KAUNAS UNIVERSITY OF TECHNOLOGY

JOLITA RUSINAVIČIŪTĖ

AN ANALYSIS OF MORPHOLOGICAL, GEOMETRICAL AND MECHANICAL INDICES OF DOGS' HAIR FIBRES AND THEIR INFLUENCE ON THE PROPERTIES OF TEXTILE MATERIALS

Summary of Doctoral Dissertation
Technological Sciences, Materials Engineering (08T)

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

JOLITA RUSINAVIČIŪTĖ

ŠUNŲ PLAUKŲ MORFOLOGINIŲ, GEOMETRINIŲ IR MECHANINIŲ RODIKLIŲ ANALIZĖ IR ĮTAKA TEKSTILĖS MEDŽIAGŲ SAVYBĖMS

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INTRODUCTION

Research Problem Justification and Relevance of the Work. Natural, biodegradable fibers are widely used in the textile industry, so in addition to the classic linen, cotton or wool yarn and thread, the modern consumer can also obtain products from bamboo, hemp, banana, casein or even peat fibre. Each fibre or blend of different fibres, has its own unique characteristics which are successfully exploited for different purpose products. The research of fiber blend or textile material properties provides the consumer with several options, depending on the price, environmental friendliness, durability and other factors.

According to statistics, sheep's wool is still the most popular and widely used in the textile industry but goats', camels', llama's, and alpaca's wool is used in spinning too. Wool-protein fibre which consists not only of more than 20 amino acids, but also contains fat and a variety of other chemical elements. Wool fibre has multifunctional properties: it is breathable, elastic, resistant to wrinkles, retains shape well, it is antistatic, ignites slowly, and is a good sound insulator. Therefore, wool fibre has an exclusive characteristic – scales on its surface – which creates great opportunities to absorb moisture and keep the body warm, while the hairs closely engage with each other. Therefore, wool fibers are widely used in clothing, household or technical textile industry.

It can be seen that nowadays yarn with dog hair is becoming an attractive trend not only in Lithuania, but in the entire world. It is known that many years ago people started to use dog hair fibre for socks, gloves, scarves in the Northern Countries, including Lithuania. Woolen yarns with dogs' hair protect from cold, have medicinal, functional and thermal properties. Today, dog hair fiber, is surviving its comeback and has just been discovered anew; however, there are not enough detailed and comparative research about different properties of dogs' hair fibres, the geometrical, mechanical and thermal properties of yarn or textiles with dog hair. This research is intended to study, analyse and compare not only German Blackface and Romanov breed sheep wool, but to include the hair of 8 different breeds of dogs: Poodle, Shih-Tzu, Bobtail, Flemish Bouvier, English, American and Russian Spaniel and Yorkshire Terrier.

One more important aspect of the use of dog hair is ecology, thus the spread of this fibre is rather important. As it is known, ecology currently occupies a significant place in the subconscious of consumers and contributes significantly to the formation of a healthy lifestyle. It is necessary to create opportunities to expand and successfully exploit the natural, organic fiber resources and use them in industrial production. It is known that a woolen yarn spinning system can be applied to mix several different components, but it is very important to choose the right ones. The average fiber length, diameter, linear density, breaking tenacity, elongation at break and other fiber strength indices affect the yarn from the fiber properties. On the other hand, the chosen yarn spinning system and a variety of technological production processes (fiber cleaning, emulsification, carding and spinning) are crucial factors which have a significant effect on the yarn properties and their further use. Thus, the yarns in this research were produced with a woollen spinning system which is most commonly used in the processing of multi-component blends of short hair.

Due to an increased demand of yarns, knits and felts with dog hair, it is extremely useful and significant to research the design, production and various properties of such textile products.

The aim of the dissertation – after the analysis and evaluation of selected sheep wool and dog hair fiber morphology, structure, chemical characteristics and geometrical, mechanical indices, to investigate and evaluate the influence of percentage of dog hair on the geometrical, mechanical and functional properties of textile fabrics.

The objectives of the research:

1. After the use of various methods, to investigate and compare the differences of sheep's wool and dog hair structure, geometrical and mechanical indices and to assess the possibilities of using these fibres in the production of woollen yarn.
2. To evaluate the relationship between fiber morphology, structure, geometrical and mechanical indices.
3. After experimentally selecting the best composition of sheep wool and dog hair, and the production of woollen yarn in different percentage composition, to evaluate the relationship between the yarn geometrical and mechanical properties as well as the percentage of fiber blends composition on these properties.
4. After experimentally selecting the best composition of fibre and the production of knits and felts, to evaluate the relationship between the structure, functional and thermal properties of textile materials, as well as the percentage of fiber blends composition on these properties.
5. To suggest recommendations for further use of the designed and researched textile materials from sheep wool and dog hair fibre.

Scientific novelty and practical importance. A literature review shows that research of protein fibres is highly relevant globally, and lot of scientist are comparatively analysing various fiber morphology, chemical, geometrical and mechanical properties and different functional properties of textile materials as well as making recommendations for the producers and users. However, it is still possible to say that the amount of research on this topic is insufficient and the results regarding dog hair, yarn, knit, felt and other textile products with this fibre are not sufficiently widespread. Although recent users are particularly interested in products containing dog hair, and most of them feel a heating-positive therapeutic effects of these products, there are no research on this field at the moment. Not only the different properties of specific protein fibers (German Blackface and Romanov sheep wool, Poodle, Shih-Tsu, Bobtail, Flemish Bouvier, English, American and Russian Spaniel, Yorkshire terrier dog hair), but also geometrical, mechanical and functional properties of woollen yarn, knits and felts from the blends of the aforementioned fibres are analysed in this research. The results of this dissertation seek to answer several questions: is the dog hair, as a protein fibre, suitable for the production of yarns, knitwear or felts? How can dog hair change (or not) the properties of textiles? What are the similarities and differences between different breeds of dog hair or between them and sheep's wool fibre? Does the textile material made from dog hair fibres have better thermal properties than that made from sheep's wool?

Hundreds of thousand tons of wool fiber is cut and used in the textile industry worldwide each year. A growing number of new members joins the sheep breeders' association in Lithuania, sheep farms are expanding, but the market is still not fully complete. Meanwhile, other types of protein fibers is thrown out each year, although it could be used for the production in various textile materials. There are about 100 officially registered veterinary clinics and animal hairdressers currently in Lithuania, where dog hair of different breeds (especially in spring) is cut and usually just thrown away every day. An examination and evaluation of the geometrical, mechanical and functional properties of dog hair fiber, woollen yarn and textiles including this fiber aims not only to use the emissions of dog hair resources, but, perhaps, to find a new niche in the natural-valuingbuyers' market.

Statements to be defended:

1. The morphology, chemical structure and degree of crystallization differ not only between sheep wool and dog hair fibres, but also among the hair of different dog breeds as well.
2. The breaking force and elongation at break of dog hair fibres depends not only on the diameter, length and linear density of fiber, but on the surface and cross-section of fibre, the type of medulla inside the hair as well. The average value of elongation at break is

larger by up to 21% for dog hair fibre than for German blackface sheep wool fibre in this research.

3. There are possibilities to use dog hair fibres in industrial woollen yarn spinning; the limited percentage amount of dog hair fibre in the blend with sheep wool fibre for the woollen yarn is 45%.
4. An increase of amount of dogs hair fibre up to 45% in the blend has no significant effect on the mechanical properties of woollen yarn from that blend, compared with yarns from 100% German blackface sheep wool fibre.
5. There is no dependence between the percentage of English Spaniel, Yorkshire Terrier, Shih–Tzu and Poodle breed dog hair fibre and the functional properties of knitted fabrics.
6. Felts made from dog hair fibres have better thermal properties than felts made from 100% of German Blackface sheep wool.
7. The processing of dog hair, which are currently unused waste, into woollen yarn and textile materials saves valuable protein fibers and expands the range of such products.

Approbation of the research results. The results of this research were presented in 7 scientific publications and 9 conferences.

Structure of the dissertation. The dissertation consists of an introduction, 3 chapters, conclusions, a list of references (173 positions) and a list of scientific publications.

CONTENT OF THE DISSERTATION

The Introduction identifies the main problem and the possible/necessary solutions for the problem of this dissertation. The aim and the tasks are provided in detail, and the defence propositions are presented at the end of the Introduction.

The first chapter provides a short literature review of publications related to the topic of dissertation. The morphology and cross section, chemical composition, geometrical and mechanical properties of protein fibre are also introduced in this chapter. It was estimated that the geometrical and mechanical indices of fiber or optimal blend from the fiber can be advanced to predict the properties of yarns from their blends. Therefore, component selection and all technological progress is very important in the production of yarn. Thermal conductivity, thermal resistance, heat absorption and heat exchange are the main characteristics of thermal insulation of textile materials in other researches. However, a review of literature showed that investigations of the adaptability and unique characteristics of dog hair, blends with them, yarn, knit and felt are still scarce.

The Research methodology chapter describes the object of research and the methodology of experimental investigations.

Experimental materials:

1. Pilot protein fibres: Lithuanian primitive breed sheep's wool from 3 different batches (ŠrA(M)I, ŠrA(M)II and ŠrA(M)III) and different kinds of combed dog hair: ČČ(M)–Chow Chow, P(M)–Pekingese and JT(M)–Yorkshire terrier. Pilot woollen blend yarns were made: A (100% ŠrA(M)I+ŠrA(M)II+ŠrA(M)III in equal amounts (33.3%) of every fibre in the blend); B (65% of ŠrA(M)I+ŠrA(M)II+ŠrA(M)III in equal amounts (21.67%)) and 35% of ČČ(M)+P(M)+JT(M) in equal amounts (11.67%) of fibre in the blend) and C (55% of ŠrA(M)I+ŠrA(M)II+ŠrA(M)III in equal amounts (18.33%) and 45% of ČČ(M)+P(M)+JT(M) in equal amounts (15%) of every fibre in the blend.

2. German Blackface sheep wool (VJ), Romanov sheep wool (R) and different kind of dogs hair: Poodle–P, Shih–Tzu–ŠC, Bobtail–B, Flemish Bouvier–FB, English–AnS, American –AmS and Russian Spaniel–RS, Yorkshire Terrier–JT. All fibres were not laundered or chemically treated.

3. Woollen yarn from 100% of German blackface sheep wool fibre VJ and woollen yarn from blends of wool VJ and AnS, P, JT, ŠC and FB hair were made where the percentage of every breed of dog hair in the blend was 15%, 25%, 35% and 45%. Woollen yarns were named, respectively: VJ-100, AnS-15, AnS-25, AnS-35, AnS-45, P-15, P-25, P-35, P-45, JT-15, JT-25, JT-35, JT-45, ŠC-15, ŠC-25, ŠC-35 and FB-15. The difference between the pilot woollen yarn and listed above: every blend was mixed from fiber VJ and only one specific breed of dog hair.

4. Single jersey knitted fabric was made on a 6E gauge (diameter 4.5 inches) "Irmac" sock-knitting machine from the aforementioned woollen yarns.

5. Felts were made from blends of wool VJ and ŠC, B, RS, JT hair. The percentage of dog hair fibers in the blends for felts was 15%, 25%, 35%, 45%, 80% and 100%. Every blend was made by mixing the VJ fibre with one specific dog breed hair. Felts were made by one person using a detailed methodology. The thickness of felts was very similar and varied only in the 4,13–4,40 mm range.

Experimental methodology:

The morphology and cross-section of fiber was analysed using the (SEM) Quanta – 200 FEG (FEI). Magnification 2000–3000×, scale 30–2000 μm. The scale frequency on the surface of fibre was determined using the "Metric 7.0 PE-Live" computer program. The photos of longitudinal image of fibers were made with the "Diapan" microscope with a "Moticam 2300" camera. Resolution – 3Mb, scale in the photo is 1 mm.

An infrared spectrum was obtained using an FTIR Spectrum GX spectrometer (Perkin Elmer, USA). Samples were prepared as pellets using 200 mg of optically pure KBr and 2 mg of cut fibres. The wave number range from 4000 cm^{-1}–500 cm^{-1}. The structure and crystallinity index of fiber was analysed on a diffractometer "D8 Advance" (Bruker AXS, Germany). Parameters: 40 kV×40 mA. Crystallinity degree was calculated according to equation (2.1):

$$KL = \frac{I_{cryst.}}{I_{cryst.} + I_{amor.}} \times 100\%; \tag{2.1}$$

where *KL* – crystallinity degree, %; $I_{cryst.}^{\circ}$ and $I_{amor.}^{\circ}$ – the maximum intensity of diffraction in the crystalline and amorphous areas, a.u.

Elemental analyses of protein fibres were performed using: SEM/EDS, Kjeldahl method and a model Elementar Analyzer CE–440. Energy dispersive spectroscopy (EDS) was performed using the Bruker XFlash® 4030 detector. Elementar Analyzer CE–440 determined the quantity of carbon, hydrogen and nitrogen in every type of fibre in this research.

The content of nitrogen in the composition of protein fibres was found using the Kjeldahl method. It was calculated according to equation (2.2):

$$N = \frac{(a - a_0) \times K \times 0{,}0014}{V} \times 100\%; \tag{2.2}$$

where *N* – the content of nitrogen, %; α – volume of 0.1 N sodium hydroxide solution for titratium of an empty sample, ml; α_0 – volume of 0.1 N sodium hydroxide solution for titratium of the tested sample, ml; *K* – correction coefficient of 0.1 mol/l sulfuric acid; *V* – volume of the tested sample, ml.

The samples were dried at 105 ± 2°C to constant weight to determine the moisture. The content of moisture of all tested samples calculated according to equation (2.3):

$$B = \frac{a - b}{a} \times 100\%; \tag{2.3}$$

where *B* – the content of moisture, %; *a* – weight of sample before drying, g; *b* – weight of sample after drying, g.

The length meter FM-04/b was used for to measure fibre length (200 for each fibre) in accordance with standard ISO 920:1976. Mean fiber diameter was estimated by three different methods: I. SEM (20 measurement for each fibre). II. Optical microscope Ascania („Karl Schröder", Germany) and digital camera Coolpix 4500 Nikon (Japan) (200 measurement for each fibre). III. Sirolan Laserscan (16,000 measurements for each fibre). The diameter of fibers in pilot woollen yarns was analysed with an optical microscope Biolan R1 („OMO“, Russia) with an ocular micrometre MOB–15×Y4.2 („Lomo“, Russia). The diameter of every fibre was determined as follows:

$$d = (a_2 - a_1)p; \tag{2.4}$$

where d – mean fiber diameter, µm; a_1 and a_2 – the ocular micrometer scale reference; p – minimal interval of ocular micrometer, µm.

In this investigation, the experimental linear density was determined from fiber bundle, as specified by the standard (ASTM 1294-95a). Experimental linear density of every fiber bundle was determined according to equation (2.5):

$$T = \frac{m}{l \times n} \times 10^{-5}; \tag{2.5}$$

where T – linear density, tex; m – mass of fiber bundle, g; l – length of fiber in bundle, mm; n – number of fibers in a bundle.

Mechanical indices of fiber and pilot/woollen blend yarn were researched with the Strength Tester BDO-FBO.5 (“Zwick/Roell”, Germany). Parameters for fibers: experimental length – 20 mm, the initial stress – 0.5 cN, clamp movement speed – 10 mm/min, according to the ISO 5079:1995 standard. Parameters for yarns are: experimental lenght – 50 cm, the initial stress – 2.0 cN, clamp movement speed – 500 mm/min according to the LST EN ISO 2062:2010standard.

The linear density of all types of woollen blend yarns was determined as specified in the ISO 2060 standard. Each type of yarn was cut in length (l = 100 cm) and weighed using a digital weighing machine EW 150-3M (Kern & Sohn GmbH, Germany).

The thickness of knits and felts was measured using the Textil-Dickenmesser DPT 60 digital (Haus Schmidt & Co. GmbH, Germany) correspondingly to the LST EN ISO 5084:2000 standard, and air permeability was investigated using the D-69450 Weinheim air permeability device (Karl Schroder KG, Germany) according to the LST EN ISO 9237:1997standard. Air permeability Q ($dm^3/(m^2s)$ was calculated as follows:

$$Q = \frac{\overline{q_v}}{A} \times 167; \tag{2.6}$$

where q_v – arithmetic mean of the air flow, dm^3/min; C – a pilot area, cm^2; *167* – coefficient of conversion.

Thermal conductivity of all tested knits was measured using the Alambeta device following the ISO 11092:2014 standard. The heat interchange of all tested knits and felts was investigated using the IG/ISOC device in this research. Course and wale density of all knits were measured according to the LST EN 14971:2006 standard. The statistical characteristics were calculated on the grounds of the known standard equations.

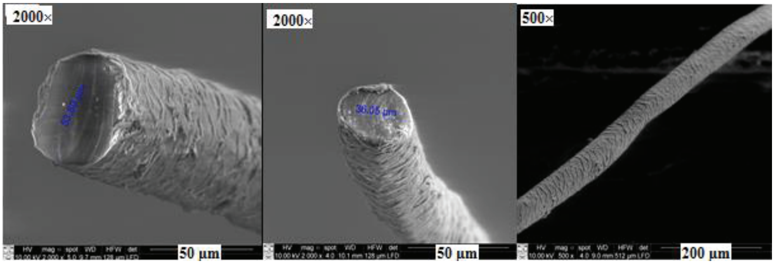
The third chapter presents the results of experimental and theoretical investigations.

Research of fibre and pilot woollen blend yarns. SEM analysis showed that all dog hair fibres have a medulla inside and the value of the medulla diameter depends on the value of fibre diameter. No medulla was found in the cross-section of primitive Lithuanian breed sheep's fibre. It was established that the geometrical indices of the fibres in pilot yarns influence their mechanical indices: ČČ(M) and ŠrA(M)II belong to the same length group, have a minimal length (57–62 mm) and maximal breaking tenacity (29–67 cN/tex); other fibres P(M), JT(M), ŠrA(M)I and ŠrA(M)III have medium and maximum values of length (71–105 mm) and the breaking tenacity of these fibres shows medium and minimum values (13–22 cN/tex), respectively.

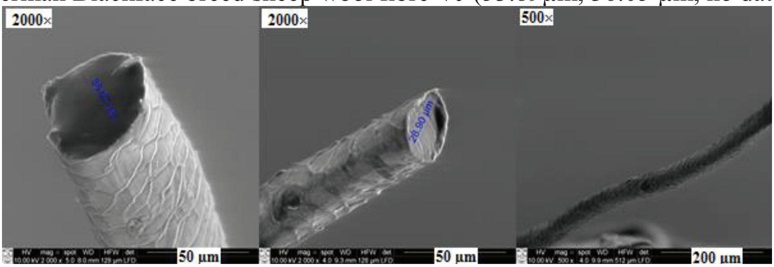
It was estimated that the average value of linear density of woollen pilot yarn A is 240.7×2 tex and the breaking tenacity is 3.44 cN/tex. Pilot yarns B and C with 35% and 45% of dog hair, respectively, have very similar values of linear density – 222.7×2 tex and 221.3×2 tex, respectively, breaking tenacity is 2.80 cN/tex and 2.65 cN/tex, respectively. It was found that woollen pilot yarn B with 35% and woollen pilot yarn C with 45% of dog's hair are weaker than the woollen pilot yarn A made from 100% sheep's wool: respectively, by 19% and 23%. There are 10% more dog's hair in pilot yarn C than in pilot yarn B, but the percentile loss of breaking tenacity between pilot yarn B and C is only 5.4%. This result shows that an increase of dog's hair fiber in the blend does not greatly affect the strength of woollen yarn made from that blend. The production of pilot yarns in this research showed that 45% of dog's hair fiber in a blend is the limit quantity for effective yarn producing with an industrial card system. Considering that the knitted fabric in this work will only contain 45% of dog hair fibres, it was decided to produce felts with 80–100% content of dog hair fibres in the succeeding stage of the investigation.

The analysis of morfology structure, chemical composition, geometrical and mechanical indices of protein fibres. This stage of investigation was aimed to analyse the surface and cross-section of protein fibres; hence, firstly, the SEM photographs (Fig. 1 and Fig. 2) of all measured fibers were made in this research. The experimental value of fibre diameter is presented as well. It can be seen (Fig. 1) that the scales on the surface of German Blackface sheep wool (VJ) and Romanov sheep wool (R) are different: the surface of the fibre (R) is smoother and more embossed than

VJ fibre surface. All investigated dog hair fibres have typical wool scales on the surface, the structure of scale is specific and differ from the sheep VJ and R wool fibers (Fig. 2): there are more scales on the surface of investigated dog fibers, the scales are smaller and more delicate.



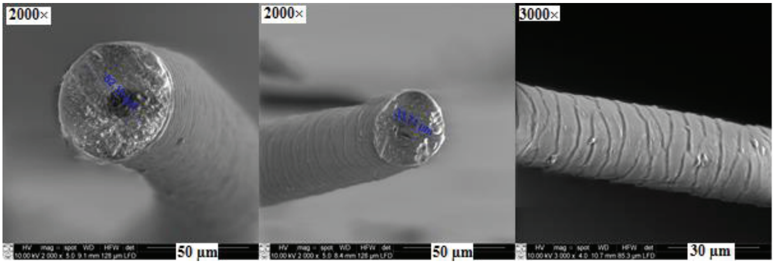
German Blackface breed sheep wool fibre VJ (53.89µm, 36.05 µm, no data)



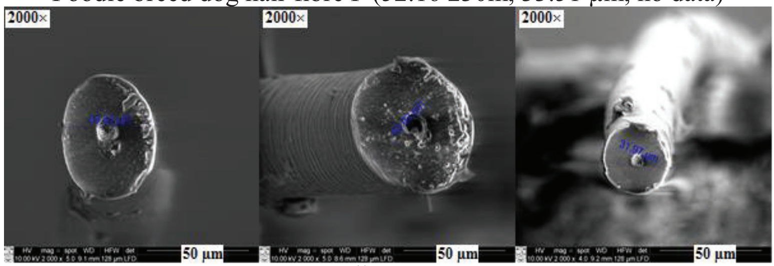
Romanov breed sheep wool fibre R (38.07 µm, 28.90 µm, no data)

Figure 1. The surface and cross-section of sheep wool fibres (SEM)

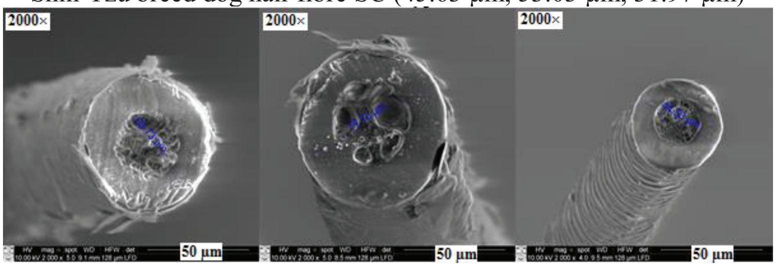
It was found (Fig. 1 and Fig. 2) that the cross-section of all investigated sheep wool and dog hair fibres (VJ, R, P, ŠC, B, FB, AnS, AmS, RS, JT) have an irregular round form. The fundamental difference between sheep and dog fibres is the medulla inside almost all dog hair cross-sections, located in the centre of the fibers (Fig. 2). Furthermore, it was found that the type of medulla of the investigated fibres is different: the fibre of a Yorkshire Terrier dog hair (JT) has a hollow medulla, while the fibre of Poodle, Shih-Tzu, Bobtail, English and Russian Spaniel dog hair present a porous medulla inside the hair. No medulla was found inside the hair of a Flemish Bouvier and American Spaniel dogs' fibers cross-section in this research. Results of this research demonstrate that sometimes thicker hair have a thicker medulla inside, but this does not refer to all cases. Such fibre as Poodle's dog hair (P) with different experimental values of diameter (33.71 µm and 46–52 µm) have a medulla in the cross-section with the same value of diameter (14 µm). The fact that dog hair fibres B and ŠC with very similar experimental values of diameter 44.53–45.63 µm have a medulla with very different experimental values of diameter (10.08–22.28 µm) inside the hair, reaffirms the fact that thicker hair has a thicker medulla inside.



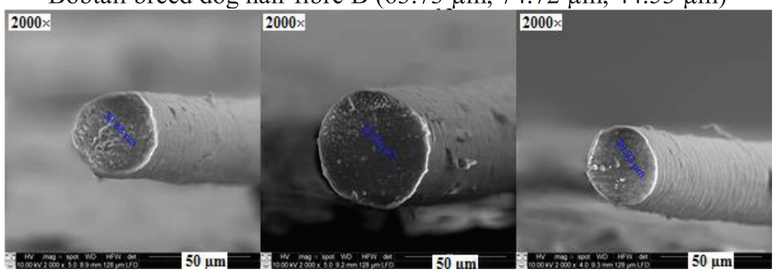
Poodle breed dog hair fibre P (52.16 230m, 33.51 µm, no data)



Shih-Tzu breed dog hair fibre ŠC (45.63 µm, 53.03 µm, 31.97 µm)

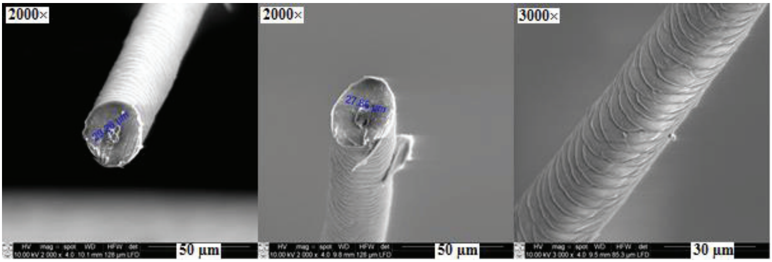


Bobtail breed dog hair fibre B (63.73 µm, 74.72 µm, 44.53 µm)

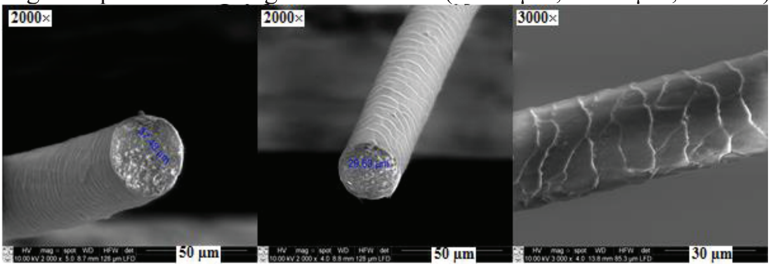


Flemish Bouvier breed dog hair fibre FB (39.88 µm, 58.25 µm, 36.93 µm)

Figure 2. The surface and cross-section of dog hair fibres (SEM) (cont. on 15 page)

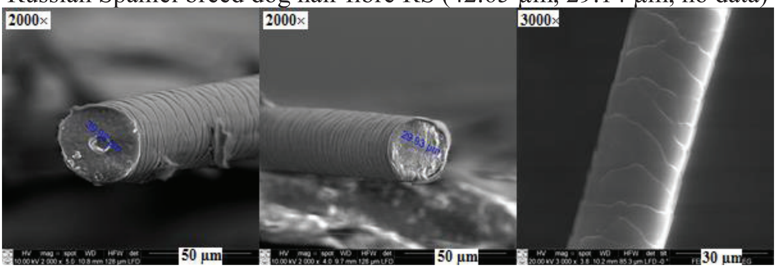


English Spaniel breed dog hair fibre AnS (29.26 µm, 27.86 µm, no data)



American Spaniel breed dog hair fibre AmS (37.48 µm, 29.63 µm, no data)

Russian Spaniel breed dog hair fibre RS (42.65 µm, 29.14 µm, no data)



Yorkshire Terrier breed dog hair fibre JT (39.98 µm, 29.93 µm, no data)

Figure 2. The surface and cross-section of dog hair fibres (SEM)

This analysis indicates that the presence of the medulla depends not only on the diameter of the fibre: protein fibres VJ, FB, ŠC have very similar experimental values of diameter but not all of them include the medulla inside. It is possible that the medulla inside a hair and the diameter of the medulla does not only depend on the diameter of hair, but on the breed, stage of hair growth, the time of cut the hair, nutrition and even grazing place as well. An analysis of literature showed that in addition to the hair surface structure and the cross-section, it is very important to determine the type of medulla in the length of a hair. It was found (using "Diapan" microscope) that the type of medulla can be (Fig. 3): fragmented (e.g. fibre P), interrupted (e.g. fibre ŠC), continuous (e.g. fibre AnS) and continuous kemp (e.g. fibre B). The results of this research show that it is recommended to use same-different methods to analyze and compare the morfology of protein fibres. Therefore, it was found (using SEM and "Diapan" microscope) that there was no medulla inside sheep wool fibre (VJ, R) and dog hair fibre (FB), while dog hair fibres P, ŠC, B, AnS, AmS, RS and JT have a medulla inside the hair.

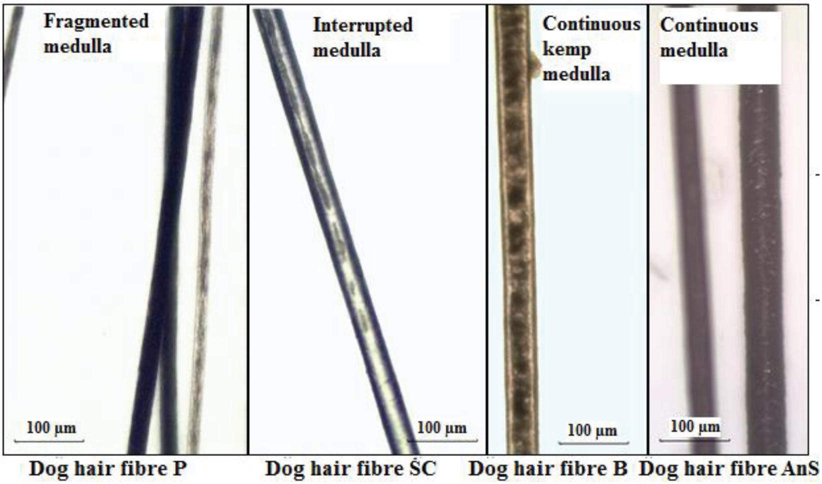


Figure 3. Longitudinal images of different dog breed hair fibres

Figure 4 shows the distribution of a medulla in the cross-section of different protein fibres. The distribution was made from all SEM and "Diapan" microscope images obtained in this research. It was established (Fig. 4.) that the hair fibre of an English Spaniel (AnS) has only one type of medulla – continuous medullated – and the maximal value of medulla distribution (61.54%) between all measured fibres. Fibres ŠC, B and AmS have maximal variation of different types of medulla inside of the cross-section.

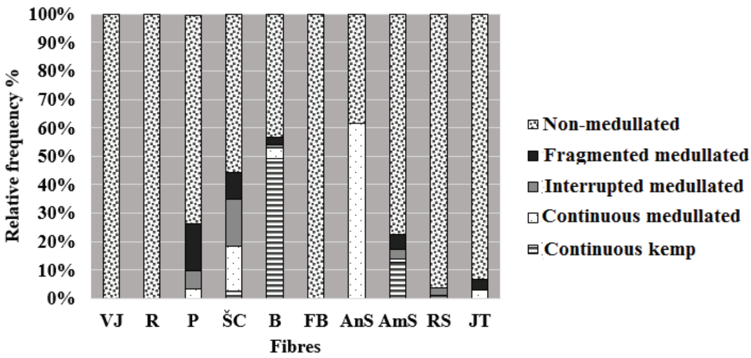


Figure 4. The distribution of medulla in different protein fibres

There are 4 different groups of wool fibres – pile, intermediate, kemp and dead – which are categorized by the average diameter of wool and medulla inside the cross-section of a hair. This research found that fibre VJ, P, AnS, AmS, RS and JT belong to the pile group according to the average diameter of fibre (21.73–30.00 μm), fibre ŠC and FB can be assigned to the intermediate group and Bobtail dog hair (B) represent the kemp group. It is known that the pile group is the most technologically valuable of all groups, because there is no medulla inside of the hair. As Figure 4 shows, only fibre VJ can be attributed to the pile group and dog hair fibres RS, JT, AmS and P are classified to the intermediate or kemp group. These morphological features can affect the thermal properties of textile products.

This study found that different protein fibers are characterized by different morphology, distinctive surface and cross-section structure of hair. It was decided that the next step of this research is to analyse and compare the differences of chemical structure and crystallization degree of all investigated sheep wool and dog hair fibres.

SEM–EDX analysis showed that the concentration of sulphur, oxygen and nitrogen in VJ sheep wool fibre was lower than in dog hair: the content of sulphur and oxygen was two times lower (except Yorkshire Terrier), and the content of nitrogen by 1.12–1.31 times. The content of carbon in dog hair fibres varied in the range of 41.6–58.7% and the highest amount (66.2%) of this chemical element was observed in the cortex of German Blackface (VJ) sheep wool fibre. The percentage amounts of carbon, hydrogen and nitrogen (using Elementar Analyzer CE–440) in sheep wool and dog hair fibres are of the same order of magnitude, and the results slightly varied in the range of C ~ 45 ± 3.0%, H ~ 6 ± 0.3% and N ~ 14.6 ± 1.0%, respectively. Overall, the percentage of C, H and N in almost all dog hair fibres (JT, FB, P, B, RS, AmS) was found to be smaller compared with sheep's wool. Only the percentage composition of Shih-Tzu (C:H:N 48.04:6.32:15.64) and English Spaniel (C:H:N 47.6:6.11:15.41) dog hair fibres are similar to German Blackface (C:H:N 47.14:6.29:15.14) sheep wool.

The content of nitrogen was determined by using different methods and the results are not the same, but the numerical values are of the same order of magnitude. Thus, the nitrogen content of protein fiber test results are ambiguous, and the information about the chemical composition of the fiber characteristics is still insufficient.

XRD diffraction analysis was performed, the maximum of diffraction in crystalline and amorphous areas was defined and the crystallinity degree was calculated for all mentioned fibres in this research. It was found that the degree of crystallinity of German blackface sheep (VJ) wool fibre is 27%, the crystallinity degree of dog hair fibre varies in the 7–30% range. The minimal value of this index was noted for AmS fibre, while JT fibre presented the maximal value. The results of X-ray diffraction of the Yorkshire Terrier fibres are presented in Figure 5.

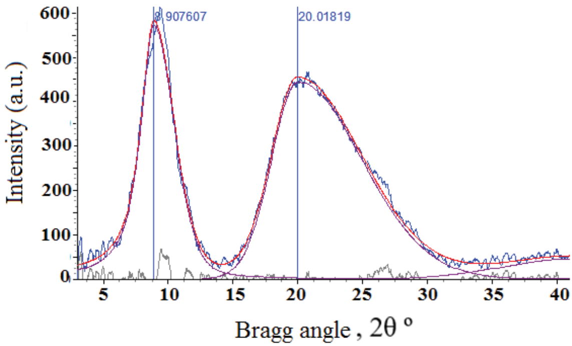


Figure 5. XRD patterns of Yorkshire Terrier’s hair fibres

XRD patterns (Fig. 5.) show a typical diffraction pattern of keratin with a medium peak at Bragg angle $2\Theta = 9^{\circ}$ and a prominent peak at $2\Theta = 20^{\circ}$. It was discovered that the values of crystallinity degree and diffraction peak in crystalline and amorphous areas are different not only between sheep wool and dog hair fibres, but also among the hair of different dog breeds as well.

To obtain additional information about possible differences between sheep wool and dog hair fibre, the IR spectra of these wool hair samples were analysed (Fig. 6).

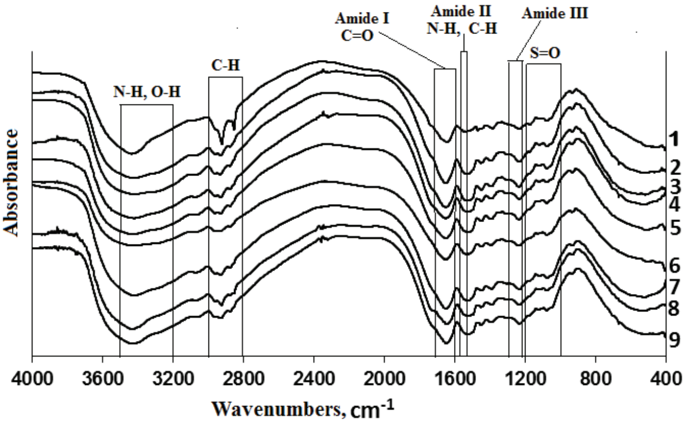


Figure 6. IR spectra of protein fibres: 1 – VJ, 2 – JT, 3 – FB, 4 – P, 5 – ŠC, 6 – B, 7 – RS, 8 – AnS, 9 – AmS

Figure 6 shows that the fibre of German Blackface sheep wool (VJ) has the most intensive and sharp peak in the region of 2920–2850 cm^{-1}. It means that the structure of this protein has C–H bond valence vibrations in the CH, CH_2 and CH_3 groups. Also, it was estimated that all spectral peaks of dog hair fibres in other intervals are more intensive and larger than VJ sheep wool fiber. Peak positions in different dog hair spectra which can be attributed to the amide I band vary slightly in the interval of 1651–1646 cm^{-1}, while the peak in the spectra of sheep wool is reached at 1643 cm^{-1}. All peaks of different dog hair spectra which can be attributed to the amide II band vary in the interval of 1514–1537 cm^{-1} and shift towards the shorter wavelength. The peak position at 1235 cm^{-1} does not change but its intensity is higher than usual in other range of wavelengths in the spectrum of dog hair. Figure 6 shows that there are three peaks in the spectra of sheep's and dog's wool, with wave numbers of 1171, 1125 and 1077 cm^{-1}. This research discovered that the hair fibres of a Poodle, an English and American Spaniel dogs have α–helix and β–sheet second structure of protein.

The diameter and length play the main role considering all geometrical indices of wool; these parameters show the quality of fiber and have direct impact on various properties of yarn: breaking tenacity, spinning process and the price. The average diameter of sheep's wool fibers VJ and R is very similar to the average diameter of Yorkshire Terrier's hair fibre, respectively 27.2 μm, 31.8 μm, and 31.3 μm (see Table 1). However, the length of the aforementioned fibers differs by 1.5–2.3 times: 49.8 mm, 88.6 mm, and 136.5 mm, respectively. This means that fibers with similar diameters are not necessarily of the same length; it depends on the breed, the time when the hair was cut and other factors.

Table 1. A summary of sheep wool and dog hair fiber diameter and length

Indices	Protein fibers									
	VJ	R	P	ŠC	B	FB	AnS	AmS	RS	JT
Length (using length meter FM-04/b)										
l, mm	88.6	136.5	29.3	43.7	139.6	68.9	47.4	25.2	39.5	49.8
Δ, mm	±0.62	±1.58	±0.42	±0.49	±1.03	±0.89	±0.64	±0.45	±0.31	±0.47
V, %	5.03	8.30	10.34	7.97	5.29	9.24	9.73	12.83	5.53	6.71
Diameter (using optical microscope „Ascania“)										
d, μm	30.00	32.50	21.73	32.12	52.33	40.05	28.20	26.01	26.88	29.55
Δ, μm	±0.31	±0.44	±0,38	±0.50	±0.67	±0.52	±0.40	±0.38	±0.50	±0.33
V, %	7.48	9.70	12.43	11.24	9.22	9.34	10.20	10.36	13.12	8.05
Diameter (using Sirolan Laserscan)										
d, μm	31.80	31.30	22.10	29.60	48.80	36.60	25.00	23.70	24.90	27.20
Δ, μm	±0.73	±0.62	±0.43	±0.90	±2.73	±0.79	±0.20	±0.33	±0.44	±0.78
V, %	25.50	30.4	27.60	31.90	28.30	25.20	26.40	33.30	25.70	27.70
Diameter (using SEM)										
d, μm	35.64	32.23	23.47	32.22	55.35	38.49	28.91	27.45	29.56	31.66
Δ, μm	±0.82	±0.54	±0.55	±0.84	±1.03	±0.69	±0.31	±0.29	±0.48	±0.58
V, %	5.63	7.49	9.46	9.67	12.94	6.24	6.55	10.14	7.61	10.86

A large variety of methods is used to determine the average diameter of wool fiber and every method has advantages and disadvantages; thus a especially important stage of research is to choose the right method to measure the diameter. There were 16,000 measurements of diameter made of every fiber using the Sirolan Laserscan method, 20 measurements – using the SEM and 200 measurements of every fiber with an optical microscope "Ascania". The coefficient of diameter variation of all fibers varied in the range of 5.63–12.94% when measuring with SEM, 7.48–13.12% when using an optical microscope "Ascania" and 25.2–33.3% by using the Sirolan Laserscan method.

Wool fibre is crimp and thus it is rather complicated to determine the linear density of this fibre. The values of linear density obtained following a standard (ASTM 1294-95a) were compared with the determined ones using a formula (3.2) (Matukonis et al. 1989):

$$T = \frac{\pi}{4} \times d^2 \times \rho \times 10^{-3}; \qquad (3.2)$$

where d – fibre diameter, μm; ρ – fibre density (1,32 g/cm^2).

It was found that Bobtail's hair fibre B has maximal value of experimental linear density (3.08 tex) among all mentioned dog hair fibers and Romanov sheep wool fibre R presented the highest density among sheep wool –1.28 tex.

As it was mentioned before, these fibers were also the longest (136.5 mm and 139.6 mm) and nearly the thickest (31.3 µm and 48.8 µm) out of all fibers analysed in this research. It was discovered that the values of theoretical and experimental linear density of all mentioned fibres were different in (2–18%) which could be due to various reasons: formula (3.2) underestimates the fact that the real diameter of all fibers is not a correctly round in form, and the medulla and air gaps.

The mechanical indices of protein fibres depend not only on the geometrical (diameter, length and linear density) indices of fiber, but also on the morphological (surface of hair, cross-section, the type of medulla) parameters. It was previously determined (see Table 1) that sheep's wool fibres VJ and R have similar diameters (30.00 µm and 32.50 µm), but different lengths (88.6 mm and 136.5 mm). Table 2 shows that fibre VJ is shorter than fibre R by 35% and weaker by 49%. This could also be explained by the unique structure of fibre R; its surface is more whole, the structure seems stronger and the scales are more frequent (see Fig.1). It was found that neither fibers have a medulla inside; they have similar linear density, but the mechanical indices of these fibers are different (see Table 2).

Table 2. A summary of mechanical indices of protein fibres

Indices	Protein fibres							
	VJ	R	P	ŠC	B	FB	AnS	JT
Breaking force, cN								
F_{tr}, cN	17.94	40.52	20.39	46.18	30.54	38.56	10.41	30.95
Δ, cN	±2.50	±2.30	±2.21	±2.31	±2.47	±2.12	±0.84	±1.90
Breaking tenacity, cN/tex								
f_{tr}, cN/tex	19.29	37.04	41.69	43.19	9.91	22.54	12.70	33.18
Δ, cN/tex	±4.49	±3.12	±3.67	±2.30	±2.40	±1.80	±1.11	±1.22
δ, %	23.27	8.42	8.80	5.33	24.22	7.99	8.74	3.68
Elongation at break, %								
ε,%	34.40	54.63	39.86	41.37	41.71	38.96	36.59	43.78
Δ, %	±1.24	±2.89	±1.72	±3.30	±2.10	±3.20	±1.14	±1.23
δ, %	3.60	5.29	4.32	7.98	5.03	8.21	3.12	2.81
Work of breaking, kJ								
W_{tr}, kJ	0.47	1.61	0.62	1.45	0.99	1.15	0.28	1.01
Δ, kJ	±2.30	±0.49	±2.10	±2.93	±2.31	±3.40	±2.02	±1.10
Breaking toughness, kJ/tex								
w_{tr}, kJ/tex	0.51	1.47	1.26	1.36	0.32	0.67	0.34	1.11
Δ, kJ/tex	±0.02	±0.06	±0.05	±0.30	±0.21	±0.24	±0.01	±0.04
δ, %	3.92	4.08	3.97	22.06	65.63	35.82	2.94	3.60

While it was expected that Bobtail's hair fiber B which are the thickest and the longest among all mentioned fibers would be the strongest too, in fact, an inverse relationship was found. The medulla ratio of fiber B is up to 52%, the relative frequency of the medulla 56.6% and the type of medulla inside the fiber B is continuous kemp. Thus, even thick and long hair are not necessarily strong; it also depends on the morphological characteristics of the fiber. It was already discussed that hair without a medulla inside have the best technological value. Table 1 shows that dog hair fibre JT and AnS have very similar values of diameter and lenght, but Table 2 shows that the average values of breaking force, breaking tenacity and breaking toughness of fibre JT are larger; respectively, by 67%, 16% and 69% that of fibre AnS. It means that the relative frequency of a medulla (61.54%) inside the hair reduces the mechanical properties of fibre AnS. A comparative diagram of mechanical properties of sheep wool and dog hair fibres (Fig. 7) shows that the average values of elongation at break of dog hair P, ŠC, FB, JT, B and AnS are 6–21% larger than those of sheep wool fibre VJ. The results of mechanical indices of protein fibres show that the strength of fibre depends not only on the existence a of medulla but on the type and distribution of the medulla, the relative frequency and, of course, the geometrical indices of fibre.

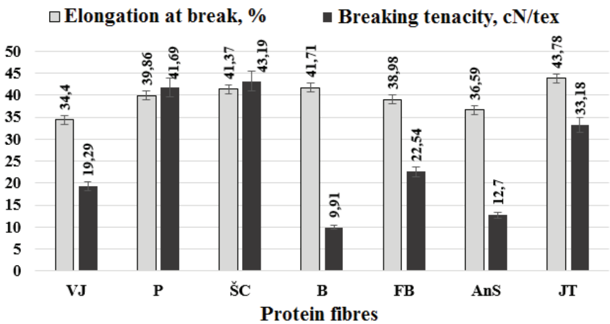


Figure 7. A comparative diagram of mechanical properties of protein fibres

<u>An analysis of geometrical and mechanical properties of woollen blend yarns.</u> A combination of different characteristics of the fibre strongly influences the mechanical properties of the blend yarns and it is very important to choose the right component for the blend in textiles. Since the scales on the surface of dog hair are small and delicate; moreover, sheep wool, characterized by a high density of scales on surface, was added to improve the adhesion between the hair to the blend. In this stage of research, woollen blend yarns with 100:0, 85:15, 75:25, 65:35, 55:45 German blackface breed sheep wool fibre VJ:different dog breed hair fibres (English Spaniel, Poodle, Yorkshire Terrier, Flemish Bouvier, Shih-Tzu) were made using a condenser spinning system. The twist of all mentioned woollen blend yarns was 240 m^{-1}. The linear density of all woollen blend yarns varied in the range of 193.2–310.2 tex, the coefficient of linear density variation was in the range of 3.62–19.08%. It is known that the variation of linear density of woollen yarn is always bigger than worsted yarns. This work investigated how the linear density and variation of this index depend on the crimp of fibre, the inequality of geometric indices of the mentioned fibres or even the technological process features (blending and the quality of carding, the shortest hair depletion during carding, the inequality of linear density of roving, and others). It is difficult to accurately assess the effects of each of these factors on the density of woollen blend yarn because the process factors in this work have not been studied.

It was noted that linear density of woollen yarns with 15%, 25%, 35% and 45% of Yorkshire Terrier hair is 203.3–218.2 tex, but the increase of dog hair from 15% to 35% in the blend reduced the mechanical properties of woollen yarns, respectively: the breaking tenacity decreased from 2.91 cN/tex to 1.88 cN/tex, the elongation at break fell from 15.5% to 10.9% and breaking toughness from lowered from 1.81 kJ/tex to 0.87 kJ/tex. The same tendency was found with woollen yarns ŠC-25 and ŠC-35, P-15 and P-35, AnS-15, AnS-35 and AnS-45. Therefore, an increase of dog hair fibre in the blend causes a decrease of mechanical properties of woollen yarns from this blend. It was also determined that by adding only 15% of dog hair fibres to the blend, the yarns from this blend improve the mechanical properties by 1.3–1.6 times; even 45% of dog hair fibre in the blend does not have significant effect on the mechanical properties of woollen yarn, compared with woollen yarn from 100% German blackface sheep wool fibre VJ. In general, this research has proven that the spinning system is suitable for spinning yarns from the blends of sheep wool and different dog breeds' hair.

An analysis of structural parameters and functional properties of knitted fabric. The main goal of this phase of research was to find out whether the percentage of dog hair in the blend has a direct impact on the thermal properties of the fabrics knitted from this blend. It was observed that the course and wale density, the loop height and the stitch is very similar between all designed and tested knits. The diameter of yarns between all mentioned knitted fabrics was varied in 0.772–0.978 mm range. The minimal value (0.772 mm) of this index was determined for woollen blend yarns AnS-25, thus the fabric knitted from AnS-25 yarns has the lowest surface density between all knits in this research. On the other hand, woollen blend yarns P-

45 showed the opposite result: the maximal diameter and surface density of knitted fabric.

The linear density of all designed and discussed woollen blend yarns vary in the range of 193.3–310.2 tex, thus, the knitted materials were categorised into 4 groups by similar linear density and raw material of yarns (see Table 3). The thickness of the knitted fabrics in every group differ by no more than 6%, the length of loop –6.6%, and the linear density of yarns in every group ranging from 7.3–9.4%.

Table 3. The structure and thermal properties of the analysed knitted fabrics

Knit	Linear density, tex	Thickness		Thermal conductivity		Thermal resistance		Air permeability	
		d, mm	*V*, %	λ, cal/°C ms	*V*, %	*R*, K.m^2/W	*V*, %	*Q*, cm^3/(m^{2}s)	*V*, %
JT-15	203.3	2.62	1.6	45.03	4.8	58.09	5.5	1179.4	12.6
JT-25	218.2	2.51	1.3	44.88	3.2	55.73	3.1	1402.9	8.6
JT-35	217.8	2.65	1.3	48.01	3.4	56.58	3.6	887.8	22.5
JT-45	211.7	2.51	1.5	45.65	1.5	55.36	2.6	1352.7	7.8
AnS-15	207.5	2.63	2.1	44.05	4.6	57.38	4.7	1385.1	9.7
AnS-25	193.2	2.67	1.3	46.39	2.9	56.26	3.5	1138.9	6.1
AnS-35	209.8	2.61	2.0	45.01	4.3	56.69	4.8	1485.5	13.4
AnS-45	213.3	2.58	2.4	45.90	2.4	55.66	2.3	1321.9	7.6
P-15	249.2	2.65	1.5	46.79	2.6	55.87	2.5	1066.0	9.7
P-35	230.9	2.52	1.5	46.82	2.8	52.43	2.9	1296.0	16.5
ŠC-25	220.2	2.72	1.6	51.83	3.9	50.34	3.8	1203.7	10.9
ŠC-35	203.2	2.61	1.5	50.52	6.6	52.86	6.8	1088.6	13.3

A comparison of knitted fabrics P-15 and P-35 (Table 3) showed that knit P-35 has 6.2% lower thermal resistance and 17.7% higher air permeability than P-15. A cross-comparison between different groups showed that knits with English Spaniel and Yorkshire Terrier hair fibres are similar in structural parameters; however, the thermal conductivity of knits with English Spaniel hair is lower by 6.3%, although air permeability is better by 6–22% than knits with Yorkshire Terrier hair.

Table 3 shows that raw material and the percentage of protein fibres in a blend has no significant effect on the thermal properties of knits. It was found that thermal conductivity, thermal resistance and air permeability of plain plated single jersey knitted fabrics does not depend on the percentage composition of the blend. No trends were established between increasing the amount of dog hair fibers in the blend and the functional properties of knits.

The thermal properties of knitted fabrics depend on the thickest fabric. Knit JT-35 was established to be the thickest (2.65 mm) and have a lower value of air permeability (887.8 cm^3/(m^{2}s)) in the group of knits with

Yorkshire Terrier hair. The same tendency was found in the group with English Spaniel hair for knit AnS-25: the thickness was 2.67 mm and the value of air permeability was 1138.9 $cm^3/(m^2s)$). Table 3 illustrates that knits JT-25 and JT-45 have the same thickness (2.51 mm) and very similar values of thermal conductivity (44.88–45.65 cal/°Cms), thermal resistance (55.73–55.36 $K.m^2/W$) and air permeability (1402.9–1352.7 $cm^3/(m^2s)$). At this stage of research, heat transfer process for knitted fabrics with Yorkshire terrier, English Spaniel, Poodle and Shih-Tzu hair were also investigated (Fig. 8).

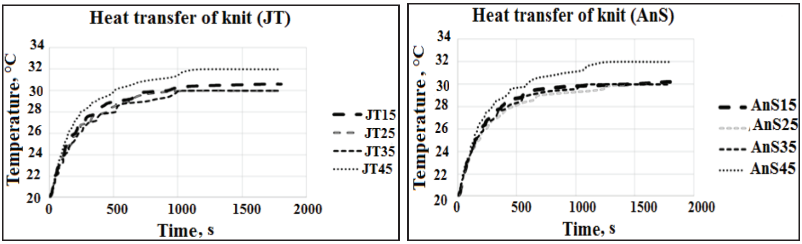


Figure 8. The process of heat transfer of knits with sheep wool and dog hair fibres

Beside the already mentioned thickness and low values of air permeability, knits JT-35 and AnS-25 also have nearly the lowest values of heat transfer (see Fig. 8): 30°C temperature transfer was recorded through knits JT-35 and AnS-25 after 1800 s. Knit JT-45 is the thinnest (2,51 µm) and transfers heat faster than other knits in group I: 32°C was recorded through the knit after 1800 s; moreover, even after 500 s, the heat transfer process through knit JT-45 was higher by 2°C than other knits in group I. This gap remained until the end of the study. The same tendency was recorded for knit AnS-45, the thinnest (2,58 µm) fabric in group II.

Therefore, not only the air permeability, but the process of heat transfer is also inversely proportional to the thickness of knits with Yorkshire Terrier and English spaniel hair fibres. A relationship between the thickness and air permeability of knits with Shih-Tzu dog hair was not found, but the results showed that thicker knit ŠC-25 (2.72 µm) in group IV release less temperature (30°C) through its surface, while the thinner (2.61 µm) more (31°C). The results of this research demonstrate that raw material or the amount of fibre in the blend are not related to the thermal properties of knits in groups I–IV. The structure of the knit determines the amount of air therein and has the main influence on thermal-functional properties of knits with dog‘s hair fibres.

An analysis of thermal properties of woollen felts. The aim of the last stage of this research was to design, produce and test woollen felts (thickness 4.13–4.40 mm) from blends of German Blackface sheep wool and

Bobtail, Russian Spaniel and Yorkshire Terrier hair fibre. It is known that thermal conductivity of woollen felts directly depends on the average diameter of wool fiber. To compare the results, fibers VJ, RS and JT with very similar average diameter (respectively, 30.00 µm, 26.88 µm and 29.55 µm) were selected for the production of woollen felts. Bobtail's hair fibre B was chosen for its unique morphological properties. Therefore, all fibres in felt production differ in medulla ratio and the relative frequency of the medulla, respectively: Russian Spaniel hair 30% and 3.65%, Yorkshire Terrier hair 20% and 6.6%, and Bobtail 68% and 56.58%. There was no medulla detected in the cross-section of German blackface sheep wool hair. The differences of these structures and geometrical indices of protein fibers should/could influence the thermal properties of felts. Thus, sheep wool fiber VJ was blended with dog hair fibers JT, RS and B in ratios of 100:0, 85:15, 75:25, 65:35, 55:45, 20:80, 0:100 and felts were made.

The results of air permeability showed that felts RS45, RS25, RS35, JT35, RS15 with the thickness 4.13–4.29 mm have medium values of air permeability (456,58–656,64 $cm^3/(m^2s)$), and the air permeability values of felts B25, B80, JT25, JT80, B45, JT100, RS100, RS80, B15, JT15, JT45 with thickness 4.30–4.40 mm varied in the 378,42–501,40 $cm^3/(m^2s)$ range. It was noticed that the air permeability of the thickest felts was lower than that of the thinnest. The average thickness of felt from 100% German blackface sheep wool is 4.34 mm; this felt has a medium value of air permeability 434.2 $cm^3/(m^2s)$ among all analysed felts.

The measurements of heat transfer process for felts with Yorkshire Terrier hair fibre are presented in Figure 9. It can be seen that an increasing amount of dog hair fibre JT in the blend relates with better thermal resistance on-time not only in comparison with the felt of 100% of the German Blackface sheep wool fiber, but also with each other.

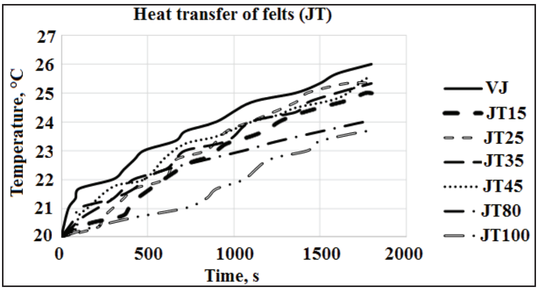


Figure 9. The heat transfer process of felts with Yorkshire Terrier hair

It was found that felt VJ releases 26°C temperature through its surface after 1800 s, meanwhile felts JT80 and JT100 (with 80% and 100% of

Yorkshire Terrier hair) – only 24°C. During the measurements, it was noted that the heat transfer process through felt VJ was the fastest and lowest through the felt JT100. Figure 9 shows that the difference of temperature through felts VJ100 and JT100 to the environment at the same time (750 s and 1800 s) is about 2.5°C. It is also very important that felt JT80 released a similar temperature as JT15, JT25, JT35 and JT45 through its surface to the environment up to 1000 s, but from that point, the heat transfer process of this felt became slower and its thermal properties were similar to felt JT100 at 1800 s. It was found that the average diameter of dog hair fibre JT and sheep wool fibre VJ is very similar (from 29.55 μm to 30.00 μm), and an increase of Yorkshire Terrier dog hair fibre does not affect the average diameter value of the blend and, therefore, change the volume of felt. Hence, the relative frequency of medulla inside fibre JT is low (6.6%) and the medulla takes up 20% of the volume of the hair, but the increase of fibre JT in the blend improves the thermal properties of felts from this blends.

Although the relative frequency of Bobtail hair fibre B medulla is almost 10 times higher and the volume of the medulla inside of the hair more than 3 times bigger than the in the previously discussed dog hair fibre JT, the heat transfer process of felts B15, B25, B35 and B45 is similar to felt VJ100. In addition, the heat transfer process through felts B25 and B35 to the environment is faster than through the woollen felt VJ. It was also found that the heat transfer process through felts B80 and B100 is slower than felt VJ100 and emits a lower temperature at the same time. It was found that felts B80 and B100 emit 25°C temperature through its surface after 1800 s. The analysis of heat exchange curves showed that the difference of temperature leak to the environment through felts VJ100 and B100 over the same time (750 s and 1200 s) is 1.4°C. Thus, it can be stated that felts with maximal quantity of Bobtail hair fibre have better thermal properties than woollen felt VJ.

Felts with 15%, 25% and 35% of Russian Spaniel hair fiber keep 1.5°C heat more than felt made of 100% of German Blackface sheep wool after 1800 s. In addition, felts with 45%, 80% and 100% of dog hair RS already have lower thermal insulation. These trends can be explained by the fact that Russian Spaniel's hair are not only the finest, but also the shortest of all used in felt, and they could spill during the carding process. SEM photographs (Fig. 2) showed that there are many scales on the surface of Russian Spaniel's hair but the scales are declivous and do not hold each other firmly. Therefore, an analysis of felts with Russian Spaniel hair showed that the selection of components to the blend is very important and it is necessarily to evaluate not only the diameter and length of the fibers, but also the morphological characteristics and structure.

Recommendations for use of knitted fabric and woollen felts from sheep wool and dog hair fibres. As it has already been mentioned in the introduction, the demand of products with dog hair has recently increased, but these natural, organic fibers are still not properly exploited. In addition, the results of this research show that dog hair blends with sheep wool perfectly, hence it can be recycled for industrial technological equipment and the production of woollen yarn and various textile materials. Woollen felts from blends of sheep wool and dog hair fibres can be used as in-trays in home slippers or shoes, inserts in baby carriages, clothing, heat-trapping containers and etc. Woollen yarn with dog hair fibres can be used for socks (especially for people with poor blood circulation), hats, scarves, gloves, sleeves, upper thick pants, sweaters, robes, and coats. Extremely important and emphasized area of application – natural medicine. Such textile fabrics can provide an excellent heating effect: corsets or back lane; neckline for neck pain or angina treatment.

CONCLUSIONS

1. This study showed that German blackface and Romanov breed sheep wool and Poodle, Shih-Tzu, Bobtail, Flemish Bouvier, English, American and Russian Spaniel dogs' hair fibres have irregular cylindrical cross-section; there are scales with different frequency on the surface, and hollow or kemp type of medulla was found inside of the dogs' hair (except for Flemish Bouvier dog hair). The ratio of a medulla in different dog hair can reach 61.5%, and the volume of medulla inside the hair can reach up to – 68.0%.
2. It was estimated that the IR spectra of German Blackface sheep wool fibre have peaks in the region of 2920–2850 cm^{-1} and 1643 cm^{-1}, while the peaks of dog hair fibres are more active with wave numbers of 2958 cm^{-1}, 1651–1646 cm^{-1} and 1514–1537 cm^{-1}. XRD diffraction patterns were found at $2\Theta = 9.04 \sim 9.08°$ and $2\Theta = 20.58 \sim 20.68°$, the degree of crystallization varies in the range of 7–30%. The percentage of carbon, hydrogen and nytrogen in sheep wool and dog hair fibres are of the same order of magnitude, and the results slightly varied in the range of $C \sim 45 \pm 3.0\%$, $H \sim 6 \pm 0.3\%$ and $N \sim 14.6 \pm 1.0\%$, respectively.
3. It was found that the diameter of all tested fibres varies from 22.10 μm to 48.80 μm, length 25.2–139.6 mm. The value of experimental linear density of German blackface and Romanov sheep wool fibres is very similar (1.04–1.28 tex), while the experimental linear density of different dog hair varies in range of 0.57–3.08 tex. It was measured that the

theoretical and experimental linear density of all mentioned fibres differ by 2.8–17.6%.

4. It was estimated that the breaking tenacity of tested protein fibres vary from 9.91 cN/tex to 43.19 cN/tex, elongation at break 34.40–54.63%, and the toughness 0.32–1.47 kJ/tex. It was found that elongation at break of all measured dog hair fibres is bigger by 6–21% than German blackface sheep wool. The mechanical indices of Poodle, Flemish Bouvier, English Spaniel and Yorkshire Terrier hair fibres depend not only on the diameter and length of fibre, but on the morphology, relative frequency of medulla inside the cross-section of hair and type of medulla; however, the mechanical indices of Shih-Tzu and Bobtail hair fibres depend mostly on the morphology of fibre.
5. An analysis of morphological, geometrical and mechanical indices of protein fibres showed that German blackface sheep wool and Poodle, Shih-Tzu, Bobtail, English Spaniel, Yorkshire Terrier and Flemish Bouvier hair fibres are suitable for making blends and woollen blend yarns can be successfully used for knits: there were no technological difficulties in ring spinning with spinner "P-114-Š" and knitting with a socks knitting machine "Irmac" (Italia).
6. It has been established that the breaking tenacity of woollen yarns from 100% German blackface sheep wool is 2.51 cN/tex, the elongation at break is 10.9% and the breaking toughness 1.06 kJ/tex. The breaking tenacity of all analysed woollen yarns with dog hair fibres vary from 1.53 cN/tex to 3.81 cN/tex, the elongation at break in the range of 8.9–17.8%, and the breaking toughness 0.58–2.57 kJ/tex. An increase of quantity of English Spaniel and Yorkshire Terrier dog hair fibre from 15% to 45%, Shih-Tzu from 25% to 35% and Poodle from 15% to 35% in the blend influence the decrease of breaking tenacity, elongation at break and breaking toughness of woollen yarns from this blend. 15% of dog hair fibres in the blend improve the mechanical properties of woollen yarns by 1.3–1.6 times, and even 45% of dog hair fibre in the blend does not reduce the mechanical properties of woollen yarn, compared with yarns from 100% German blackface sheep wool fibre.
7. It was experimentally verified that the limited amount of dog hair fibres in a blend for industrial production of woollen blend yarn is 45%; in such cases, yarn can be produced on the same technological production parameters as woollen yarns from 100% sheep wool.
8. It was also found that thermal conductivity, thermal resistance and air permeability of knitted fabrics from woollen blend yarns with Yorkshire Terrier, English Spaniel, Poodle and Shih-Tzu hair fibres are not related to the composition of the yarns. An increase of dog hair fibres up to 45%

in the blend has no significant effect on the functional properties of knitted fabrics.

9. It was discovered that the heat transfer process of felts from different protein fibres depends not only on the geometrical indices of fibres – diameter and length, but on the breed of dog, the morphology, relative frequency of the medulla inside of the hair, and especially on the amount of dog hair fibres in the blend. Felts from Yorkshire Terrier hair, with a maximal quantity of Bobtail hair and minimal/medium quantity of Russian Spaniel hair fibres have better thermal resistance and the heat transfer process is slower than that of felts from 100% German blackface sheep wool fiber.
10. It is recommended to use Poodle, Shih-Tzu, Bobtail, English, American and Russian Spaniel, Yorkshire Terrier dogs' hair fibres in the production of felts, because they have a medulla inside of the hair which improves the thermal properties of felts in many cases. It is very important to choose the right components for the felts not only according to their geometrical but according to their morphological indices: diameter and lenght of fibre, frequency distribution of scales on the surface of fibre, the diamater of medulla and the relative frequency of medulla inside of the hair.

A LIST OF PUBLICATIONS ON THE TOPIC OF THIS DISSERTATION

Articles in journals in the *Thomson Reuters Web of Knowledge* list

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2. Rusinavičiūtė, Jolita; Ragaišienė, Audronė; Biniaś, Wladislaw. Influence of the Fibre Origin on its Structure and Geometrical Indices // Journal of Natural Fibers. ISSN 1544-046X. 2016, vol. 13, no. 5, p. 585-596.
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REZIUMĖ

<u>Tiriamos problemos pagrindimas ir darbo aktualumas.</u> Natūralūs, biodegraduojantys pluoštai yra labai plačiai naudojami tekstilės pramonėje, todėl be klasikinių linų, medvilnės ar vilnos pluošto verpalų bei siūlų, šiuolaikinis vartotojas gali įsigyti ir gaminių iš bambuko, kanapės, bananų, kazeino ar net durpės pluošto. Kiekvienas pluoštas ar skirtingų pluoštų mišinys pasižymi tik jam būdingomis, savitomis savybėmis, kurios sėkmingai išnaudojamos skirtingos paskirties gaminiuose. Pluoštų mišinių savybių ir iš jų pagamintų tekstilės gaminių tyrimai vartotojui sudaro galimybes rinktis iš kelių galimų variantų, atsižvelgiant į kainą, ekologiškumą, ilgaamžiškumą ir kitus veiksnius.

Remiantis statistika, tekstilės pramonėje populiariausia ir vis dar plačiausiai naudojama avių vilna, tačiau verpiama ir ožkų, kupranugarių, lamų, alpakų bei kitų gyvūnų vilna ir plaukai. Vilna – baltyminis pluoštas, sudarytas ne tik iš daugiau kaip 20 aminorūgščių, bet taip pat turintis ir riebalų bei kitų įvairių cheminių elementų. Vilnos pluoštas pasižymi daugiafunkcėmis savybėmis: yra laidus orui, mažai teplus, tamprus, atsparus raukšlėms, gerai išlaiko formą, antistatinis, lėtai užsidega, yra geras garso izoliatorius. Išskirtinė vilnos pluošto sandaros savybė – žvyneliais padengtas plauko paviršius – sukuria galimybes puikiai sugerti drėgmę, sulaikyti šilumą, o plaukeliams tampriai sukibti vieniems su kitais. Taigi, vilnos pluoštas yra labai plačiai naudojamas tiek gaminant aprangą, tiek buitinės ar techninės tekstilės pramonėje.

Pastaruoju metu Lietuvoje ir pasaulyje vis paklausesni tampa verpalai su šunų plaukais. Tokių verpalų funkcinės, šiluminės ir netgi gydomosios savybės žinomos jau seniai, kai Šiaurės šalių, tarp jų ir Lietuvos, moterys iš jų megzdavo kojines, pirštines, šalikus, megztinius. Galima sakyti, kad šunų plaukų pluoštas, išgyvena renesansą, po ilgo laiko tiesiog atrandamas iš naujo, tačiau išsamių skirtingų veislių šunų plaukų savybių, jų lyginamosios analizės bei verpalų ar tekstilės medžiagų su šunų plaukais geometrinių, mechaninių ar šiluminių savybių – tyrimų aptikta ypač mažai. Todėl šiame darbe tiriami, analizuojami ir tarpusavyje lyginami ne tik Vokietijos juodgalvių ir Romanovų veislių avių vilnos pluoštai, bet ir net 8 skirtingų veislių šunų: pudelio, ši cu, bobteilo, flamandų buvjė, anglų, amerikiečių ir ausų spanielių bei Jorkšyro terjero plaukai.

Ne mažiau svarbus šunų plaukų naudojimo aspektu veiksnys − šio pluošto ekologiškumas, todėl jų populiarinimas yra visuomeniškai skatintina akcija. Kaip žinoma, ekologija šiuo metu užima itin svarbią vietą vartotojų sąmonėje ir daug prisideda formuojant sveiką gyvenseną. Taip sukuriamos galimybės išplėsti ir sėkmingai išnaudoti natūralių, ekologiškų pluoštų

resursus, juos sėkmingai panaudojant pramoninėje gamyboje, kartu prisidedant prie atsinaujinčių resursų naudojimo, puoselėjimo ir išsaugojimo. Žinoma, kad, siekiant gerai sumaišyti kelis skirtingus komponentus, tikslinga naudoti kočiotinę verpalų verpimo sistemą, o šitaip verpiant labai svarbu parinkti tinkamus komponentus. Vidutinis pluošto ilgis, skersmuo, ilginis tankis, savitoji trūkimo jėga, santykinė trūkimo ištįsa bei kiti pluošto stiprumą nusakantys rodikliai turi įtakos verpalų iš šių pluoštų savybėms. Kita vertus, pasirinkta verpalų verpimo sistema ir įvairūs jų gamybos technologiniai procesai (pluošto valymas, emulsavimas, karšimas ir verpimas) yra itin svarbūs veiksniai, turintys reikšmingą įtaką verpalų savybėms ir tolimesniam jų naudojimui. Taigi, darbe sukurti verpalai yra pagaminti naudojant kočiotinę verpimo sistemą, kuri dažniausiai naudojama perdirbant trumpų plaukelių daugiakomponenčius mišinius. Įvertinus padidėjusią verpalų, mezginių ar veltinių su šunų plaukais paklausą, ne tik aktualūs, bet ir labai reikšmingi yra tokių tekstilės medžiagų kūrimo, gamybos bei įvairių jų savybių tyrimai.

Darbo tikslas – išanalizavus ir įvertinus pasirinktų avių vilnos ir šunų plaukų pluoštų morfologinius, sandaros bei cheminius yptumus, geometrinius ir mechaninius rodiklius, ištirti ir įvertinti procentinio šunų plaukų kiekio įtaką tekstilės medžiagų iš jų geometrinėms, mechaninėms ir funkcinėms savybėms.

Darbo uždaviniai:

1. Įvairiais metodais ištirti ir tarpusavyje palyginti skirtingų veislių avių vilnos ir šunų plaukų sandaros, geometrinius ir mechaninius rodiklius bei įvertinti galimybes panaudoti juos gaminant kočiotinius verpalus.
2. Įvertinti priklausomybę tarp tirtų pluoštų morfologijos, sandaros, geometrinių ir mechaninių rodiklių.
3. Eksperimentiškai parinkus geriausias pluoštines sudėtis ir pagaminus skirtingos procentinės sudėties kočiotinius avių vilnos ir šunų plaukų verpalus, įvertinti priklausomybę tarp tirtų verpalų geometrinių ir mechaninių savybių bei procentinės pluoštinės mišinių sudėties įtaką šioms savybėms.
4. Eksperimentiškai parinkus reikiamą komponentų sudėtį ir pagaminus megztas bei veltas medžiagas, įvertinti priklausomybę tarp tirtų tekstilės medžiagų struktūros, funkcinių ir šiluminių savybių bei procentinės pluoštinės mišinių sudėties įtaką šioms savybėms.
5. Pateikti tekstilės medžiagų iš avių vilnos ir šunų plaukų naudojimo rekomendacijas.

Darbo mokslinis naujumas ir praktinė reikšmė. Išsami literatūros išsami išanalizė rodo, kad pasaulyje baltyminių pluoštų tyrimai yra labai aktualūs, jų atliekama daug ir įvairių: pradedant pluoštų morfologijos, cheminių, geometrinių ir mechaninių rodiklių ir baigiant tekstilės medžiagų skirtingų funkcinių (tarp jų vartojamųjų bei šiluminių) savybių tyrimais, lyginamąja analize bei rekomendacijomis gamintojams ir vartotojams. Tačiau galima konstatuoti faktą, kad šunų plaukų ar iš jų pagamintų verpalų, mezginių, veltinių ir kitų tekstilės medžiagų tyrimų įdirbis bei tyrimų rezultatų sklaida mokslinėje literatūroje yra labai nedideli. Taigi, nors pastaruoju metu vartotojai yra ypač susidomėję gaminiais, kurių sudėtyje yra šunų plaukų, ir nors dauguma jų teigia jaučiantys teigiamą šildomąjį ir gydomąjį šių gaminių poveikį, mokslinių tyrimų šia tema kol kas nėra. Šioje disertacijoje yra tiriamos ne tik įvairios konkrečių baltyminių pluoštų (Vokietijos juodgalvių ir Romanovų veislių avių vilna bei pudelio, ši cu, bobteilo, flamandų buvje, anglų, amerikiečių ir rusų spanielių bei Jorkšyro terjero veislių šunų plaukai) savybės, bet ir, iš jų pagaminus bei ištyrus kočiotinių verpalų, mezginių ir veltų tekstilės medžiagų geometrines, mechanines ir funkcines savybes, mokslinių tyrimų metu gautais rezultatais siekiama atsakyti į keletą klausimų: ar šunų plaukai, kaip natūralus baltyminis pluoštas, gali būti naudojamas gaminant verpalus ar mezginius? ar šis pluoštas yra tinkamas veltoms tekstilės medžiagoms gaminti? kaip šunų plaukai keičia (nekeičia) įvairias tekstilės medžiagų savybes? kuo panašūs ir kuo skiriasi skirtingų veislių šunų plaukai tarpusavyje ir palyginti su avių vilna? ar iš šunų plaukų pluošto pagaminti tekstiliniai gaminiai pasižymi geresnėmis šiluminėmis savybėmis nei iš avių vilnos?

Statistiniai duomenys rodo, kad ir Lietuvoje į avių augintojų asociaciją įstoja vis daugiau naujų narių, avių ūkiai plečiasi, kartu vis daugiau tiekiama avių vilnos pluošto perdirbėjams, tačiau rinka vis dar nėra iki galo užpildyta. O štai kitos rūšies baltyminis pluoštas – šunų plaukai - kiekvienais metais yra išmetamas, nors galėtų būti panaudojamas gaminant įvairias tekstilės medžiagas. Šiuo metu Lietuvoje yra apie 100 oficialiai registruotų įvairių veterinarijos klinikų ir gyvūnų kirpyklų, kuriose kiekvieną dieną (ypač pavasarį) yra nukerpami ir dažniausiai tiesiog išmetami skirtingų veislių šunų plaukai. Ištyrus ir įvertinus šunų plaukų pluošto, kočiotinių verpalų ir tekstilės medžiagų su jais geometrines, mechanines ir funkcines savybes, siekiama ne tik panaudoti iki šiol išmetamus šunų plaukų resursus, bet, galbūt, ir rasti naują nišą natūralumą vertinančių pirkėjų rinkoje.

IŠVADOS

1. Nustatyta, kad tirtų Vokietijos juodgalvių ir Romanovų veislių avių vilnos bei pudelio, ši cu, bobteilo, flamandų buvjė, anglų, amerikiečių ir rusų spanielio bei Jorkšyro terjero veislių šunų plaukų skerspjūvis yra

netaisyklingo apskritimo formos, plaukelių paviršius padengtas žvyneliais, kurių pasiskirstymo dažnis plauko paviršiuje skiriasi, o šunų plaukelių (išskyrus flamandų buvjė šunų veislę) skerspjūvyje yra tuščiaviduriai arba korėti įvairaus pasiskirstymo dažnio per plauko ilgį kanalai. Rasta, kad kanalo dažnis skirtingų veislių šunų plaukelių skerspjūvyje siekia 61,5 proc., o kanalo užimamas tūris – 68,0 proc.

2. Nustatyta, kad Vokietijos juodgalvių avių vilnos FTIR absorbcijos smailės yra 2920–2850 cm^{-1} ir 1643 cm^{-1} regionuose, o šunų plaukų FTIR spektrai yra intensyvesni 2958 cm^{-1}, 1651–1646 cm^{-1} ir 1514–1537 cm^{-1} smailių regionuose. Kristalografinės smailės ir difrakciniai intensyvumai rasti ties $2\Theta = 9.04 \sim 9.08$ ° ir $2\Theta = 20.58 \sim 20.68$ °, tirtų baltyminių pluoštų kristalizacijos laispnis kinta 7–30 proc. ribose. Procentinis anglies, deguonies ir azoto kiekis avių vilnos ir šunų plaukų cheminėje sudėtyje yra tos pačios eilės, atitinkamai: C ~ 45 ± 3.0 proc., H ~ 6 ± 0.3 proc. ir N ~ 14.6 ± 1.0 proc. ribose.
3. Rasta, kad tirtų pluoštų skersmuo kinta nuo 22,10 μm iki 48,80 μm, o ilgis svyruoja 25,2–139,6 mm. Vokietijos juodgalvių ir Romanovų veislių avių vilnos eksperimentinis ilginis tankis yra panašus (1,04–1,28 tex), o skirtingų veislių šunų plaukų ilginis tankis svyruoja 0,57–3,08 tex ribose. Nustatyta, kad eksperimentinės ir teorinės pluoštų ilginio tankio vertės skiriasi 2,8–17,6 proc.
4. Nustatyta, kad tirtų pluoštų savitoji trūkimo jėga kinta nuo 9,91 cN/tex iki 43,19 cN/tex, santykinė trūkimo ištįsa yra 34,40–54,63 proc., o savitasis trūkimo darbas svyruoja 0,32–1,47 kJ/tex. Tirtų šunų plaukų santykinė trūkimo ištįsa yra 6–21 proc. didesnė nei Vokietijos juodgalvių avių vilnos pluošto. Pudelio, flamandų buvjė, anglų spanielio ir Jorkšyro terjero veislių šunų plaukų mechaniniai rodikliai priklauso ne tik nuo jų skersmens ir ilgio, bet ir nuo plaukelio morfologijos, santykinio kanalo dažnio plauko skerspjūvyje bei kanalo tipo, tačiau ši cu ir bobteilo veislės šunų plaukų mechaniniams rodikliams, be struktūros rodiklių, didžiausią įtaką turi būtent plauko morfologija.
5. Įvertinus tirtų baltyminių pluoštų morfologiją, geometrinių ir mechaninių rodiklių tyrimų rezultatus, nustatyta, kad Vokietijos juodgalvių avių vilna ir pudelio, ši cu, bobteilo, anglų spanielio, Jorkšyro terjero ir flamandų buvjė veislių šunų plaukai yra tinkami mišiniams sudaryti, o iš jų pagaminti kočiotiniai verpalai toliau gali būti naudojami gaminant mezginius: verpimas žiediniu verptuvu „P-114-Š“ ir mezgimas kojinių mezgimo automatu „Irmac“ (Italija) technologinių sunkumų nesudarė.
6. Nustatyta, kad kočiotiniai Vokietijos juodgalvių avių vilnos verpalai pasižymi 2,51 cN/tex savitosios trūkimo jėgos, 10,9 proc. santykinės trūkimo ištįsos ir 1,06 kJ/tex savitojo trūkimo darbo vidutinėmis

vertėmis. Verpalų su šunų plaukais savitosios trūkimo jėgos, santykinės trūkimo ištįsos ir savitojo trūkimo darbo vertės atitinkamai kito 1,53–3,81 cN/tex, 8,9–17,8 proc. ribose, 0,58–2,57 kJ/tex ribose. Gauta, kad anglų spanielio ir Jorkšyro terjero veislių šunų plaukų procentinį kiekį mišinyje didinant nuo 15 proc. iki 45 proc., ši cu nuo 25 proc. iki 35 proc. ir pudelio nuo 15 proc. iki 35 proc., kočiotinių verpalų iš tų mišinių savitoji trūkimo jėga, santykinė trūkimo ištįsa ir savitasis trūkimo darbas mažėja. Į pluoštų mišinį įdėjus vos 15 proc. ši cu ar pudelio veislės šunų plaukų, verpalų iš šių mišinių mechaninių rodiklių vertės padidėja 1,3–1,6 karto, o net ir 45 proc. šunų plaukų priedas mišinyje nepablogina verpalų su jais mechaninių savybių, palyginti su verpalais iš 100 proc. Vokietijos juodgalvių avių vilnos.

7. Eksperimentais nustatyta, kad, pramoniniu būdu gaminant kočiotinius verpalus ribinis procentinis šunų plaukų kiekis mišinyje yra 45 proc. Neviršijus šio šunų plaukų kiekio mišiniuose, verpalai gali būti gaminami įprasta kočiotinei verpimo sistemai gamybos technologija, kaip ir grynavilniai kočiotiniai verpalai.
8. Nustatyta, kad lygiojo skersinio pynimo mezginių iš kočiotinių verpalų su Jorkšyro terjero, anglų spanielio, pudelio ir ši cu veislės šunų plaukais, šiluminis laidumas ir varža bei laidumas orui nepriklauso nuo mišinio procentinės sudėties. Didinat procentinį šunų plaukų kiekį mišiniuose iki 45 proc., funkcinių mezginių savybių kitimo tendencijų nenustatyta.
9. Nustatyta, kad veltinių iš skirtingų baltyminių pluoštų šiluminių mainų procesas priklauso ne tik pluošto geometrinių savybių – skersmens ir ilgio, bet ir šunų veislės, jų plaukų morfologijos, santykinio kanalo dažnio plauko skerspjūvyje, ir ypač, nuo procentinio šunų plaukelių kiekio mišinyje. Veltiniai su Jorkšyro terjero, maksimaliais bobteilo ir minimaliais bei vidutiniais rusų spanielio kiekiais mišinyje geriau sulaiko šilumą, o šiluminiai mainai per juos yra lėtesni nei veltinių iš 100 proc. Vokietijos juodgalvių avių vilnos.
10. Rekomenduojama veltiniams gaminti naudoti pudelio, ši cu, bobteilo, anglų, amerikiečių ar rusų spanielio bei Jorkšyro terjero veislės šunų plaukus, kurių skerspjūvyje yra kanalai, nes jie dažniausiai pagerina veltinio šilumines savybes. Parenkant komponentus veltiniams labai svarbu įvertinti pluoštų geometrinius ir morfologinius rodiklius: vidutinį pluoštų skersmenį ir ilgį, žvynelių pasiskirstymo dažnį plauko paviršiuje, vidutinį kanalo skersmenį bei santykinį kanalo dažnį plauko skerspjūvyje.

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E. Majui už pagalbą gaminant modelinius verpalus ir nuoširdžią meilę tekstilės pramonei.

Doc. dr. R. Ivanauskui ir dr. J. Širvaitytei už pagalbą atliekant baltyminių pluoštų cheminius tyrimus.

Dr. A. Baltušnikui už atliktą baltyminių pluoštų rentgeno struktūrinę analizę, skirtą laiką konsultacijoms ir labai vertingus mokslinius patarimus.

Dr. inž. W. Biniaś už baltyminių pluoštų paviršiaus tyrimus.

UAB „Litwool“ direktoriui Algirdui Pupšiui už tiesioginę pagalbą įsigyjant Vokietijos juodgalvių avių vilnos pluošto bei gaminant kočiotinius mišriapluoščius verpalus.

Gintui Mizeikiui už pagalbą gaminant mezginius.

Dr. D. Milašienei už atliktus termomechaninius mezginių tyrimus Lenkijoje ir įdėjines mintis disertacijos metu atliekant tyrimus.

G. Pupšienei už profesionalų darbą veliant veltinius.

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Tiems, kurių jau nebėra, tačiau kuriuos jaučiu šalia...

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