the thermal conductivity by togmeter

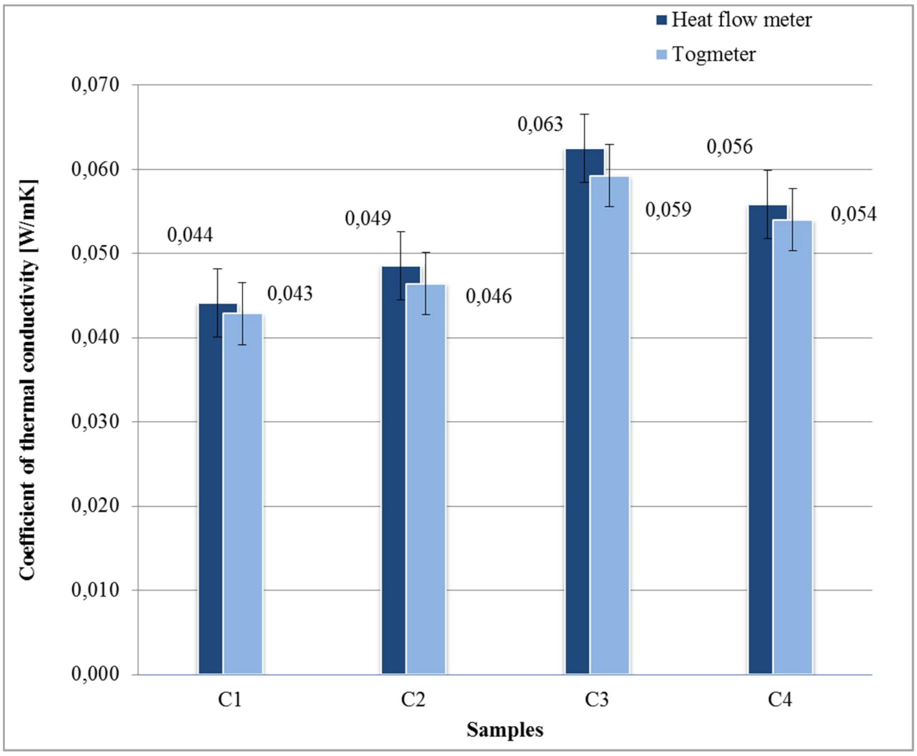

**Figure 3** The comparison of results of coefficient of the thermal conductivity

### 3.3 The comparison of results of coefficient of thermal conductivity by two units

The comparison of measurement results of coefficient the thermal conductivity for sandwich structure by using two devices is shown in Figure 3.

The values obtained of the two devices are equivalent and the percent deviation is very small.

### 3.4 Analysis of sandwich structures using microtomography

Sandwich structures were scanned by microtomography with the same scanning parameters (Table 2).

**Table 2** Scanning parameters

| | |
|---|---|
| **Source Voltage [kV]** | 50 |
| **Source Current [µA]** | 200 |
| **Image Pixel size [µm]** | 4 |
| **Exposure [ms]** | 531 |
| **Rotation Step [deg]** | 0.2 |
| **Scan duration [min]** | 53 |

The obtained datasets were reconstructed and then were made visualization of these structures (Figure 4). Finally the 3D analysis of samples was performed using specific software (Table 3).

**Table 3** The results of 3D analysis by using CT-microtomography

| Characteristics of sandwich structures | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| **Total VOI volume [mm$^3$]** | 121 | 168 | 93 | 130 |
| **Total porosity [%]** | 77 | 86 | 61 | 61 |
| **Connectivity** | 99 921 | 73 568 | 291 874 | 399 903 |

Note: The total porosity of the each samples corresponds to the total VOI volume of the test material shown in table.

### 3.5 The influence of the porosity on the thermal properties of sandwich structures

Also, pore size distribution was analyzed for each sample. The pore size was distributed at the following ranges: 0 – 0.21 mm, 0.22 – 0.40 mm, 0.41 – 0.60 mm, 0.61 – 0.80 mm, 0.81 – 1.00 mm and 1.00 – 1.44 mm. Percent volume in range for each material is shown in Figure 6.

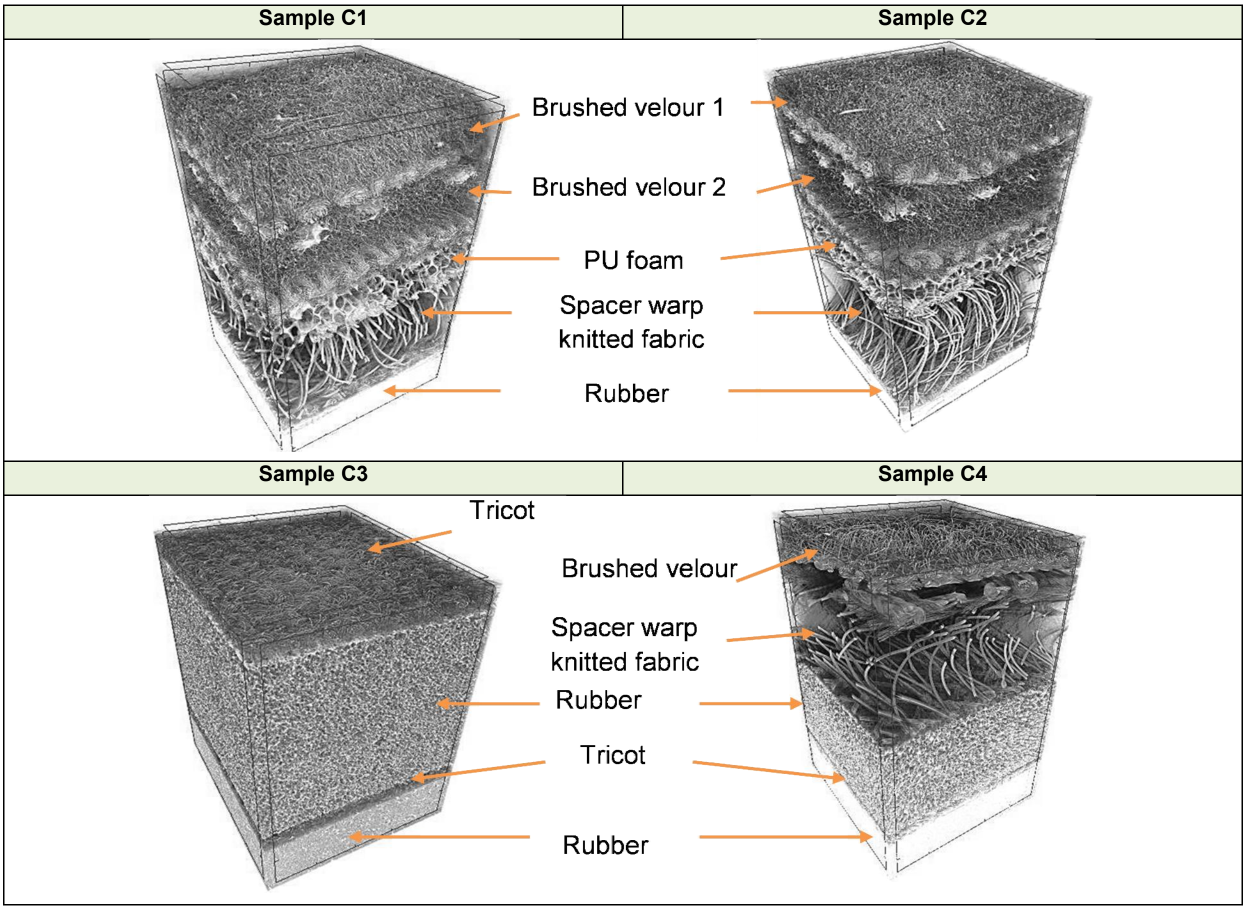

**Figure 4** The visualization of sandwich structures by specific software CTVox

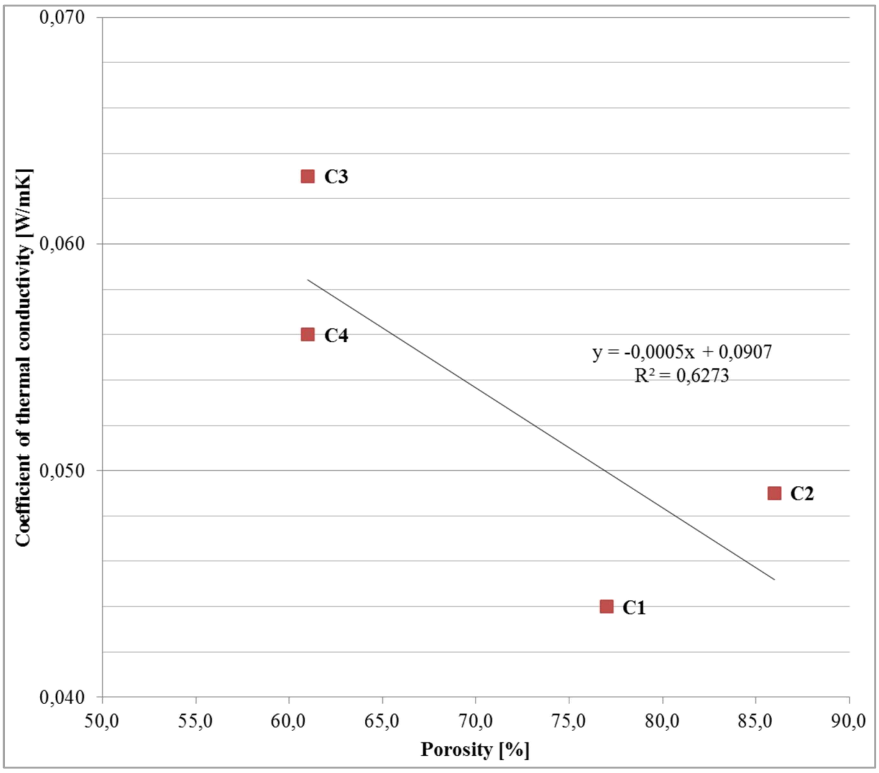

**Figure 5** The influence porosity on the coefficient of thermal conductivity

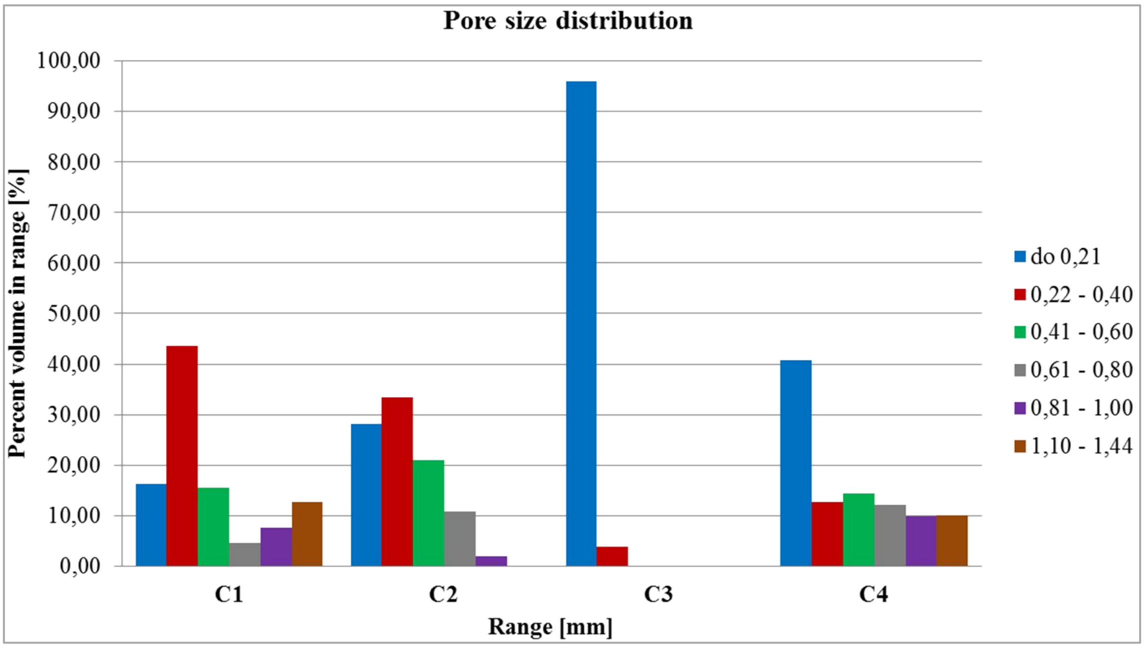

**Figure 6** Percent volume in range of each tested sample

## 4 CONCLUSION

In this paper were tested thermal insulating and porous properties of the sandwich structures defined for production of the protective footwear (Table 4). The coefficient of thermal conductivity was tested by two devices including a comparison of the measurement results. Porous properties were investigated by X-ray non-destructive analysis including pore size distribution for the studied samples.

**Table 4** Detected values of tested samples

| Samples | Coefficient of thermal conductivity [W/mK] | Connectivity | Porosity [%] |
|---|---|---|---|
| **C1** | 0.044 | 99 921 | 77 |
| **C2** | 0.049 | 73 568 | 86 |
| **C3** | 0.063 | 291 874 | 61 |
| **C4** | 0.056 | 3 993 | 61 |

1. By testing of the coefficient thermal conductivity by the heat flow meter was found that a sandwich structure containing a spacer warp knitted fabric (especially the samples C1 and C2) show better thermal insulation properties i.e. lower coefficient of thermal conductivity. Compared to that the sandwich with predominant component of foam rubber present worse thermal insulation properties (C3). Samples C1 and C2 have identical composition and they differ only in the material thickness. It causes the differential coefficient of thermal conductivity. Sample C4 is a structure similar to the sample C3 containing also a thin layer of the spacer warp knitted fabric.
2. The results of experimental measurement of the coefficient thermal conductivity by the togmeter showed a very similar measured value as in the point 1. Comparison of these results of the coefficient of thermal conductivity by the two devices is comparable though the methodology is different for each device.
3. The spacer warp knitted fabrics have big amount of air in the pores and therefore the coefficient of thermal conductivity of sandwich structures containing spacer warp knitted fabric decreases. Samples C1 and C2 due to the content of these spacer warp knitted fabric have higher porosity. It indicates good permeability and it leads to improved thermal insulation properties. Conversely connectivity of these structures is increased in materials without the 3D knitted (samples C3 and C4). The pores size distribution for tested sandwich structures is follows:
   - Sample C3 contains about 96% pores in range to 0.21 mm. Other samples contain less - C1 (16%), C2 (28%) and C4 (41%).
   - In the range from 0.22 – 0.40 mm, the sample C1 contains 44%, sample C2 34% and C4 contains 13% of pores. Sample C3 contain these pores size only 4%.
   - In the biggest pores size in the range 1.10 – 1.44 are included samples C1 (about 10%). Samples C2 a C3 does not content these pores.

The sandwich structures defined for the production of specific protective footwear are good insulators with high-porous characteristics especially containing spacer warp knitted fabric. Their wide use is also applied in the production of specific protective footwear and it contributes to increase the thermal insulating and porous properties of the whole sandwich structure. Further research will be focused on quality rubber and subjective testing of heat-insulating properties. Comfort is important and depends on the individual feeling of the user.

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