The influence of compressibility on the thermal contact conductivity of diamond-shaped quilted lining for special purpose clothing

Nikolina Jukl*, Snježana Firšt Rogale, Dubravko Rogale
University of Zagreb Faculty of Textile Technology, Zagreb, Croatia
*Correspondance: nikolina.jukl@ttf.unizg.hr

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In this paper, the influence of compressibility on the thermal contact conductivity of diamond-shaped quilted lining for special purpose clothing will be determined with the aim of obtaining the accurate data essential for the technical design of special purpose clothing, the required thermal properties. The tests were carried out on the basis of the newly established measurement method using a multipurpose differential conductometer, developed, patented, calibrated and installed in the Laboratory for thermal insulation properties of clothing at the Department of clothing technology. The materials mentioned are used for the production of thermal inserts and linings for special purpose clothing and have excellent thermal properties. Two specimens were oversewn using the sewing technique with square chamber segments, while the third specimen was joined using the ultrasonic welding technique with the so-called mirror-image trajectory of the ultrasonic welding, but in practice they are also called diamond-shaped quilted lining. The geometric parameters of the seam/weld and chamber segments, which also influence the thermal properties of the materials used, are determined with regard to the sewing or welding technique.

Key Words: *technical design of clothing; multipurpose differential conductometer; thermal contact conductivity; compressibility*

Izvorni znanstveni rad

U radu je određen utjecaj stlačivosti na kontaktnu toplinsku vodljivost romboidno prošivenih materijala za namjensku odjeću, a u cilju određivanja egzaktnih podataka bitnih kod tehničkog projektiranja namjenske odjeće potrebnih toplinskih svojstava. Ispitivanja su izvodena na temelju novouspostavljene mjerne metode na višenamjenskom diferencijalnom konduktometru, koji je realiziran, patentiran, umjeren te instaliran u Laboratoriju za termoizolacijska svojstva odjeće u Zavodu za odjevnu tehnologiju. Navedeni materijali se koriste za izradu toplinskih umetaka i podstave namjenske odjeće, te imaju izvrsna toplinska svojstva. Dva mjerna uzorka su prošivena tehnikom šivanja s kvadratnim korakom komore, dok je treći mjerni uzorak spojen ultrazvučnom tehnikom s tzv. zrcalno protusmjernom putanjom ultrazvučnog spajanja, ali se također, u realnom sektoru, naziva romboidno prošivenim materijalom. S obzirom na tehniku izrade prošiva, odnosno spojeva i korak komore korištenih materijala određeni su geometrijski parametri prošiva / spoja, koji također utječu na toplinska svojstva namjenske odjeće.

Ključne riječi: tehničko projektiranje odjeće; višenamjenski diferencijalni konduktometar; kontaktna toplinska vodljivost; stlačivost

1. Introduction

Special purpose clothing is clothing designed for a specific purpose, e.g. for civil protection (police and firefighters, special forces, doctors, hospitals and rescue workers), for laboratory technicians and scientists, for the military (soldiers and pilots), for road workers and maintenance services, for postmen, for workers on platforms for the extraction of natural resources (gas, oil, water), for astronauts, sailors and divers, for the manufacturing industry, for the pharmaceutical industry and many other activities.

The technical design of special purpose clothing is a complex process in which the influence of human anatomy and physiological characteristics, as well as the environment and activity in which the clothing is used, must be taken into account. In addition, the influence of the construction of the garment, the structure and properties of the embedded materials from which the garment is made, thermal and tactile comfort, etc. must be taken into account.

In the technical design of special purpose clothing, the specific conditions under which this clothing is to be used must be examined. On this basis, the technical design process begins, focusing on functionality as the first and fundamental requirement that must be met. Although they are very important for the subjective sense of physical and psychological comfort of the wearer, aesthetics and design become secondary elements in the realisation of special purpose clothing.

The thermal properties of clothing are influenced by the type and duration of the wearer's activity, their state of health, age, gender, etc., the environmental conditions (temperature, air flux, relative humidity) and the type and properties of the materials, the construction parameters of the clothing and layering. It is therefore necessary to select suitable embedding materials depending on the intended use of the clothing.

2. Embedding materials for the production of special purpose clothing

The embedding materials used to produce thermal inserts and linings for special purpose clothing to protect against low temperatures are high-tech materials with specific properties adapted to the user's needs. Laminated materials are generally used for the outer shell.

Laminated textile materials consist of one or two layers of textile material and a membrane layer that makes these materials breathable. In the production of textile laminates, the membrane can be applied to any layer of the materials that make up the laminate. So if it is attached to the back of the outer shell and the garment has no lining, it is in direct contact with the human body. In some versions, the membrane may be a separate layer from the outer material. It is placed on a layer of material between the lining and the outer shell of the garment, creating layers of trapped air. The membrane may also be placed over the lining fabric so that it is not in direct contact with the human body [1].

R. Plunkett, who worked for DuPont, developed polytetrafluoroethylene (PTFE) in 1938, which the company later trademarked under the name Teflon®. At the request of the US Army, this invention was protected as a military secret and used exclusively for military purposes during the Second World War, so that DuPont was unable to market its product. DuPont was only allowed one patent application in 1941 so that the company could continue to protect its right to use the invention and market it after the end of the war. However, the company continued to develop Teflon with improved properties for the needs of the army, which was completed after the end of the war.

B. Gore, who worked on the development of PTFE at DuPont, did not find his superiors understanding of the further development and founded his own company W. L. Gore & Co. in 2008. His idea was to develop a PTFE that had improved properties in terms of porosity, air permeability and strength through the expansion process, and he called the newly developed membrane ePTFE. He continued the development and perfected the so-called expanded polytetrafluoroethylene (ePTFE) and had it trademarked under the name Gore-Tex. ePTFE membranes are < 1 μm thick, and 1 cm^2 contains over 1,4 billion pores. These pores are 20 000 times smaller than a drop of water and 700 times larger than a water vapor molecule. This is exactly what makes the clothing waterproof and breathable at the same time.

So-called micro-fleece materials are used as a thermal insulation materials that can be used as outerwear, linings or thermal inserts. Fleece materials are very comfortable, soft to the touch and provide good thermal properties.

The diamond-shaped quilted lining, Fig.1, is also used as a thermal insulation material, i.e. for the making of a thermal insert or lining. It consists of two layers of outer material (usually lining fabric) and polyester filler. This type of lining can also consist of five layers, whereby in addition to the layers already mentioned, there are two further layers, the so-called blocks, which are intended to prevent the polyester fibers of the filler material from escaping on the outer layer [2].


a. b.

Fig.1 Diamond-shaped quilted lining with a. sewing machine and b. ultrasonic welding technique [3, 4]


a. b. c.

Fig.2 Examples of the use of diamond-shaped quilted lining s: a. protective vest, b. removable thermal insert that serves as a separate jacket, c. sewn-in jacket lining [5]

Diamond-shaped quilted lining can be used in special purpose clothing as a non-removable thermal insert permanently attached to clothing, as a removable thermal insert in the form of a vest or jacket, and as a lining fabric in a vest, jacket, coat, etc., Fig.2. At the same time, they can be attached to outerwear with fasteners, buttons, metal clips, velcro fasteners, etc.

3. Thermal properties of clothing

According to ISO 7730:2008, thermal comfort is defined as a state of awareness that expresses satisfaction with the thermal conditions of the environment [6]. Thermal comfort is achieved when body temperature is within small fluctuations, skin moisture is low and only minimal physiological responses are required to regulate body temperature. The study of thermal comfort is based on the study of the state of thermal equilibrium of the environment and the ability of the human body to adapt to the thermal conditions of the environment, or the ability of humans to adapt to the environmental conditions, usually indoors, to achieve a sense of thermal comfort [7]. To maintain the thermal balance of the human body, the organism uses the system of thermoregulation to maintain a constant body temperature by constantly balancing the amount of heat produced and the amount of heat lost [8]. Thermoregulation loses efficiency at very low and very high ambient temperatures, which can lead to heat stroke or freezing of the organism [8-10].

Heat transfer is a dynamic process in which heat is spontaneously transferred from a body at a higher temperature to a body at a lower temperature. Heat transfer takes place until thermal equilibrium is reached. Heat can be transferred in three ways [11, 12]:

- By conduction - thermal energy is transferred from places of higher temperature to places with a lower temperature by vibrations and collisions of neighboring atoms. Heat conduction is characteristic of solids and liquids when they are at rest.
- By flux or convection of heat - typical for fluids (liquids and gasses). The particles begin to move when they are heated and the hotter particles transfer their energy to the colder ones.

- By heat radiation or radiation **-** the only transfer of thermal energy that takes place without the mediation of matter. The thermal energy of the body is converted into electromagnetic radiation, which the body emits into the surrounding space. The radiated energy depends on the body temperature; there is no contact and the temperature changes.

The heat transfer rate is defined as the heat flux per unit area. The amount of heat transferred, i.e. the total heat flux, can be calculated using the following expression [11, 13]:

$$Q = q \cdot A \tag{1}$$

where:

Q – heat flux [W]

q – heat flux density [W/m^2]

A – surface area [m^2]

Clothing has a considerable influence on thermal comfort. For this reason, clothing made of lighter and breathable materials with good thermal conductivity is worn in the warmer seasons and clothing made of bulkier and thicker materials with good thermal insulation is worn in the colder seasons. The clothing ensures the thermal comfort of the wearer in the environment in which they are located [14].

Heat transfer in textile materials shows that thermal energy is transferred between two media due to a temperature difference, whereby heat is transferred from a medium with a higher temperature to a medium with a lower temperature. The heat transfer continues until the two media have reached the same temperature. Heat can be transferred in textile materials by conduction, by air and fibers, by air convection within the fabric structure and by radiation, from fiber to fiber. Heat transfer by conduction takes place between two physical objects in contact, whereby the heat flux depends on the temperature differences. The greater the temperature difference, the faster the heat transfer between two surfaces [13]. In the heat transfer of clothing and clothing systems, heat is transferred by conduction between two materials or between a material and the human skin, whereby the heat is transferred from the human body to the clothing or clothing system and then to the environment. In this way, heat is transferred to the environment by conduction and radiation. Heat transfer can also occur by convection, but the stronger influence of convection occurs at a higher airflux velocity [11, 13].

Very important parameters of the thermal properties of a material are thermal resistance and thermal conductivity. These thermal properties are influenced by material properties such as material structure, density, moisture, material type and fiber properties, surface treatment, processing and compressibility, air permeability, ambient temperature and the like [14]. Thermal conductivity is a material property that expresses its ability to allow heat to flux, and thermal insulation is the property of clothing to retain heat. [15-17].

The heat transfer through the embedded material, the clothing composite or the clothing is influenced by the processes of heat transfer by conduction and radiation. Heat transfer by conduction is determined by the thickness of the material and its thermal conductivity, i.e. the transfer of heat from a body with a higher temperature to a body with a lower temperature [18]. The rate of heat transfer by conduction through a given material of constant thickness is proportional to the temperature difference between the upper and lower surfaces of the material and the observed surface perpendicular to the direction of heat transfer and inversely proportional to the thickness of the material. According to Fourier's law of heat transfer by conduction, the heat is transferred in the direction of the lower temperature and the temperature difference becomes a negative amount, i.e. as the thickness of the material increases, the temperature decreases [19]:

$$q = \frac{Q}{t} = -\lambda \cdot A \cdot \frac{\Delta T}{h} \tag{2}$$

where:

q – heat flux density [W/m^2]

Q – heat flux rate [W]

t – heat conduction time [s]

λ – thermal conductivity coefficient [W/mK]

A – surface area [m^2]

ΔT – temperature difference between the two sides of the sample [K]

h – material thickness [mm]

The thermal conductivity coefficient defines the heat flux through the surface over a certain period of time, taking into account the thickness of the material and the temperature differences, and is defined by the expression [18, 20, 21]:

$$\lambda = \frac{Q \cdot h}{A \cdot t \cdot \Delta T} \tag{3}$$

where:

λ – thermal conductivity coefficient [W/mK]

Q – heat flux rate [W]

h – material thickness [m]

A – surface area [m^2]

t – heat conduction time [h]

$T_1 - T_2 = \Delta T$ – temperature difference between the two sides of the sample [K]

The time parameter t in expression (3) is not used for measurement methods where the sample is exposed to ambient conditions. For example, in the case of a hot plate, where there is no upper plate to compress the sample, but the heat of the sample is transferred directly to the environment by convection (air flux). The time parameter is used in the application of measurement methods where the measured parameter must be measured and observed over a certain period of time, which is usually defined by a standard.

A lower value of thermal conductivity by conduction means that the rate of heat transfer through the surface under consideration is lower and the material is therefore a better thermal insulator because it retains the heat [18, 21].

The thermal resistance can be calculated using the following formula [20, 21]:

$$R = \frac{h}{\lambda} \qquad (4)$$

where:

R – thermal resistance [m^2K/W]
h – material thickness [m]
λ – thermal conductivity coefficient [W/mK]

The heat transfer coefficient indicates the amount of heat that the material loses per square meter of surface at a temperature difference of one degree per second.

$$U = \frac{\lambda \cdot A}{\Delta h} = \frac{\lambda \cdot A}{h}\ [W/m^2K] \qquad (5)$$

where:

λ – thermal conductivity coefficient [W/mK]
A – material surface perpendicular to the direction of heat transfer [m^2]
h – material thickness [m]

The thermal contact conductivity represents the heat transfer between the contact points of two materials. It is the heat flux density (q_{max}) at the contact surfaces and is expressed in units of W/m^2. If two materials or, for example, two measuring plates and a specimen are placed so that they touch each other, complete surface contact between them is never achieved. The reason for this is the surface structure of solid materials, i.e. their roughness, which leads to a reduction in the contact points, their size and the appearance of air layers between the contact points. These air layers reduce the thermal conductivity of the material. The greater the number of contact points, the higher the thermal conductivity of the contact. The thermal contact conductivity is also influenced by the compressibility of the material, as the number of contact points between the materials increases when a certain force is applied.

During the production of clothing, the materials are exposed to various stresses: stretching during the laying of the cut layers, compressive stress during cutting due to the vacuum that helps stabilize the cut layer, and their transformation from two-dimensional structures into three-dimensional clothing during the sewing process. Some parts of the ready-made garments are subjected to compression during use, such as the area of the shoulders, back, elbows, etc., caused by carrying a backpack or other load, tight belts, straps, etc., Fig.3.

The strength of the force exerted on the body by the fabric, strap, etc. depends on the type and shape of the body, the type and structure of the fibers and the structure of the embedded materials, but also on the strength with which the load is pressed or the strap tightens. In order to achieve the desired properties of the garment, it is necessary to determine the compressibility of the material [22].

Fig.3 Representation of compression points on clothing [23, 24]

The compressibility of the material has a significant influence on the thermal conductivity of the clothing and therefore on the thermal comfort of the wearer. The higher the compressibility of the material, the higher the thermal conductivity, as the thickness of the material decreases. The compressibility of the material increases with the density of the fibers per unit area, while at the same time the amount of air in the material structure decreases [22]. In addition to thermal comfort, compressibility also plays an important role when it comes to the feel and comfort of the material. It influences the feeling of softness and fullness of the material and is an important property that should be considered when handling the material during clothing production. When automating the production of garments, the compressibility of the material affects the process of separating a layer of material from the bundle and placing it on the work surface using a machine or device [25].

Various measuring devices have been developed to investigate the compressibility of materials. Several research groups have developed different methods to determine the compressibility of materials, such as a compressometer to evaluate the compressibility of thickness and the resistance of materials to compression or a thickness gauge. The FAST and KES measuring systems are among the most commonly used measuring devices for determining the compressibility properties of materials. To determine the compressibility of the material according to the measurement method and test procedure specified in the standards (ISO 5084, DIN 53855/1,2,3, ASTM D 1777), it is necessary to first define the thickness of flat products. The thickness of the material is defined as the distance between two flat, parallel metal plates separated by a flat product, where the upper plate is under the influence of a certain force and is called a presser [26]. The measurement result depends directly on the force applied to the material during the test, and compresses it. Therefore,information about the applied force must be given when presenting the test results. According to the DIN standard, it is necessary to calculate the relative compressibility using the expression in addition to the thickness information:

$$s_x = \frac{d_x - d_{10x}}{d_x} \cdot 100\ [\%] \qquad (6)$$

where:

s_x – relative compressibility of the material [%]

d_x – the thickness of the flat product measured with the pressure force of the upper plate according to the DIN 53855 standard [mm]

d_{10x} – thickness measured at 10 times higher pressure [mm]

4. Overview of previous research

Some authors investigate the influence of the structure and type of material as well as the surface treatment of the material on the thermal conductivity properties with the aim of defining the comfort perception of the material in relation to the sensation of heat/cold on contact with the human body [27-30]. In some studies, the authors ignore the thickness of the material, which has a very significant influence on the thermal properties. In a similar study, L. Hes investigated the properties of thermal conductivity, thermal resistance and tactile sensation on contact with 15 artificial furs and 16 animal furs [31]. Alambeta and Permetest measuring devices were used for the measurements. The author comes to the conclusion that artificial furs have a lower thermal resistance, but provide a better feeling of warmth oncontact with the body. When comparing the water vapor permeability between natural and faux fur, natural furs have a lower permeability of 5% on average, but the author is of the opinion that their thermal properties are still very good due to another advantage, namely the high moisture absorption.

Alambeta, textile measuring device that simulates human skin, is often used for the rapid measurement of transient and stable thermal insulation properties, i.e. for measuring thermal resistance and thermal contact properties. Alambeta works semi-automatically and enables statistical evaluation of the measurement results. It also has an auto-diagnostic function that reduces possible errors during the measurement. With this measuring device it is possible to carry out measurements [14] of the thermal conductivity λ [W/mK], the thermal resistance R [m^2K/W], the thermal diffusion a [m^2s^{-1}], the maximum contact conductivity q_{max} [W/m^2], the heat absorption b [$W\ s^{1/2}\ m^{-2}\ K^{-1}$] and the material thickness h [m].

Alambeta consists of two measuring plates or heads, between which a fabric sample or a clothing composite is placed. Both measuring plates are equipped with thermocouples and sensors that measure the heat flux. The measurement method refers to the measurement of the heat flux (heat flux density) through the material sample. The upper plate is heated to a specific, constant temperature (the so-called hot plate), while the temperature of the lower measuring plate is maintained at the value of the ambient temperature (the so-called cold plate). The sensors for measuring the heat flux perform the measurement at the moment of contact between the measuring surfaces plate-sample-plate, i.e. they measure the contact conductivity of the sample. When the upper measuring plate is lowered onto the sample, it is possible to measure the heat flux on the upper surface of the sample as a function of time [31, 32].

With Alambeta it is possible to measure the ratio of maximum and stationary heat flux as well as the constant density of the heat flux on contact surfaces (thermal contact conductivity).

The measurement of the thermal contact conductivity on the Alambeta is carried out after the establishment of thermal equilibrium, in contrast to the method described above, in which the author measured the thermal contact conductivity when the measuring plate first came into contact with the material. The thermal contact conductivity is also influenced by the compressibility of the material, as the compressibility of the material increases the number of contact points between the materials.

M. Matusiak and S. Kowalczyk used the Alambeta measuring device to investigate the relationship between the thermal properties of embedded materials and the clothing composites made from them [33]. They measured the thermal conductivity, thermal resistance, heat absorption, material thickness and maximum heat flux during contact. The authors came to the conclusion that the thermal resistance of two-layer clothing composites corresponds approx. to the sum of the thermal resistances of the individual material layers. However, this is not the case for multi-layer clothing composites, as the difference in values increases with the number of material layers. The same was observed in the results of the thermal conductivity measurements.

P. Lizak et al. investigated the influence of the knitted structure of the polypropylene fiber material on heat transfer, which was measured experimentally on six samples, each sample being tested with three measuring devices: Alambeta, Togmeter and PSM2 meter [14, 34]. According to the authors, the results showed that the dependence between the observed properties of the material structure and the thermal resistance is not high. They concluded that the Alambeta device is the most objective method for measuring the thermal parameters of knitted fabrics due to the speed of measurement and the reproducibility of the results. D. Atalie et al. investigate the influence of the twist of the weft yarn on the thermal conductivity of the woven material [35]. The measurements have shown that the thermal conductivity of the material increases with increasing twist of the weft yarn. S. Mohapatra et al. investigated the thermal conductivity of polyester materials [36] and came to the conclusion that the structure of the material, i.e. the type of fibers, the density of the material and the length of the stitches of the knitted material, significantly influence the thermal conductivity. The Permetest and Alambeta measuring devices were used for the study. The authors found that the thermal conductivity of the material increased with decreasing material thickness. The same was observed with longer stitch lengths in the knitted material. Z. E. Kanat carried out similar investigations and also came to similar conclusions [37].

D. Rogale et al. also investigated the thermal insulation of the outer shell, thermal inserts and clothing systems as well as multilayer thermal inserts in special purpose clothing intended for use in cold conditions [38]. The measurements were carried out on a thermal manekin and the results showed that the thermal insulation increases with increasing mass of the clothing system and its thickness.

Many authors investigate the influence of the compressibility of materials on their thermal properties. For example, A. Begum and V. Subramanjam investigated the compressibility of materials produced with different stitch lengths depending on the type of stitch formation in the base knit [39]. According to the authors, the compressibility of the material is influenced by the length of the stitches and the surface density of the fibers.

Alimaa et al. carry out similar studies on materials made of cashmere fibers and textured polyester materials [40]. According to the authors, the compressibility of the material is influenced by the structure of the material, i.e. its mass, the type of fibers from which it is made, and the length of the stitches. A. Asayesh et al. conducted a similar study in which they investigated the influence of the weave type and the density of the weft on the compressibility of the material [41].

K. A. Asanovic et al. researched the compressibility of woven materials [42]. According to the authors, the raw material composition of a blend of cotton and polyester in twill weave showed the best compressibility properties, while the raw material composition of cotton in linen weave showed the worst properties. A similar study was conducted by J. O. Ukponmwan, who investigated the effects of wear under wet and humid conditions on the compression behavior of materials [43].

Due to the widespread use of so-called spacer materials, many authors have investigated their compressibility [41, 44, 45]. They investigated the influence of their structure, their thickness, the layering of the clothing composite, which also includes the spacer material, the seams and quilt and other parameters on compressibility. In all studies, the authors came to the conclusion that the parameters mentioned have a pronounced influence on the compressibility of the so-called spacer material.

M. Venkataraman stated that the thermal conductivity is approximately constant for the material and is inversely proportional to its thickness [46]. As the thickness of the material and the number of layers increases, the thermal conductivity decreases due to the increased amount of trapped air.

L. Schacher et al. investigated the influence of compressibility in determining the thermal conductivity of polyester microfiber fabrics [27]. The thickness measurement was carried out in the same way as the compressibility test using the KES-FB4 measuring device. The results showed a small difference in the value of thermal conductivity between the two materials, which the authors explained by a small difference in the porosity of the structure of both materials. The results also showed that the microfiber polyester material gave a warmer sense on contact, depending on the pressure applied.

G. Gnanauthayan et al. investigated the thermal resistance of multilayer nonwovens made of polyester fibers [47]. They investigated the influence of different fiber densities, the shape of the fiber cross-section, the positioning within the layers and the compressibility on the thermal resistance. The tests were carried out on a hot plate. By controlling the thickness of the samples during the test, the authors wanted to avoid the influence of air on the results to focus on the influence of the fiber density and the positioning of the nonwovens, which is why they always measured with the same thickness. The measurements showed that three-layer nonwoven structures have a better thermal resistance than single-layer structures. This is not due to the presence of an air layer between the material layers, which was eliminated in this study, but to lower heat loss by conduction, which occurs due to better air entrapment in the individual material layers, which also affects heat loss by radiation and convection. Based on the results, the authors concluded that a mixture of hollow and solid filled fibers achieved the best properties of the material in terms of thermal resistance and behavior at different values of compressive force, i.e. load and compressibility of the material. A three-layer clothing composite is the subject of investigations by Shabaridharan Karunamoorthy and A. Das [48] on the influence of compressibility on thermal resistance. The investigation was carried out with three measuring devices: Alambeta, a hot plate and a measuring device developed by the authors of this article. The measurements with the newly developed device were carried out at three pressure loads of 100, 1400 and 2100 Pa, after which the results were statistically analysed. The comparison of the results showed that the thermal resistance decreases by 68,82-89% compared to the results of the measurement on a hot plate.

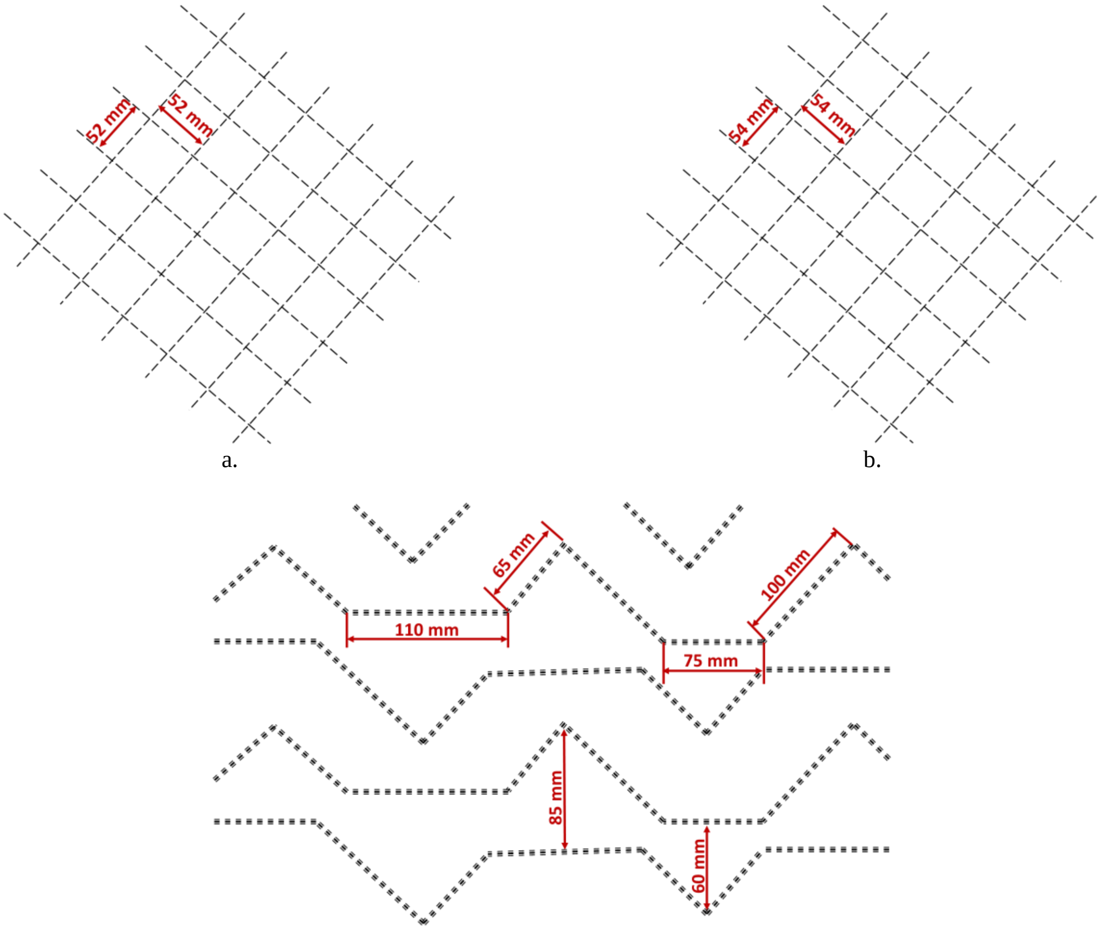
Some authors have produced cotton materials in such a way that they improved their thermal conductivity by producing materials with different porosity and thickness. There have also been attempts to regulate the thermal conductivity of cotton materials by overlaying them with other materials or applying special coatings. In this way, it is possible to improve thermal conductivity as well as the absorption and release of moisture into the environment. In some studies, an increase in thermal conductivity of 151% was observed after the application of a coating of carbon nanotubes - MWCNT [49].

5. Experimental

The influence of compressibility on the thermal contact conductivity of diamond-shaped quilted lining for special purpose clothing was investigated using a multipurpose differential conductometer. Three types of diamond-shaped quilted lining were used (Fig.4), two of which were joined using the sewing technique and the third using the ultrasonic welding technique. The difference also lies in the appearance of the seams. The first two samples, Fig.4, have a square chamber segments, the third was produced using the so-called mirror-image trajectory of the ultrasonic welding. Fig.5 shows the geometric parameters of the materials used.


a. b. c.

Fig.4 Materials used in the experimental part of the work: a. Material M1; b. Material M2; c. Material M3



a.

b.

c.

Fig.5 Representation of the geometric parameters of the diamond-shaped quilted lining s: a. square chamber segments with the dimensions 52x52 mm, material M1; b. square chamber segments with the dimensions 54x54 mm, material M2; c. mirror-image trajectory of the ultrasonic welding of material M3

The thickness of the materials used was determined using a Dino-Lite digital microscope. The microscope was used to determine the thickness of the diamond-shaped quilted lining at a magnification in the range of 50-200 times, depending on the thickness of the material and its properties. After a magnified image of the material was obtained with the microscope, the thickness of the material was measured five times with the Dino Capture program and the average thickness of the material was determined by calculating the arithmetic mean of the measured values. The multi-purpose thermal conductometer used in this paper [50] is shown in Fig.6. All measurements performed on the multipurpose differential conducto-meter are non-destructive [51, 52]. The steady state of the heat flux from the measuring cylinder to the measuring base is used to determine the thermal resistance. The thermal resistance is determined by the expression:

$$R_{ct0} = \frac{(T_s - T_a) \cdot A}{H_0} \tag{7}$$

where:

R_{ct0} – resultant total thermal resistance of the measuring device including the thermal insulation of the boundary air layer of the multipurpose differential conductometer [m^2K/W]

A – total surface area of measuring bases [m^2]

T_s – mean skin surface temperature of the measuring bases and measuring cylinder of the multipurpose differential conductometer [°C]

T_a – air temperature [°C]

H_0 – total heating power supplied to the multipurpose differential conductometer [W]

Fig.6 Multipurpose differential conductometer

At the moment of establishing thermal equilibrium (steady state), the necessary power of the measuring cylinder to maintain the thermal equilibrium of the measuring cylinder, H_0, is calculated using the expression:

$$H_0 = \frac{U_g^2 \cdot P_{PWM}}{R_g} \qquad (8)$$

where:

U_g – the voltage of the stabilized source that supplies the non-inductive point heaters of the multipurpose differential conductometer [V]

P_{PWM} – the ratio of the PWM at the interface output

R_g – the total electrical resistance of the non-inductive point heaters [Ω]

The general expression for calculating the thermal resistance (R_{ct} or R_{ct0}) using the six necessary parameters shown, which are measured or determined by the design of the conductometer, takes the form of the expression:

$$R_{ct} = \frac{(T_s - T_a) \cdot R_g}{U_g^2 \cdot P_{PWM}} \qquad (9)$$

The measuring system regulates the electrical power while maintaining the parameters in the establishment of thermodynamic equilibrium, on the basis of which it is possible to measure the influence of compressibility on thermal contact conductivity [52].

The properties of the materials are listed in the tab.1.

6. Results

The influence of compressibility on the thermal contact conductivity of diamond-shaped quilted lining for special purpose clothing was tested using a multipurpose differential conductometer.

According to the measurement method for the test on the multipurpose differential conductometer, the force value on the dynamometer is determined acc. to DIN 53855/1,2,3 and ASTM D 1777, whereby the specific pressure of the conductometer is adjusted to the surface of the measuring base of the conductometer. Based on this calculation, the pressure force of the conductometer roller was 0.95 N and 9.5 N. A statistical analysis of the results was carried out using a one-way analysis of variance (ANOVA) at a load of 0.95 N and 9.5 N for all three diamond-shaped quilted lining, Fig.7. Statistical analysis confirmed that there is a significant difference between the observed results, indicating that compressibility has an influence on thermal contact conductivity. Reducing the thickness of the material by applying a higher compression force, i.e. its compressibility property, affects the increase in thermal contact conductivity in such a way that the number and surface area of the contact points between the fibers and the measuring plates increases, allowing a greater, i.e. faster, heat flux between the measuring base, material and measuring roller.

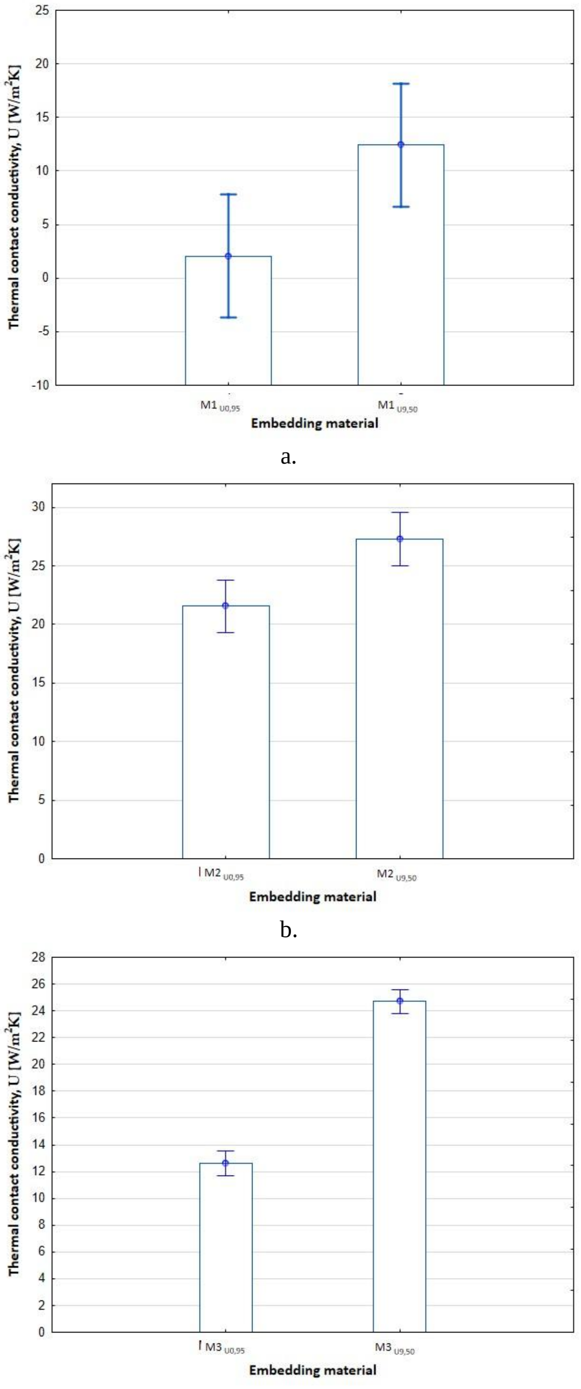
The compression of the material increases the fiber density per unit area and the number of contact points, while at the same time reducing the amount of air in the material structure.

The thermal contact conductivity at a force of 0.95 N is 2.05 W/m^{2}K for M1, 21.55 W/m^{2}K for M2 and 12.61 W/m^{2}K for M3, Fig.8.

The contact conductivity in the compressed state, i.e. with a force of 9.5 N, is 12.41 W/m^{2}K for M1, 27.27 W/m^{2}K for M2 and 24.70 W/m^{2}K for M3, Fig.9.

Tab.1 Properties of the used diamond-shaped quilted lining

Sample	**Raw material composition**		**Surface mass [g/m^2]**	**Material thickness, d_m [mm]**		
				Force = 0 N	**Force = 0.95 N**	**Force = 9.5 N**
M1	Cover fabric:	100% polyester	260	9.65	5.88	4.60
	Lining:	100% polyester				
	Padding:	100% polyester				
	Lining:	100% polyester				
	Cover fabric:	100% polyester				
M2	Cover fabric:	100% polyester	316	1.43	1.31	0.37
	Membrane:	100% polypropylene				
	Padding:	100% polypropylene				
	Cover fabric:	100% polyester				
M3	Cover fabric:	100% polyester with square woven carbon threads	368	3.41	1.90	0.87
	Membrane:	100% polypropylene with dot aluminum coating				
	Padding:	100% polyester				



a.

b.

c.

Fig.7 The range of mean values of the results of the determination of the thermal contact conductivity of diamond-shaped quilted lining at a load of 0,95 N and 9,50 N with indicated variations for: a) material M1, b) material M2, c) material M3

The results of the calculating of compressibility of diamond-shaped quilted lining, Fig.9, show that the material with the highest compressibility is M1 with the greater thickness at compression force of 0 N (78,23%), then M3 (45,79%) and the lowest M2 which has the lowest thickness at compression force of 0 N (28,24%).

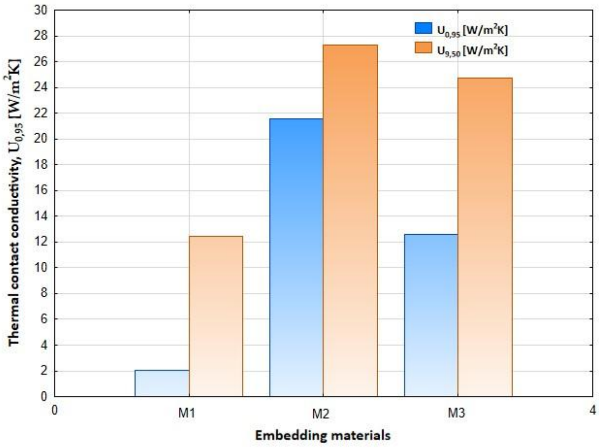


Fig.8 Results of measurements of thermal contact conductivity at loads of 0,95 N and 9,50 N carried out on diamond-shaped quilted lining

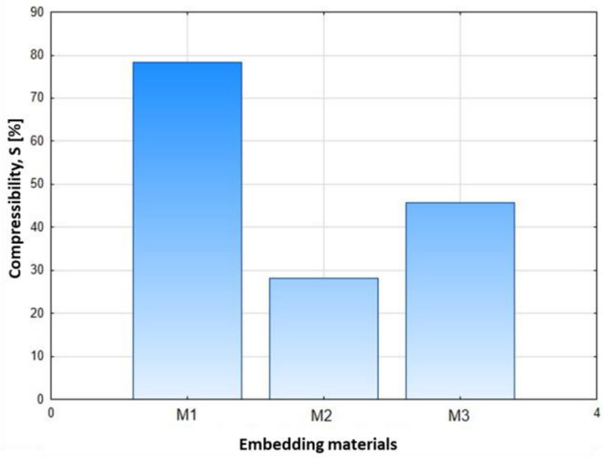


Fig.9 Results of determining the compressibility of diamond-shaped quilted lining

From this it can be concluded that the greater the thickness of the material and the more quilting stitches, the more trapped air appears, which contributes to lower thermal contact conductivity, etc., Fig.10a.

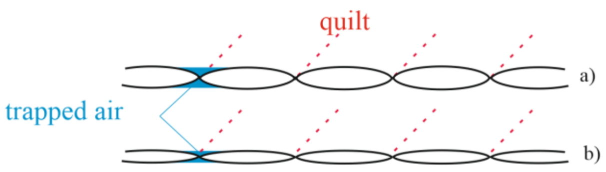


Fig.10 Cross-section of a diamond quilted lining: a. with low compressibility; b. with higher compressibility

However, the higher the compressibility, the lower the thickness of the material and the smaller the air pockets in the seams, the greater the contact conductivity, which contribute to the resistance to heat transfer, etc. Fig.10b.

7. Conclusion

One of the most important parameters in the technical design of clothing is thermal comfort, and it is necessary to properly select the embedded materials that provide satisfactory thermal insulation. The paper investigates the influence of compressibility on the thermal contact conductivity of diamond-shaped quilted lining with different geometric parameters. Test were carried out on the thermal contact conductivity at certain degrees of compression. Based on the research on the influence of compressibility on the thermal contact conductivity of diamond-shaped quilted lining for special purpose clothing, it can be found that the diamond-shaped quilted lining with the most pronounced bulkiness (M1), imperated by the filler, has the highest compressibility because a large amount of air is trapped between the fibers. By applying force and compress the material, the fibers can fit into the free space between them. In addition, the amount of trapped air is reduced, which also leads to an increase in thermal contact conductivity, which increases significantly with a tenfold higher compression force. Diamond-shaped quilted linings, which have a less pronounced volume and thickness (M2 and M3), have the lowest compressibility. The increase in thermal contact conductivity when greater force is applied, i.e. when the material is compressed more, can be clearly seen for all materials and clothing composites. This confirms the influence of the contact area when measuring the thermal conductivity, the structure of the material, the amount of trapped air in the material as well as the thickness and compressibility of the material and the clothing composite. The results obtained confirmed that compressibility has a significant influence on the thermal contact conductivity of diamond-shaped quilted lining for special purpose clothing, i.e. on the thermal properties of the clothing. It was also found that the structure of the material and the amount of trapped air within the material has a major influence on the thermal properties of the clothing.

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