How high-loft textile thermal insulation properties depend on compressibility

Viera Glombikova, Petra Komarkova, Eva Hercikova, Antonin Havelka
Technical University of Liberec, Faculty of Textile Engineering, Department of Clothing Technology, Liberec, Czech Republic
Corresponding author: Viera Glombikova, tel: 00420 5353124
Email: viera.glombikova@tul.cz, petra.komarkova@tul.cz, eva.hercikova@tul.cz

1. Introduction
A number of studies deal with research of thermal insulation effectivity of filling materials up to now [1-3]. Apart from natural filling material as the goose down, the synthetic nonwoven insulations and newly “artificial down” are well known for their superior thermal insulating properties and these are widely used as an insulating filling material for winter outerwear or sleeping bags [4-6]. Researchers often refer to thermal insulation performance of fillings in relation to their thickness or weight. In general, thermal resistance of fillings increases with the increase in their thickness [2, 5]. If the porosity of nonwoven fabrics remains constant, the change in thickness (in range of 6-9 mm) has no significant impact on the conductive heat transfer and radiative heat transfer according to the study by Zhu et al. [7]. Physical properties of insulation materials such as bending stiffness, compressibility and recoverability are key determinants to provide the required thermal protection [6, 8]. Furthermore, effects of fiber cross-sectional shapes and fabric weight on thermal insulation, thickness, density, compression and air permeability of polyester needle-punched fabrics have been studied by Debnath and Madhusothanan [9]. One of the conclusions in this report was that the percentage compression decreases with the increase in fabric weight regardless of cross-sectional shapes of polyester fibers. Although some research has been carried out on the topic of insulation performance, there has been no detailed investigation of the relationship between the compression ratio after cyclic loading (simulating real conditions of use) and the decrease in insulation of fillings. This study tries to analyze how much thermal insulation can deteriorate during lifetime period of products made from the tested materials. This study is a follow-up of our earlier study that dealt with the assessment of thermal resistance of synthetic fillings used for sportswear (the same tested material as in the current study), intended for low ambient temperatures (below zero) [10].

2. Experimental details
2.1. Materials
Two sets of insulation materials frequently used in the production of highly functional sportswear and sleeping bags, high-loft insulation materials ClimaShield® and Primaloft® were evaluated in the study. It was interesting to evaluate the influence of weight on compressibility and relaxation behavior of samples after dynamic loading and their thermal performance. Therefore, six groups of samples were tested depending on different weights of fillings. Furthermore, change in thermal properties of samples before and after loading was analyzed. The basic characteristics of the tested samples are shown in Table 1. Sample A (Primaloft®) uses patented structure of fine microfibers with hollow fibers of higher diameters, by which efficient thermal insulation properties are achieved (Figure 1). Higher amount of air that ensures the thermal insulation capacities even in small thickness of the insulation layer is bound on the cavities between microfibers due to their microscopic dimensions. Thanks to the hollow fibers of bigger diameters, elasticity and thermal insulation properties are maintained even after long-term use, compressing, washing and drying.

Abstract:

This paper investigates the performance of high-loft thermal insulations in terms of their compression properties, recovery behavior and thermal resistance. The aforementioned properties belong to the basic producer requirements for winter functional sportswear, sleeping bags or blankets. Majority of thermal insulation producers declare high quality of their products claiming durability and insulation within beginning of their application. But, it is important to uncover how dynamic compressive loading (which simulates real condition of using) influences heat transport of tested filling for the whole lifetime period. Therefore, two groups of top synthetic thermal insulation materials were tested before and after compression loading. Subsequently, relaxation behavior of samples was determined by thickness recovery after the compression test. Furthermore, thermal resistance was measured before and after the compression test to find out the change in thermal effectivity of samples. In summary, these results have not met expectations and show a rather poor correlation between the rate of compression after dynamic loading and the drop of thermal resistance of tested fillings.

Keywords:

Thermal insulation, compressibility, recovery, relaxation, thermal resistance
Three-dimensional (3D) structure of B (ClimaShield®) textil (as well as in down) is created by thermally bonded cross fibers with hollow channels of triangular cross-section. Diameter of the fibers is in the range of classic hollow fibers and microfibers but due to the cross-section, the fibers are mechanically stronger than common hollow fibers (Figure 1). A batting is a typical chemically tied web of synthetic fibers with subsequent longitudinal layering. Before being measured, the samples had been air-conditioned for 24 hours. The measurement was carried out in an air-conditioned room under constant conditions at a relative humidity of 65% and the standard temperature of 20°C.

### 2.2. Methods

The experiment simulated real wearing conditions of winter jackets including carrying a backpack. The performance of the tested insulations was investigated by the following ways:

- measuring of **compression and relaxation behavior** by static and dynamic loading and
- measuring of the **thermal resistance before and after the test of dynamic loading**.

The results from the abovementioned methods were compared and discussed to detect the real efficiency of the tested materials. Final values (means) of all the tested parameters correspond to five measurements on average.

#### 2.2.1. Compression and relaxation behavior

**Static loading**

Repeated compression-recovery test was carried out by the device developed by the Technical University of Liberec [11], as shown in Figure 3. This simple device consists of a transparent perspex cylinder (base diameter is 14 cm) and a pressure plate for a set of required compression values. To ensure accuracy of measurements, five layers of materials were measured simultaneously and the image processing method NIS Element system was used for both before and after loading measurements.

Mutual combinations of two different settings of loading time (10 and 30 min) and two settings of relaxation time (15 and

### Table 1. Specification of the tested samples

<table>
<thead>
<tr>
<th>Sample codes</th>
<th>Raw material</th>
<th>Structure</th>
<th>Weight (g/m²)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A A1</td>
<td>100% polyester</td>
<td>Nonwoven (hollow fibers)</td>
<td>73</td>
<td>9.4</td>
</tr>
<tr>
<td>A A2</td>
<td></td>
<td></td>
<td>102</td>
<td>9.9</td>
</tr>
<tr>
<td>A A3</td>
<td></td>
<td></td>
<td>142</td>
<td>13.5</td>
</tr>
<tr>
<td>B B1</td>
<td></td>
<td>Nonwoven (hollow fibers, microfibers)</td>
<td>55</td>
<td>8.5</td>
</tr>
<tr>
<td>B B2</td>
<td></td>
<td></td>
<td>92</td>
<td>9.3</td>
</tr>
<tr>
<td>B B3</td>
<td></td>
<td></td>
<td>119</td>
<td>13.2</td>
</tr>
</tbody>
</table>

![Figure 1. Sample A of textile insulation, magnification of 10 mm and 100 mm [10]](image1)

![Figure 2. Sample B of textile insulation, magnification of 10 mm and 100 mm [10]](image2)

![Figure 3. Schema of static loading measurement](image3)
40 min) were used for the testing. In total, five cycles were done for each type of the test and each sample. The pressure of static loading was 300 Pa. The measuring conditions were arranged according to the standard EN ISO 33886-1: Polymeric materials, cellular flexible – Determination of stress–strain characteristic in compression.

The compression $C$ [%] and recovery $R$ [%] were determined by means of equations (1) and (2). Generally, compression is reduction in volume when pressure was applied. In this case, the compression after relaxation (15 min or 40 min) was measured.

$$ C = \left( \frac{h_1 - h_2}{h_1} \right) \times 100 \quad [\%] $$

(1)

where $h_1$ is the original height of the samples and $h_2$ is the height of the samples after removal of load (after relaxation time).

Recovery is given by equation (2) as the degree to which a sample mass recovered to its original height upon unloading.

$$ R = \left( \frac{h_3 - h_1}{h_3 - h_4} \right) \times 100 \quad [\%] $$

(2)

where $h_1$ is the original height of the samples, $h_3$ is the height of the samples under load, and $h_4$ is the height of samples after removal of load.

Dynamic loading

To study the thickness variation of insulation fabrics under dynamic loading, the measurement device shown in Figure 4 was used. This instrument was developed at the Technical University of Liberec [12]. A pressure plate with a contact area of 78.5 cm² (diameter is 10 cm) moved vertically up and down with a frequency of 400 cycles per min, applying a dynamic load of 6 kPa on the samples. The applied pressure of static loading corresponds to the average loading by straps of a 10 kg backpack. This pressure was determined by the XSENSOR® X3 pressure mapping system. Twenty-four thousand cycles were applied to each tested sample to simulate real conditions of backpack wearing. Number of applied cycles should be reflecting how many times wearer uses backpack (puts backpack on or off) during two seasons approximately.

The variation of thickness of the tested samples was measured by digital thickness gauge SDL M034A both before and after dynamic loading. Applied pressure (during all measurements of thickness) was set to 50 Pa because the other devices use a low pressure for the measurement of thermal properties, for example, for Togmeter SDL M 259 the pressure is 5 Pa and equipment Fox 314 according to ASTM D1518 measures under a pressure of 70 Pa. Moreover, the carried experiment for fixing thickness of sample by different pressures confirmed the abovementioned conclusion.

The compression $C$ [%] was determined by means of equation (1). Parameter $h_2$ is the height of the samples, which was measured immediately after the removal of load on the contrary of static loading that is measured under load. This parameter should simulate the sample behavior of the sample after taking the backpack off.

### 2.2.2. Measurement of thermal resistance

Thermal resistance $R_{ct}$ [m²K/W] of samples both before and immediately after dynamic loading was investigated by a hotplate system developed at the Technical university of Liberec [10]. The equipment (Figure 5) for measuring thermal resistance consists of two principal parts, namely, thermal resistance measuring the equipment itself and an air-conditioning chamber. The air-conditioning chamber allows creation of an environment (humidity and temperature), which corresponds to the real conditions (temperatures below zero included), in which the tested materials for sportswear are actually used. Maximum deviation of temperature and humidity in the chamber was set at the requested value of ±1ºC, ±2% RH. This chamber controls the air velocity on the outer surface of the tested sample as well. The air velocity corresponds to 1 m/s. The measuring equipment consisting of a heating plate, the constant surface temperature of which is ensured using a simple regulation circuit with a thermocouple sensor at the value of 35 ± 1ºC, is placed into the air-conditioning chamber. The tested sample, edges of which are fixed by a frame, is placed onto the heating plate. Thermal resistance $R_{ct}$ is determined on the basis of sensing the sample surface temperature on both fabric sides of the fabric and the quantity of heat flowing through the fabric measured by a thermal flux sensor. The data obtained from the abovementioned sensors...
are wirelessly transferred from the measuring center to a PC. Standardized measurement of thermal insulation properties was carried out under standard laboratory conditions, i.e. ambient temperature of 20°C and relative humidity of 65%. The used method performs well in accordance with the standard EN 31092:1993 (ISO 11092) by Sweating Guarded Hotplate System 8.2 [10]. Furthermore, the aforementioned device enables us to test small size samples, which are impossible to measure by the SGHP system.

![Sensor of heat flux](image)

Environment temperature held at required value e.g. 20 °C and 65 % humidity

Heat flux sensor on the top of the fabric

Thermocouple on the bottom of the fabric

**Figure 5. Schema of TUL measuring equipment [10]**

3. Results and discussion

3.1. Variability of thickness

Producers declare the weight of the tested samples to be 60, 90 and 130 g/m². Experimentally measured weights of the tested samples are in the range of 55–142 g/m². The thickness was measured under pressure equal to 50 Pa at steady state thickness. Coefficient of thickness variation is in the range of 18–40%, as shown in Figure 6. It is a well-known fact that both rate of weight irregularity and thickness irregularity of tested nonwovens are caused by the way of web processing. The abovementioned fact can influence variation degree of the tested samples from point of view of their compressibility and thermal properties.

![Variability of thickness](image)

**Figure 6. Thickness variability of the tested samples**

3.2. Compression and relaxation behavior

The results of compression C [%] and recovery [%], equations (1) and (2), are particularly shown in Figures 7 and 8.

**Figure 7. Compression C [%] of the tested samples after static loading**

**Figure 8. Recovery R [%] of the tested samples after static loading**

3.3. Thermal resistance

The graph in Figure 10 summarizes the results of influence of compressibility on thermal insulation properties of filling materials. The thermal resistance $R_{ct}$ [m²K/W] was chosen as an indicator of thermal insulation.
4. Conclusion

This research extends the knowledge of high-loft thermal insulation materials that considerably affect the wearing comfort of sportswear or sleeping bags. The tested group of filling materials was investigated with respect to compression behavior and thermal properties. This investigation confirmed that intensity of high-loft insulations compressibility is influenced by loading time and time of relaxation.

Furthermore, the study complements earlier studies particularly regarding the impact of both weight (thickness) and compressibility on thermal properties of fillings. The results of this study indicate that the compressibility of filling becomes smaller as the weight of fillings increased. The degree of compression is heavily dependent on the mass unevenness of filling. Variations of thickness can reach even 40%. On the other hand, this drawback can be balanced out by input raw material, namely appropriate ratio of microfibers and hollow fibers of bigger diameters in the filling structure. The relevance of the above is clearly supported by the current findings regarding the poor correlation ($R^2 = 0.4$) between the compression rate (up to 28%) and the corresponding rate of change in thermal resistance (7–18%).

Figure 10 provides the results obtained from the analysis of influence of dynamic loading on thermal resistance. The fillings are forced to regroup their internal structure and the air is discharged out of the fabric due to the applied pressure.

Generally, the thermal resistance of air is much bigger than thermal resistance of fibrous polymers. This fact causes a decrease in thermal resistance of filling [13, 14].

$R_{ct}$ difference [%] was determined by means of equations (3) as follows:

$$R_{ct}\text{ difference} = \left(\frac{R_{ct1} - R_{ct2}}{R_{ct1}}\right) \times 100\ [%]$$

(3)

where $R_{ct1}$ is the value of thermal resistance measured before the dynamic loading (before compression), and $R_{ct2}$ is the thermal resistance measured after application of dynamic loading (after removal of load).

The good news is that the drop in thermal insulation (i.e., "$R_{ct}$ difference [%]") ranged from 7 to 15% even in the case of compression after dynamic stress loading was about 28%, see sample B1 in Figure 11. In addition to that Figure 12 shows poor correlation between compression C [%] and $R_{ct}$ difference [%].

Figure 12. Effect of compression C [%] to $R_{ct}$.
Further research should focus on determining the relation between long-term stress on the filling and its moisture management transport under pressure.

Acknowledgement

This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic and the European Union – Operational Programme Research, Development and Education – project Hybrid Materials for Hierarchical Structures (HyHi, Reg.No.CZ.02.1.01/0.0/0.0/16_019/0000843).

References
