KAUNAS UNIVERSITY OF TECHNOLOGY

ASTA VELIČKIENĖ

EVALUATION AND FORECASTING OF PROPERTIES OF TERRY FABRICS WOVEN FROM NATURAL FIBERS

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

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ASTA VELIČKIENĖ

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INTRODUCTION

The Problem of the Research and Relevance of the Work. Terry fabrics are very popular materials which may be used for home textile, bath and sauna products, specifically, towels, bathrobes, slippers, bath mats, sauna skirts, sauna bags, cosmetic sponges, sauna turbans, bath washers, sauna gloves, etc. Terry woven fabrics can be adapted for consumers with a variety of needs. The use of appropriate technologies and the modern methods of finishing allows creating the desired quality as well as the set of features of the manufactured products.

In order to produce good quality terry fabrics, first of all, one must ideally perceive the structure of terry fabrics. The structure of the terry fabric is characterized by its complex weave which is obtained through interlacing two systems of warp and one system of weft. Thus terry fabric consists of the terry fabric ground (the ground warp and the ground weft) as well as the loop pile (the pile warp). The loop pile is one of the most important elements of the terry woven fabric structure because the appearance of the product and many other properties depend on the loops formed on the surface of terry fabrics. The loop pile of terry woven fabrics is obtained from the yarn of different linear densities and various fiber compositions; it can also be of different heights.

With the increasing consciousness of manufacturers and consumers, in the modern textile industry, particular attention is being paid to environmentally-friendly natural fibers. Not only must the product be ecological but its manufacturing process is required to be nature-friendly as well. In the present dissertation, terry woven fabrics manufactured from natural yarns are investigated: cotton, flax, hemp and ramie. These yarns are made from the corresponding natural fibers which are environment-friendly. The use of the outlined fibers for terry woven fabrics has developed great future prospects due to a large extent to which terry fabrics are known to be used in the household, because of the broad assortment of baby clothes and as a result of the large scale of production of medicine and hygiene products.

Manufacturing of good quality terry woven fabrics requires extensive knowledge of not only the structure of the woven fabric but also of physical and mechanical properties of such fabrics. Physical properties of woven fabrics determine the comfortability of the product. Water absorption is important for terry fabrics as well; therefore, this property is frequently investigated. Consequently, in this study, water vapour absorption and water evaporation from terry fabrics are investigated. Another extremely important physical property of terry woven fabrics is their permeability. Absorption and desorption properties of woven fabrics depend on their air permeability.

Mechanical properties of textile fabrics are among the most important characteristics determining the service capability of the product; not only does the durability of the product depend on the fiber strength but also it is heavily affected by the manufacturing process as well. Another method of the assessment of terry fabric wear is the change in mechanical properties after abrasion impact has been imposed on the fabric. The present research is important regarding the aspect that certain errors in the yarn or woven fabric production may deteriorate some usage-related properties of the product, and such shortcomings emerge just as a result of gradual wear-and-tear.

Terry fabric finishing methods are being developed seeking not only to improve the fabric's appearance or to provide it with additional functional properties but also in order to increase the demand for terry woven fabrics. Still, the improperly chosen fabric treatment mode may deteriorate the product's appearance and its real-life usage properties. Therefore, in order to assess the impact of water, heat and mechanical and chemical substances, macerating or washing in water has been carried out without using any chemical substances or any finishing.

The present research also features attempts of predicting the woven fabric quality by seeking to establish the dependence of parameters on water, heat and mechanical or chemical impact/finishing procedures. Also, comparative analysis of terry woven fabrics of different fiber compositions, treatment with the application of different finishes and different structures has been conducted. The established mathematical relations allow predicting the parameters on the basis of which it will be possible to develop high quality terry woven fabrics.

The Aim of the Work. To determine and assess the structural, physical and mechanical properties of grey (i.e. without finishing) terry woven fabrics of various fiber compositions including treated ones by applying various impacts and finishings; to predict structural, physical and mechanical parameters of terry woven fabrics describing them by mathematical dependencies enabling the creation of new and superior terry woven fabrics.

The Scientific Tasks of the Work:

1. To investigate the influence of the terry fabric structure and finishing on the percentage composition of terry fabric yarn systems and the area density of woven fabrics.
2. To assess the influence of terry fabric fiber composition, its structure and finishing on the water vapour absorption in woven fabrics and water evaporation.
3. To investigate the resistance to the pile loop extraction of terry fabrics with different pile heights as well as the resistance of specimens treated by applying different impacts/finishings; to analyze the pile yarn stick-slip phenomenon in woven fabrics.

4. To conduct analysis of terry fabric abrasion resistance and mass loss during abrasion; to investigate how air permeability changes when woven fabrics are being worn.
5. To describe structural, physical, and mechanical indicators of terry fabrics mathematically and to perform their forecasts; to conduct comparative analysis of the quality indicators of terry fabric.

The Novelty of the Work and its Importance. Terry fabrics investigated in literature sources are mostly manufactured from cotton yarn. Thus, evidently, a shortage of research in terry fabrics from linen yarn is currently observed in the context of Lithuanian-made pure linen woven fabric having become extremely popular. In the present dissertation, terry fabrics from such rarely used natural vegetative fibers as hemp and ramie (nettle) are also analyzed. Hemp fiber shows good physical and mechanical properties whereas woven fabrics from hemp fiber after finishing become soft and delicate thus delivering a pleasant feel). Products from ramie fiber have good absorption properties as well; they are lightweight and are thus comfortable to wear. The fiber has a natural white color; therefore, it does not need bleaching. Previous scholarly research materials on the properties of ramie fabric are virtually nonexistent, and the number of experimental tests is extremely small. The situation is even worse because the available researches were only carried out on plain weave woven fabrics. No literature sources on ramie woven fabrics of complex structure, such as terry woven fabrics, have been found. Therefore, it is particularly relevant to investigate the structural, physical and mechanical properties of new terry fabrics featuring ramie, linen and hemp pile warp and their interdependencies as well as to analyze the possibilities of the application of the above listed types of fiber yarns for terry woven fabrics.

The physical appearance of a terry fabric depends not only on the woven fabric structure and its properties but also on the end-use conditions. Good end-use properties of a woven fabric first of all depend on its strength. The majority of researchers investigate physical properties of terry fabrics; thus there is only a minor number of studies discussing their mechanical properties. In the present dissertation, mechanical tests have been carried out in order to determine the wear properties of the product. The terry fabrics have been worn via abrasion, and the product breakdown as well as the mass loss have been evaluated. During the present research, air permeability of terry fabrics during the wear has also been assessed so that to identify the extent to which the woven fabric is suitable to use. This type of research was deliberately intended for terry woven fabrics as no similar analysis has been found in scholarly sources.

The investigation of resistance to pile loop extraction is important and relevant in terms of the terry fabric mechanics and the assessment of product aesthetics. The sources in academic literature concerning the resistance to pile loop extraction are very scarce, and the already existing references are mostly not intended to research the case of terry fabric; most frequently, technical textile fabrics are investigated whose weave structure is elementary. Also, in the present dissertation, analysis of the terry fabric resistance to pile loop extraction has been conducted, and the pile yarn stick-slip phenomenon relevant for wear has been investigated.

Statements to Be Defended:

1. Weft density of ramie/cotton terry fabrics has greater influence on the woven fabric structural and geometric parameters as well as on its physical and mechanical properties than the pile height.
2. The capacity of liquid absorption has influence on water evaporation of ramie/cotton, linen/cotton, hemp/cotton and linen terry fabrics; the area density has influence on water vapour absorption. A number of structural and geometric features of woven fabric, specifically, area density, weft density and fiber composition exert major influence on the mechanical properties of terry woven fabrics.
3. The finishing carried out on linen/cotton, hemp/cotton and linen terry fabrics improves their physical and mechanical properties; still, excessive duration of the finishing operations, especially in the case of a large number of them, can have a negative impact on the woven fabric quality.
4. The yarn stick-slip phenomenon in the woven fabric when pulling out a pile loop from it depends not only on the terry fabric structure as the lack of regularity of yarns in this case bears significant influence as well.
5. The investigation of ramie/cotton, linen/cotton, hemp/cotton and linen terry fabrics allows to predict the parameters of the woven fabric quality and the woven fabric raw material consumption, which is important in terms of economics, whereas the obtained results enable the design of new high quality terry fabrics from natural fibers which would possess the desired physical and mechanical properties as well as deliver economical consumption of fibers.

Approval of the Research Results. The topic of this dissertation has been presented in 17 scientific publications, among which 4 articles are listed among *Thomson Reuters Web of Knowledge* base publications with a citation index (IF/AIF > 0.2). The research results have been discussed in 12 conferences including 7 international and 5 national conferences. Total number of reports at conferences is 14.

The Structure of the Doctoral Dissertation. The present dissertation consists of the following parts: Introduction, 3 Chapters, Conclusions, a List of References (214 entries) and a List of Scientific Studies. The dissertation material is submitted on 123 pages displaying 5 Tables, 48 Figures and 17 formulas.

THE CONTENT OF THE DISSERTATION

The **Introduction** presents an assessment of the properties of terry woven fabrics whose composition includes ramie, flax, hemp and cotton fibers provides a forecast of such properties.

Chapter One **Literature Review** covers a number of works by Lithuanian and foreign authors. After reviewing the relevant scholarly papers, it became evident that studies concerning research in terry woven fabric structure have previously been conducted. Most commonly, cotton and flax fibers are used for terry woven fabrics; still, the yarns from extremely rare fibers, for example, ramie and hemp fibers, are occasionally used. One of the most important purposes of terry woven fabrics is to absorb water to the best of their ability; therefore, a major part of the conducted investigation research has been intended for dynamic and static water absorption. The research demonstrates that water absorption in terry woven fabrics depends on the fiber composition, the woven fabric structure and its geometric properties as well as on the impact/finishing which has been carried out on the woven fabric.

A major part of researchers maintain that the comfort features of textile fabrics are related to heat and moisture transporting through textile fabrics and their air permeability. Therefore, it is extremely important to investigate the permeability of textile fabrics, water vapour absorption and the drying velocity. There is a shortage of similar investigations concerning terry woven fabrics in literature sources; therefore, it is necessary to extend our investigation to terry structures as well because terry woven fabrics are used in wet environments and in temperatures which are higher than usual.

Literature review evidently demonstrates that terry woven fabrics have been investigated in terms of their physical properties; however, there is a shortage of analyses in the field of their mechanical properties, especially regarding special structure woven fabrics. Research has shown that different regimes of industrial washing and softening differently affect not only the physical properties of woven fabrics but also mechanical ones as well. Still, there is a significant lack of analyses of the mechanical parameters of terry woven fabric, and especially exploration of mathematical dependencies which could assist in predicting the quality of new terry products.

Chapter Two **Research Methodology** indicates the object of the investigation, namely, grey (without finishing) terry woven fabrics and terry woven fabrics treated by applying various impacts/finishings, fabrics featuring differences in fiber composition, pile height, linear density of yarn and weft density.

Table 1. Fiber composition of woven fabric variants *a*, *b*, *c*, *e*, *k*, *r* and *R*

Designa- tion	Height of pile, mm	Fiber composition, the linear density of yarns, tex			Yarn density, cm^{-1}	
		pile warp	ground warp	ground weft	warp (pile and ground)	weft
a	6 9 12	unbleached yarn linen, 68	folded yarn cotton, 25 x 2	cotton yarn, 50	25	20
b	6 9 12	bleached yarn linen, 50	folded yarn cotton, 25 x 2	cotton yarn, 50	25	20
c	9 12	unbleached yarn linen, 68	unbleached folded yarn linen, 56	unbleached yarn linen, 56	25	18
e	9	unbleached yarn linen, 50	folded yarn cotton, 25 x 2	cotton yarn, 50	25	20
k	9	hemp yarn, 72	folded yarn cotton, 25 x 2	cotton yarn, 50	25	20
r	4.5 6 7.5 9 10.5	rame yarn, 67	folded yarn cotton, 25 x 2	cotton yarn, 50	25	12
	6 10.5	ramie yarn, 67	folded yarn cotton, 25 x 2	cotton yarn, 50	25	8 10 14 16
R	-		ramie yarn, 67 and folded yarn cotton, 25 x 2	cotton yarn, 50	25	8 10 12 14 16

Terry woven fabrics, the pile warp and the ground warp of which consist of linen/cotton (*a*, *b*, *e*), linen (*c*), hemp/cotton (*k*) and ramie/cotton (*r*) yarns were used during the experiments. Also, a part of woven fabrics without the loop pile were investigated: they were woven from ramie/cotton (*R*) yarn with different weft densities. Woven fabric variants *R* were used for comparative analyses with terry woven fabrics of the same fiber composition. Loading data for all types of woven fabrics is given in **Table 1**.

Table 2. Variants of the investigated woven fabrics and the type of impact/finishing carried out on them; woven fabric characteristics

Designa-tion		***Fabric's variant***	***Impact/finishing***	***Duration***
Z		$Zr4.5_{12}$, $Zr6_{12}$, $Zr7.5_{12}$, $Zr9_{12}$, $Zr10.5_{12}$, $Zr6_{8}$, $Zr6_{10}$, $Zr6_{14}$, $Zr6_{16}$, $Zr10.5_{8}$, $Zr10.5_{10}$, $Zr10.5_{14}$, $Zr10.5_{16}$, *Za6*, *Za9*, *Za12*, *Zb6*, *Zb9*, *Zb12*, *Zc9*, *Ze9*, *Zk9*, R_{8}, R_{10}, R_{12}, R_{14}, R_{16}	Grey fabric (without impact/finishing)	
V		*Va6*, *Vb6*, *Va9*, *Vb9*, *Va12*, *Vb12*, *Vc12*, *Ve9*	Macerating (20 ± 2 ºC) in water → drying in air	
S	***S^{10}***	$Sa6^{10}$, $Sb6^{10}$, $Sa9^{10}$, $Sb9^{10}$, $Sa12^{10}$, $Sb12^{10}$, $Sc12^{10}$, $Se9^{10}$, $Sk9^{10}$	Washing (40 ºC) in water → centrifuging → drying in air	10 min
	S^{30}	$Sa6^{30}$, $Sb6^{30}$, $Sa9^{30}$, $Sb9^{30}$, $Sa12^{30}$, $Sb12^{30}$, $Sc12^{30}$, $Se9^{30}$, $Sk9^{30}$		30 min
	S^{120}	$Sa6^{120}$, $Sb6^{120}$, $Sa9^{120}$, $Sb9^{120}$, $Sa12^{120}$, $Sb12^{120}$, $Se9^{120}$, $Sk9^{120}$		120 min
P		*Pa6*, *Pa9*, *Pb9*, *Pa12*, *Pb12*, *Pc12*, *Pe9*	Washing with a detergent (60 ºC, 60 min) → centrifuging → drying in air	
M		*Ma6*, *Mb6*, *Ma9*, *Mb9*, *Ma12*, *Mb12*, *Me9*, *Mk9*	Washing with a detergent (60 ºC, 60 min) → softening (60 ºC, 40 min) → centrifuging → drying in air	
K		*Ka9*, *Kb9*	Washing with a detergent (60 ºC, 60 min) → softening (60 ºC, 40 min) → centrifuging → calendering	
T	***T^{30}***	$Ta6^{30}$, $Tb6^{30}$, $Ta9^{30}$, $Ta12^{30}$, $Tb12^{30}$, $Tc12^{30}$, $Te9^{30}$, $Tk9^{30}$	Washing with a detergent (60 ºC, 60 min) → softening (60 ºC, 40 min) → centrifuging → tumbling → drying in air (if required)	30 min
	T^{60}	$Ta6^{60}$, $Tb6^{60}$, $Ta9^{60}$, $Ta12^{60}$, $Tb12^{60}$, $Te9^{60}$, $Tk9^{60}$		60 min
	T^{90}	$Ta6^{90}$, $Tb6^{90}$, $Ta9^{90}$, $Ta12^{90}$, $Tb12^{90}$, $Tc12^{90}$, $Te9^{90}$, $Tk9^{90}$		90 min
	T^{120}	$Ta6^{120}$, $Tb6^{120}$, $Ta9^{120}$, $Tb9^{120}$, $Ta12^{120}$, $Tb12^{120}$, $Tc9^{120}$, $Tc12^{120}$, $Te9^{120}$, $Tk9^{120}$		120 min
	T^{150}	$Ta6^{150}$, $Tb6^{150}$, $Ta9^{150}$, $Tb9^{150}$, $Ta12^{150}$, $Tb12^{150}$, $Tc12^{150}$, $Te9^{150}$, $Tk9^{150}$		150 min

All the woven fabrics have been specially woven for the research conducted in the framework of this dissertation investigation at "A grupė" JSC (lt. Abbreviated as *UAB*, Jonava Township, Lithuania); a part of the woven fabrics were woven in accordance with the plan of the experiment. In the present dissertation, the total number of different woven fabrics being investigated amounted to 120 units.

In order to investigate the influence of water, heat, mechanical and chemical impacts on the quality of terry woven fabric, in accordance with a special plan, grey (*Z*) woven fabrics were treated by applying different impacts or types of finishing. The types of impact on terry woven fabrics were as follows: macerating in water (*V*), washing in water for different time intervals (*S*). The types of finishing of terry woven fabrics were: washing with a detergent (*P*), washing with a detergent followed by softening (*M*), washing with a detergent, softening and calendering (*K*), washing with a detergent, softening and tumble-drying for different time intervals (*T*). The link between the type of terry woven fabrics being investigated and the impact/finishing carried out is shown in **Table 2**.

All the experiments were carried out in the standard atmosphere according to LST EN ISO 139:2005/A1:2011 Standard (relative humidity φ = (65 ± 4) % and temperature T = (20 ± 2) °C). For the photographing of experiments, digital camera *Nikon Coolpix 4500* (*Nikon Corporation*, Japan) and stereo microscope *Nikon Stereoscopic Zoom microscope SMZ 800* (*Nikon Corporation*, Japan) connected to a computer were used. Analysis of fiber surfaces was performed by using Scanning Electron Microscopy (*SEM*) *FEI Quanta 200 FEG* (USA) (10 kV, the magnification range of the specimen is 3000x).

In order to identify the properties of terry woven fabrics, the following structural, physical and mechanical parameters of these woven fabrics have been investigated and the outlined below economic (fabric structure) factors important for their production were considered:

***Structural and Geometric Parameters of Terry Woven Fabrics*:**

✓Area Density of Woven Fabrics. Woven fabric area density has been identified referring to LST EN 12127:1999 Standard ("Textiles – Fabrics – Determination of Mass per Unit Area Using Small Samples").

✓Percent Composition of Woven Fabric Yarn System. The percentage of the composition of yarn systems of terry woven fabrics was calculated for all the three yarn systems: the percentage of the composition of pile warp, ground warp and ground weft.

***Investigation of Physical Properties of Terry Fabrics*:**

✓*Water Vapour Absorption in Woven Fabrics*. Water vapour absorption investigation was conducted referring to LST EN 13515:2004 Standard.

✓Water Evaporation from Woven Fabrics. Water vapour evaporation investigation was carried out referring to FTTS-FA-004 Standard in which the information on the investigation of the fluid evaporation process by using the drop method is provided.

✓Air Permeability of Woven Fabrics. Air permeability testing was conducted by referring to LST EN ISO 9237:1997 Standard defining the method of measuring air permeability in flat textile fabrics. During the testing, the yield of air flow permeating through a determined area of fabric at a pre-established difference in pressures is measured. Air permeability testing was performed by using the *LI4DR* instrument (*Karl Schroder KG*, Germany).

***Investigation of Mechanical Properties of Terry Fabrics*:**

✓Resistance to Pile Loop Extraction of Terry Fabrics. The conducted experiments refer to LST EN 15598:2008 Standard, in which the method of testing and identification of terry fabric resistance to pile loop extraction is outlined. Resistance to pile loop extraction was assessed by using the *Zwick/Z005* (*Zwick GmbH & Co. KG*, Germany) stretch testing machine and *testXpert*® software.

✓Abrasion Resistance of Woven Fabrics: Specimen Breakdown and Mass Loss. In order to assess the abrasion resistance of textile fabrics, i.e. the breakdown and the mass loss, *Martindale* method was applied. This method is based on the following standards: "Textiles – Determination of the Abrasion Resistance of Fabrics by the Martindale Method – Part 2: Determination of Specimen Breakdown" – LST EN ISO 12947-2:2001 and "Textiles – Determination of the Abrasion Resistance of Fabrics by the Martindale Method – Part 3: Determination of Mass Loss" – LST EN ISO 12947-3:2001.

Factors determining the quality of terry fabrics are their pile height, weft density, fiber composition and the completed procedure of yarn or woven fabric finishing or some impact imposed on them. **Fig. 1** demonstrates the significance and links between the properties of terry fabric.

Having completed the testings, the possibility of rejection of questionable results of observation was verified. Also, errors were taken into consideration so that to assess the reliability of testing. Statistical calculations for all the obtained results were made. Checking was also conducted whether the variances of experiment points are homogeneous, i.e. whether they are of the same order. In the case of homogeneous variances, the informativeness of the experiment was calculated. At the meantime, empirical equations between the variable factor and the relevant property of the textile item were assessed for the informative experiment. The coefficient of determination, R^2 was calculated for the assessment of experimental points in order to achieve the equation compliance to enable prediction of structural, physical and mechanical parameters of terry woven fabrics. In order to compare the results of different measurements concerning fabric parameters or quality indicators, a comparison between the results of two tests was conducted, i.e. it was established whether the difference(s) between the results under investigation are significant or not. In other words, the correlation between results expressed as the function $y = f(x)$ was assessed in order to define to what extent the correlation dependency is close to the functional dependency.

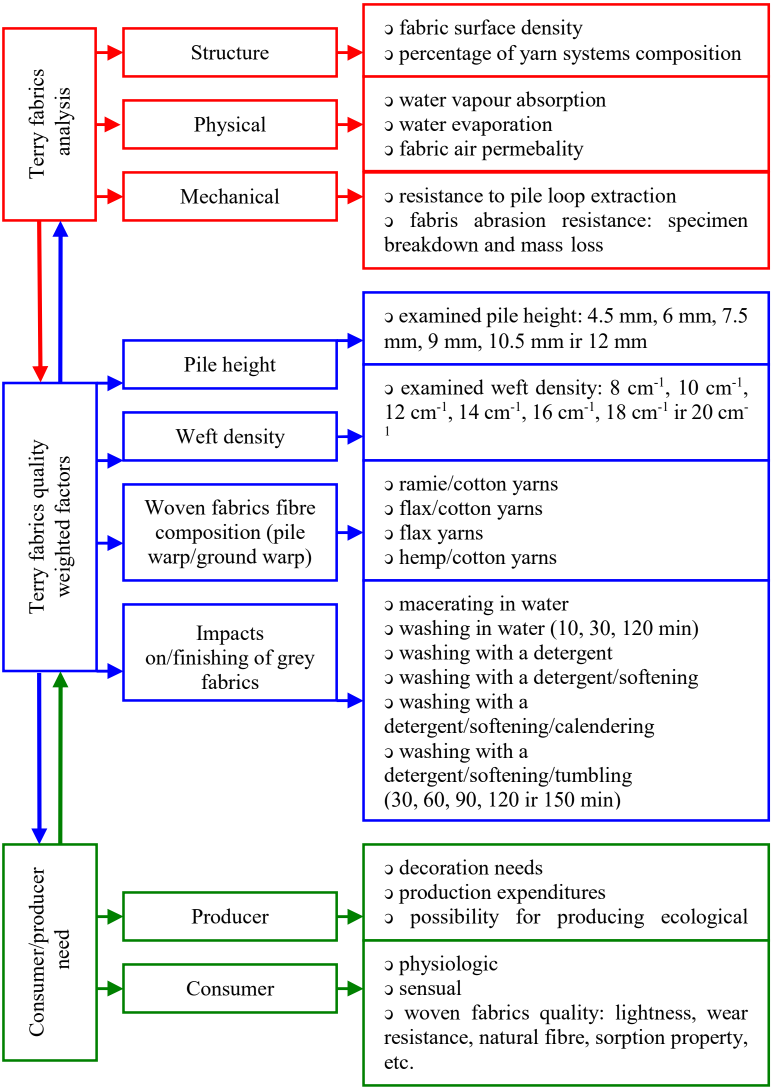


Figure 1. Importance and inter-correlations between the properties of terry fabric

Chapter Three **Results of Investigation** presents the results of theoretical and experimental investigation and their analysis.

***Area Density and Percentage Composition of Woven Fabric Yarn System*.** On the basis of the investigation carried out on the terry fabric area density and the yarn system percentage of composition it is entirely possible to compute more precisely the resources of raw materials for production. Thus whenever investigating the area density of the ramie/cotton terry fabric dependency on the woven fabric structure it could be observed that the area density was increasing with the terry fabric pile and weft density increasing from 230.4 to 574.2 g/m^2. When investigating the percentage of composition of the ramie/cotton terry fabric yarn it was established that the pile warp made up the greatest part of the terry fabric yarn system, i.e. from 54.8 to 74.4 % of the terry fabric when the pile height and weft density were changing. With increasing the pile and weft density, the pile warp composition quantity increased as well. The analysis of the accuracy of predictions revealed that the calculated values of the surface density and the percentage of the pile warp yarn amount and that of the terry fabrics are the closest to the experimental values and never exceed 7.1 %.

When investigating the percentage of the composition of linen, linen/cotton and hemp/cotton terry fabric yarns, it was established that the pile warp accounts for 60.1 to 76.9 % of the woven fabric part. Our research showed that the most significant influence on the percentage of composition of the terry fabric yarn is made by the pile height and the finishing carried out on the woven fabrics, i.e. with increasing the extent of finishing, the percentage part of pile warp yarn decreases while by increasing the pile height we also increase the percentage values of the pile warp yarn.

***Water Vapour Absorption in Terry Fabrics*.** The complex structure of terry fabric developing when the pile height and the weft density are changing forms a distinctive surface of the woven fabric which has a significant impact on the water vapour absorption. After conducting the experimental investigation on ramie/cotton terry fabrics, it was established that the water vapour absorption increases and that the weft density has a greater influence on the water vapour absorption than the pile height. The results demonstrate that the water vapour absorption increases from 21.4 to 61.5 g/m^2 when increasing the weft density. It was also established that a strong link exists between the woven fabric structure and the water vapour absorption: when describing dependencies with logarithmic equations, the coefficient of determination was calculated to equal $R^2 = 0.9699$.

After performing the analysis of the results concerning the linen/cotton grey terry fabrics and macerated terry fabrics, it was established that woven fabrics with the 12 mm pile absorb the greatest quantity of water vapour. Having compared the grey (without finishing) terry fabrics and the macerated in water terry fabrics, it was established that even a slight impact of water exerts influence on the water vapour absorption results (**Fig. 2**).

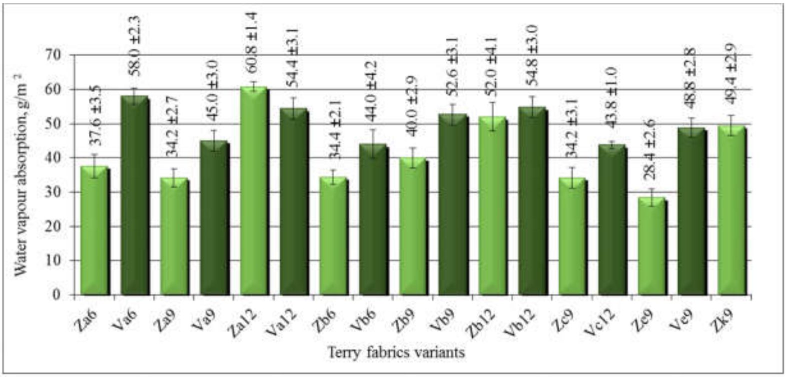


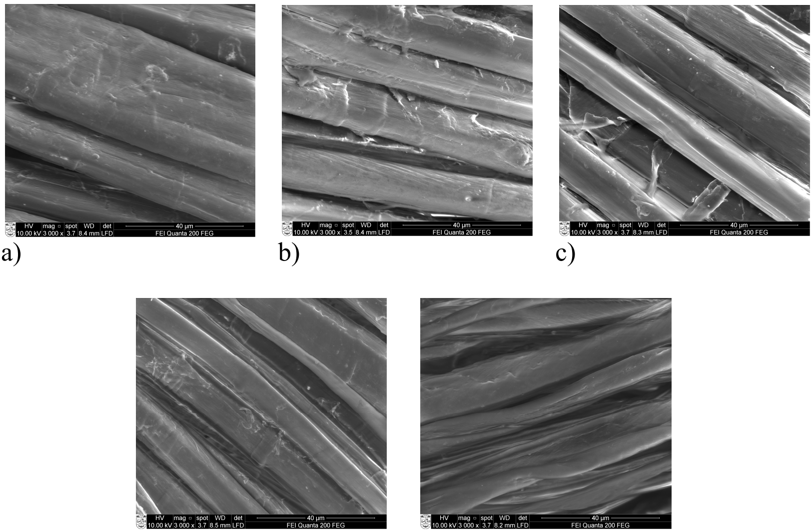
Figure 2. Water vapour absorption of grey (without finishing) terry fabrics and macerated terry fabrics of variants *Za*, *Va*, *Zb*, *Vb*, *Zc*, *Vc*, *Ze*, *Ve* and *Zk*

Having conducted analyses of linen/cotton terry fabrics with unbleached pile warp, it was established that the more terry fabrics experience water, heat and mechanical (*Sa*) impact as well as chemical substance impact (*Pa* and *Ma*), the more water vapour they are able to absorb. Also, a greater level of water vapour absorption is determined by the greatest pile height. The results showed that the terry fabrics, the pile warp of which is bleached (*b*), are able to absorb more water vapour than terry fabrics with the unbleached (*a*) pile warp.

Water vapour absorption of linen (*Sc12*), linen/cotton (*Se9*) and hemp/cotton (*Sk9*) woven fabrics is determined by the duration of the finishing which was carried out on them. Our investigation showed that when washing woven fabrics in water for 10 and 30 min, water vapour absorption has a tendency to increase; still, when washing for 120 min, the nap from the fiber surface got removed; therefore, the porosity of the woven fabric increases and the fabric absorbs a lower quantity of water vapour.

Not only does the appearance of a terry fabric change after it has undergone a tumbling operation following wet finishing but also water vapour absorption results are affected. Having carried out investigation on water vapour absorption in linen/cotton woven fabrics (*Ta*, *Tb*, *Te*), an empirical dependency between the duration of tumbling and water vapour absorption was established. The obtained results demonstrate that the greatest quantity of absorbed water vapour was observed in the terry fabrics with the 12 mm pile. In addition, the terry fabric finishing duration also affects the water vapour absorption results, i.e. different durations of tumbling were investigated. It is believed that the longer the terry fabric is being tumbled, the softer it becomes, and, because of this, the fabric is capable of absorbing more water vapour. Still, if tumbling takes place for too long, the nap is removed from the fabric, the fabric thus becomes thinner, it becomes more air and water vapour-permeable; therefore it can absorb less and less water vapour.

Water Evaporation from Terry Fabrics**.** All the fibers investigated in this study are hygroscopic; those are ramie, hemp, flax and cotton fibers. Ramie, hemp and flax fibers have similar structures, i.e. they are produced from stems and their fiber is denoted by a round shape. It is hollow inside; still, the view of their surfaces is different (**Fig. 3**).



a) b) c) d) e)

Figure 3. Surface view of terry fabrics, *SEM* pictures (40 µm): a) ramie fiber, b) unbleached flax fiber, c) bleached flax fiber, d) hemp fiber, e) cotton fiber

In the *SEM* picture, it may be observed that the ramie fiber surface is of relief type (a) whereas the hemp fiber surface is slightly smoother (d), the bleached flax surface is much smoother (c) than that of the unbleached flax (b). The cotton fiber is flattened, it has a twisted diameter (e). Due to different morphologic structures of the fibers, when contacting with water vapour or liquids, the behavior of such fibers does differ.

When conducting our investigation on water evaporation from terry fabrics, the following two factors were taken into account: the duration of water evaporation and the evaporation intensity. Terry fabrics evaporated water in 80 – 180 min depending on the fabric structure, fiber composition, executed treatment or finishing as well as on the duration. The intensity of water evaporation of terry fabrics depends on the duration of fabric water evaporation, i.e., if a fabric evaporated water within approximately 80 – 120 min, the water evaporation process proved to be intensive from the very first minutes. Still, in various variants of woven fabric, in which the water evaporation process lasted for about 120 – 180 min, the water evaporation process started taking place intensively just from the moment of 20 – 40 min. **Fig. 4** shows the changes in the ratio of the remaining water in ramie/cotton terry fabrics at various water evaporation time intervals.

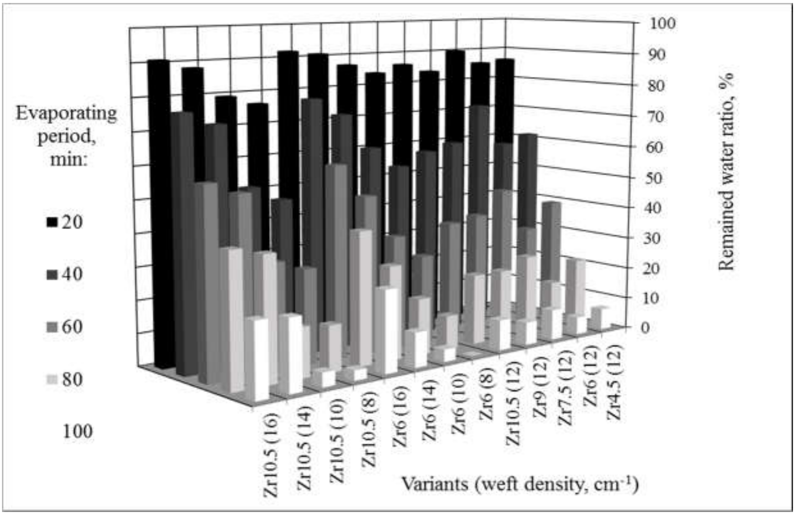


Figure 4. Changes in the ratio of the remaining water of terry fabrics *Zr*

Having analyzed the dependence of water evaporation from grey ramie/cotton (*Zr*) terry fabrics (without finishing) on the woven fabric structure, it was established that the greatest influence on the duration of evaporation was observed in the case of pile weft of terry fabrics (up to 90 – 140 min), i.e. the denser is the fabric, the longer is the duration of water evaporation. Having analyzed the dependence of water evaporation of grey linen/cotton terry fabrics (without finishing) (*Za*, *Zb*) and those macerated in water (*Va*, *Vb*) on the pile height, it was established that the fabrics with the 9 and 12 mm piles evaporated water the fastest. What concerns the duration of the water evaporation of linen/cotton terry fabrics washed in water for different time intervals (*Sa*, *Sb*), neither the washing time nor the pile height seemed to have any influence. Water evaporation took place faster in those linen/cotton terry fabrics which were being washed with a detergent (*Pa*, *Pb*) and featured medium size and large piles (9 and 12 mm). Whereas the fabrics washed with a detergent/softener (*Ma*, *Mb*) with the 6 mm piles evaporated water the fastest.

When analyzing linen/cotton terry fabrics washed with a detergent/calendered (*K*), it was established that woven fabrics with the bleached pile warp evaporated the water the fastest of all. Considering linen (*Tc*), linen/cotton (*Ta*) and hemp/cotton (*Tk*) terry fabrics after wet finishing which were tumble-dried for different time intervals, the fabrics which were tumbled for the shortest and longest periods evaporated the water the fastest of all. It is of interest that this process took the longest time span for those fabrics which underwent the medium duration of tumbling (90 min). The duration of water evaporation of fabrics treated with wet finishing depends not only on the duration of tumbling but also on the pile height.

For the majority of the investigated terry fabrics, water evaporation results showed a prominently strong link between the duration of water evaporation and the ratio of the remaining water (R^2 even up to 0.9999) while the established mathematical relations allow predicting the qualitative parameters.

***Resistance to Pile Loop Extraction of Terry Fabrics*.** The greatest influence on the resistance to the pile loop extraction of ramie/cotton terry fabrics takes place in the structure of terry fabric, i.e. the resistance to the pile loop extraction depends on the intersection points. It was established that a greater pulling force is required for the terry fabrics with a lower pile and a larger weft density as the intervals between intersection points are more frequent. When pulling out a larger pile from a fabric, or in the case of a lesser weft density, due to a looser structure of the fabric and the longer intervals between intersection points, smaller pulling force is required. Thus when analyzing the ramie/cotton terry fabrics with different pile height and weft densities, it was discovered that the resistance against the loop pile extraction within the entire interval measured from 99.0 mN to 1728.3 mN. For the major part of ramie/cotton terry fabrics, a strong link between the elongation and the tensile force was identified: $R^2 = 0.9807 – 0.9967$. Our analysis of the accuracy of predicting revealed that the calculated values of resistance to the pile loop extraction of terry fabrics are extremely close to the experimental values and tend not to exceed 5.9 % except for singular cases.

Having compared the results of the resistance against pile loop extraction between grey linen/cotton terry fabrics (without finishing) and those macerated in water, it was established that the fabrics with the 6 and 12 mm pile are most resistant to pile loop extraction. Also, the obtained results demonstrate that in the case of the bleached pile warp, the resistance to the pile loop extraction was significantly lower than that of fabrics with the unbleached pile warp. Thus the bleaching of the pile warp reduces the strength of yarn.

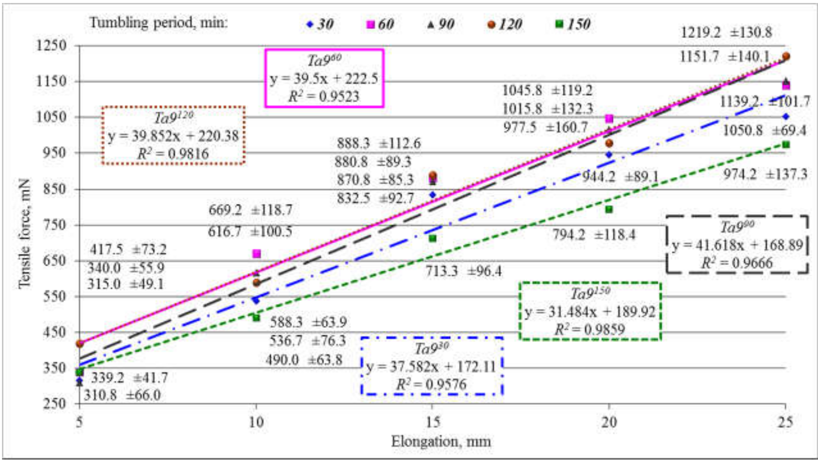


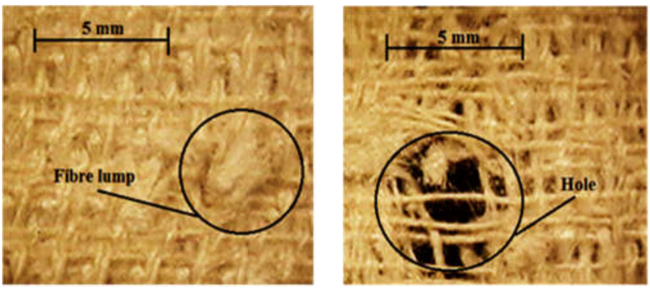
Figure 5. Dependence of tensile force parameter of terry fabrics variant $Ta9^{30\text{-}150}$ on the pile loop pulling distance

When investigating the dependence of the resistance to the pile loop extraction of linen/cotton terry fabrics with the unbleached pile warp (*Sa*) which were washed in water without any chemical substances on the pile height, it was found that the fabrics with the 6 mm piles proved to be the most resistant. Taking into account the duration of washing, it was discovered that the most resistant were those terry fabrics which had been washed in water for 30 min; whilst among the terry fabrics with the bleached pile warp ($Sb^{10\text{-}120}$), the terry fabrics with the 9 mm pile were the most resistant to the pile loop extraction . Taking into account the duration of washing in water, it was measured that those terry fabrics were more resistant which had been washed in water for 10 and 120 min. After the investigation of terry fabrics which had been washed with a detergent (*Pa*) and those which were washed with a detergent/softening (*Ma*), it was demonstrated that those terry fabrics were the most resistant to the pile loop extraction which featured the 12 mm pile, while among fabrics *Pb* and *Mb* it was discovered that the fabrics with the 9 mm pile were more resistant to the pile loop extraction.

When analyzing the terry fabrics washed with a detergent/softener/calendered (*K*), the extremely prominent tensile force was obtained. It is believed that after mechanical finishing (calendering), the fabric evolves a more binding and rigid structure, and the yarns are bent more closely towards each other. When analyzing linen/cotton fabrics on which tumbling

(*Ta*) was carried out after the wet finishing for various time intervals, the greatest force of the pile loop extraction was found to be necessary for the fabrics which had been tumble-dried for 60, 90 and 120 min (**Fig. 5**). It is believed that in the case of the medium duration of tumbling, the fiber nap is more felted; therefore it is much more difficult to pull the pile warp from the fabric. When analyzing the fabrics with the bleached pile warp (*Tb*), it was noticed that the loop pile extraction force is greater in those fabrics which had been tumbled for a shorter time. It is presumed that bleaching exerts influence on this pile warp, after which additionally a number of wet finishing operations were executed on the fabric.

***Abrasion Resistance of Terry Fabrics*.** Having conducted the investigation on the abrasion resistance of ramie/cotton terry fabrics, it can be maintained that the pile height does not have influence on fabric abrading. Having analyzed terry fabrics with different pile heights ($Zr4.5_{12}$ – $Zr10.5_{12}$), the results demonstrate that fabrics with 4.5 – 9 mm and 10.5 mm piles withstood 40.000 cycles, the fabric with the 6 mm pile withstood merely 25.000 cycles while mass loss intensity in different variants proved not to be the same it ranged – approximately from 1.29 % to 31.15 % when changing the number of cycles from 5000 to 25.000 (40.000). For example, instances of the mass loss of the fabric with the 9 mm pile ($Zr9_{12}$) at a certain number of cycles are shown in **Fig. 6**.



a) b)

Figure 6. Change in the view of ramie/cotton terry fabric variant $Zr9_{12}$ during abrading: a) after 25.000 cycles; b) after 40.000 cycles

When analyzing ramie/cotton terry fabrics with different weft densities ($Zr6_{8\text{-}16}$, $Zr10.5_{8\text{-}16}$), the obtained results showed that the abrasion resistance depends on the weft density, i.e. terry fabrics with the highest weft density (up to 50.000) were the most resistant. The mass loss of these fabrics ranged from 0.97 to 32.24 % when increasing the number of abrading cycles.

Having analyzed grey linen/cotton terry fabrics, it was discovered that the fabric with the 6 mm pile (*Zb6*) disintegrated after 40.000 cycles while the fabric with the 9 mm pile (*Zb9*) disintegrated as early as after 25.000 cycles. The woven fabrics after finishing with 6 and 9 mm piles disintegrated after 50.000 cycles (*Tb6*, *Tb9*). When comparing the mass loss results between grey fabrics (without finishing) and those with finishing, it can be seen that the greatest quantity of the fabric mass was lost by grey fabrics.

Terry Fabric Air Permeability Dependence on Abrading**.** It was discovered that when increasing the number of abrading cycles, initially, air permeability decreases, whereas after a certain number of cycles, the air permeability starts to increase. This tendency was noticed when analyzing terry fabrics with different pile heights, weft density, various fiber compositions; this also happens in grey fabrics (without finishing) and in those which underwent finishing.

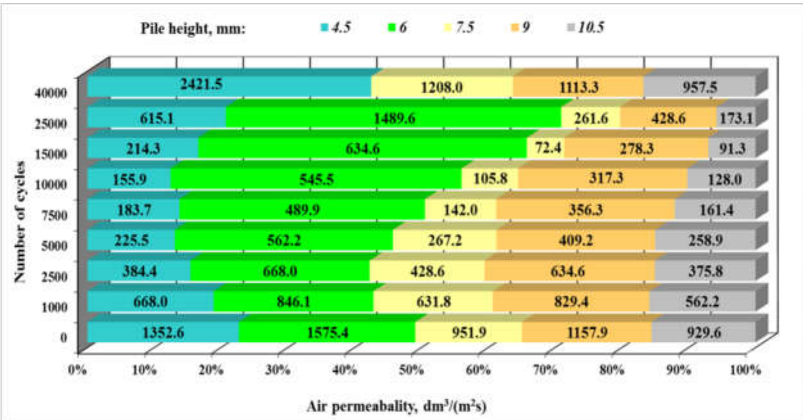


Figure 7. Air permeability results of ramie/cotton terry fabrics variants $Zr4.5_{12}$ – $Zr10.5_{12}$

When investigating ramie/cotton terry fabrics with different pile heights ($Zr4.5_{12}$ – $Zr10.5_{12}$), the air permeability ranged from 929.6 to 2421.5 $dm^3/(m^2s)$ (**Fig.7**) while in the case of different weft densities ($Zr6_{8\text{-}16}$, $Zr10.5_{8\text{-}16}$), the air permeability ranged from 540.0 to 2761.1 $dm^3/(m^2s)$ when changing the number of abrading cycles. The obtained results demonstrate that air permeability rather depends on the weft density, i.e. when the weft density is increasing, the air permeability is decreasing.

In order to determine air permeability, some investigation on grey (without finishing) (*Zb*) and with finishing (*Tb*) linen/cotton terry fabrics was carried out. The results of this investigation demonstrated that grey fabrics (without finishing) were air permeable to the greatest extent while after finishing the air permeability of terry fabrics decreased from 2.9 to 14.0 times. It is presumed that the greatest air permeability of grey fabrics is determined by perpendicular loops through which the air flow passes easily while the yarn softness increases after finishing, and the fabric becomes less air permeable.

***Possibilities of Practical Application of the Research Results and Recommendations*.** In order to expand the assortment of terry fabrics made from natural fibers (flax, cotton, hemp), ramie fiber yarns could be used for terry fabrics. Ramie fiber does not require long finishing operations, because it is denoted by natural silky gloss and is extremely soft.

The results of the investigation performed on ramie/cotton, hemp/cotton, linen/cotton and linen terry fabrics constitute a data base; its use enables the creation of new terry fabrics of superior quality while the established mathematical relations allow predicting structural, geometric, physical and mechanical qualitative parameters.

CONCLUSIONS

1. The fabric structure has significant influence on the ramie/cotton terry fabric area density: when increasing the pile height from 4.5 to 10.5 mm, the area density of the woven fabric increases from 274.8 to 441.9 g/m^2, and, when increasing the weft density from 8 to 16 cm^{-1}, the area density correspondingly increases from 230.4 to 574.2 g/m^2. It was discovered that a strong link exists between the fabric structure parameter and its area density: when describing dependencies with linear equations, the coefficient of determination has been found to vary between $R^2 = 0.9393 – 0.9755$.
2. It is estimated that the pile warp of terry fabrics with the ramie pile warp accounts for 54.8 to 74.4 %. In addition, in the case of the increasing pile height and weft density, the percentage of the ramie pile warp also increases. The pile warp of woven fabrics with the linen and hemp pile warp accounts for 60.1 to 76.9 %. It has been observed that at higher piles and a smaller number of finishing actions, the percentage composition of the linen and hemp yarn system of the terry fabrics increases.
3. When investigating the ramie/cotton terry fabrics, it has been discovered that the weft density has a greater impact on water vapour absorption than the pile height. The results demonstrate that water vapour absorption increases from 21.4 to 61.5 g/m^2 when increasing the weft density while with the increase of the pile height, water vapour absorption only increases from 24.5 to 29.1 g/m^2. Also, it has been established that a strong link exists between the woven fabric structure and water vapour absorption: the

description of dependences by logarithmic equations produces the coefficient of determination equaling $R^2 = 0.9699$.

4. When investigating water vapour absorption in linen/cotton, hemp/cotton and linen terry fabrics, it has been found that the more impact of water, heat as well as mechanical and chemical impact terry fabrics undergo, the greater quantity of water vapour they absorb. Especially significant difference in water vapour absorption has been identified when investigating grey fabrics (without finishing) and macerated terry fabrics. Also, the fabrics with the maximum pile height measuring 12 mm are denoted by the greater quantity of absorbed water.
5. It has been found that with the duration of washing in water becoming longer (from 10 to 120 min) as well as by increasing the duration of the tumbling of woven fabrics from 30 to 150 min after undergoing wet finishing, terry fabrics are able to absorb more vapour; yet if the fabric has been washed in water or tumbled for too long, the capability of water vapour absorption decreases. This is explained by the fact that fibers gradually crumble and the yarn is lost.
6. The terry fabric structure has a significant impact on the duration of water evaporation. Water evaporation length of ramie/cotton terry fabrics lasted up to 90 – 140 min at different weft densities (8 to 16 cm^{-1}). Whereas, linen/cotton terry fabrics evaporate water for 90 to 180 min; still, this process is the fastest among woven fabrics, the pile height of which equals 9 mm. It has been discovered that there is very strong relationship between the duration of water evaporation and the amount of the remaining water: when describing dependences with empirical equations, the coefficient of determination has been up to 0.9999.
7. It has been discovered that terry fabrics evaporate water with different intensiveness, i. e., in terry fabrics, the duration of water evaporation has been shorter – about 80 to 120 min, while the process of water evaporation has taken place most intensively straight from the very first minute. What concerns these terry fabrics, the duration of water evaporation from which is longer – about 120 to 180 min, water the most intensive period of water evaporation only starts with the period of 20 to 60 min after the beginning of evaporation.
8. It has been established that washing in water for varying time intervals does not have significant impact on the duration of terry fabric water evaporation, or no impact is observed at all; still, the tumbling, which takes place after the wet finishing for various time intervals, has an impact on the duration of water evaporation: the terry fabrics which have been tumble-dried for 30, 60 or 150 min have evaporated the water the fastest.

9. It has been found that the resistance to pile loop extraction of ramie/cotton terry fabrics ranges from 99.0 to 1728.3 mN at 5 to 25 mm elongation. It has been observed that the pile loop extraction force is greater for the lower piles of the fabric and the higher weft density.
10. Having investigated the linen/cotton terry fabrics which have been washed using detergent/softener/tumbling, the pile warp of which is unbleached linen yarns, it has been discovered that the greatest pile loop extraction force is necessary in the case of those woven fabrics which after wet finishing have been tumbled for a longer time period, i.e. for 90, 120 or 150 min. While investigating terry fabrics with the bleached linen pile warp, it has been observed that the loop pile extraction force is greater in the cases when the fabric has been tumbled for shorter time periods (30 to 90 min).
11. When investigating the loop pile pulling distance for linen/cotton, hemp/cotton and linen terry fabrics, it has been found that the yarn frequently sticks; while investigating ramie/cotton woven fabrics, it has been found that ramie yarn slips and does not stick virtually at all. These results confirm quite significant inequality in the parameters of resistance to the loop pile extraction. For the major part of ramie/cotton terry fabrics, a strong link between the elongation and tensile force has been identified ($R^2 = 0.9807 – 0.9967$).
12. Abrasion resistance before breakdown (50.000 cycles) of ramie/cotton terry fabrics is the highest among all terry fabrics while the mass loss of the ramie/cotton terry fabrics varies from 0.97 to 32.24 % depending on a number of abrading cycles (5000 to 50.000 cycles). Terry fabrics with the pile height of 10.5 mm have demonstrated the highest abrasion resistance, and their weft density has been the highest (16 cm^{-1}).
13. When analyzing the dependence of air permeability of ramie/cotton terry fabrics on the number of abrading cycles, a significant impact of the woven fabric structure has been established. It has been observed that air permeability has decreased 8.5 times when changing the weft density within the entire interval of the experiment: from 8 to 16 cm^{-1} and by 1.4 times when changing the pile height within the entire interval of the experiment: from 4.5 to 10.5 mm. When the number of abrading cycles is increasing, at first, the air permeability decreases, yet, after a certain number of cycles, the air permeability begins to increase.
14. The analysis of the accuracy of predictions revealed that the calculated values of surface density and the percentage of the pile warp yarn amount as well as the resistance to pile loop extraction of ramie/cotton terry fabrics are the closest to experimental values; it does not exceed 7.1 % except for single cases when this index is higher. A significant difference was also established between the indicators of surface density and the water vapor

absorption, water evaporation, air permeability and between the mass loss and surface density. Commonly, the correlation coefficients reveal that the correlation dependence actually exists.

LIST OF PUBLICATIONS ON THE THEME OF THE DISSERTATION

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

1. Petrulytė, Salvinija; Veličkienė, Asta; Petrulis, Donatas. Influence of terry fabrics structure and finishing on yarn pull-out behaviour // International journal of clothing science and technology. Bradford: Emerald. ISSN 0955-6222. 2014, Vol. 26, No. 4, p. 305-315. DOI: 10.1108/IJCST-06-2013-0068. [Science Citation Index Expanded (Web of Science); 0,333]. [IF: 0,350, AIF:1,663 (2014)].
2. Petrulytė, Salvinija; Dapšauskaitė, Dalia; Veličkienė, Asta; Petrulis, Donatas. Investigation of the resistance to pile loop extraction of linen and ramie fabrics // Fibres and textiles in Eastern Europe. Lodz: Institute of Chemical Fibres. ISSN 1230-3666. 2013, vol. 21, No. 5(101), p. 54-58. [Science Citation Index Expanded (Web of Science); 0,250]. [IF: 0,541, AIF:1,355 (2013)].
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Articles in other periodical reviewed scientific journals

1. Veličkienė, Asta; Petrulytė, Salvinija; Petrulis, Donatas. Experimental determination of abrasion properties of ramie/cotton terry fabrics // Magic world of textiles: 7th international textile clothing & design conference, October 5-8, 2014, Dubrovnik, Croatia: book of proceedings / University of Zagreb. Faculty of Textile technology. Zagreb: University of Zagreb, ISSN 1847-7275. p. 493-498. [0,333].
2. Petrulytė, Salvinija; Veličkienė, Asta; Petrulis, Donatas. Predicting of loop yarn pull-out properties of grey and finished terry fabrics // Magic world of textiles: 7th international textile clothing & design conference, October 5-

8, 2014, Dubrovnik, Croatia: book of proceedings / University of Zagreb. Faculty of Textile technology. Zagreb: University of Zagreb, ISSN 1847-7275. p. 430-435. [0,333].
3. Kiviliūtė, Lina; Veličkienė, Asta; Petrulytė, Salvinija. Kilpinių audinių apdailos ir kilpos aukščio įtakos skysčio išgarinimo procesui tyrimas // Gaminių technologijos ir dizainas: konferencijos pranešimų medžiaga / Kauno technologijos universitetas. Kaunas: Technologija. ISSN 1822-492X. 2012, p. 254-257. [0,333].
4. Skripkiūnaitė, Martyna; Veličkienė, Asta; Petrulytė, Salvinija. Audinių su balintais ir nebalintais lininiais kilpiniais metmenimis džiūvimo tyrimas // Gaminių technologijos ir dizainas: konferencijos pranešimų medžiaga / Kauno technologijos universitetas. Kaunas: Technologija. ISSN 1822-492X. 2012, p. 258-261. [0,333].
5. Veličkienė, Asta; Petrulytė, Salvinija. Skysčio išgarinimo proceso kilpiniuose audiniuose tyrimas // Gaminių technologijos ir dizainas 2010: konferencijos pranešimų medžiaga / Kauno technologijos universitetas. Kaunas: Technologija. ISSN 1822-492X. 2010, p. 247-251. [0,500].
6. Veličkienė, Asta; Petrulytė, Salvinija; Petrulis, Donatas. Forces and displacements associated with pulling a yarn from hemp and ramie terry fabric // AUTEX 2014 [electronic resource]: proceedings of the 14th AUTEX World Textile Conference, 26-28 May, 2014, Bursa, Turkey / Uludag University. Bursa: Uludag University, 2014, ISBN 9786056311246. p. [1-4]. [0,333].
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9. Veličkienė, Asta; Petrulytė, Salvinija; Samuson, Roberta. Lininių ir puslininių kilpinių audinių vandens garų absorbcinių savybių tyrimas // Pramonės inžinerija 2014: jaunųjų mokslininkų konferencija, 2014 m. gegužės 8 d. : pranešimų medžiaga / Kauno technologijos universitetas,

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3. Veličkienė, Asta; Petrulytė, Salvinija; Petrulis, Donatas. Experimental investigation of yarn pull-out of linen/cotton terry fabrics // Advanced materials and technologies: book of abstracts of the 15th international conference-school, 27-31 August 2013, Palanga, Lithuania. Kaunas: Technologija. ISSN 1822-7759. 2013, p. 153. [0,333].
4. Petrulytė, Salvinija; Veličkienė, Asta; Petrulis, Donatas. Effect of finishing treatment on yarn pullout behaviour in terry fabrics // Baltic polymer symposium 2013: Trakai, Lithuania, September 18-21, 2013: programme and abstracts / Vilnius University, Kaunas University of Technology. Vilnius: Vilnius University Publishing House, 2013, ISBN 9786094592270. p. 170. [0,333].

Participation in conferences
International conferences

1. International Conference "7th International Textile Clothing & Design Conference", two reports: "Experimental determination of abrasion properties of ramie/cotton terry fabris" (A. Veličkienė, S. Petrulytė, D. Petrulis) and "Predicting of loop yarn pull-out properties of grey and finished terry fabrics" (S. Petrulytė, A. Veličkienė, D. Petrulis). October 5-8, 2014, Dubrovnik, Croatia.
2. Worldwide Conference "14th Autex World Textile Conference"; report "Forces and Displacements Associated With Pulling a Yarn from Hemp and Ramie Terry Fabric" (A. Veličkienė, S. Petrulytė, D. Petrulis). May 26-28, 2014, Istanbul, Turkey.

3. Worldwide Conference "13th AUTEX World Textile Conference 2013": report "Analysis of Water Vapour Absorption and Water Evaporation Process in Ramie/Cotton Fabrics" (Petrulytė, Salvinija; Veličkienė, Asta; Petrulis, Donatas). May 22-24 2013, Dresden, Germany.
4. Worldwide Conference AUTEX 2012 Innovative Textile for High Future Demands: report "Effect of Fabric Structure and Finishing on Water Vapour Absorption" (Petrulytė, Salvinija; Veličkienė, Asta; Petrulis, Donatas). June 13-15, 2012, Zadar, Croatia.
5. International Conference "Baltic Polymer Symposium 2014": report "Influence of Finishing on Abrasion Characteristics of Terry Fabrics with Bleached Pile" (A. Veličkienė, S. Petrulytė, D. Petrulis). September 24-26, 2014, Laulasmaa, Estonia.
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7. International School-conference "15th International Conference-School: Advanced Materials and Technologies": report "Experimental Investigation of Yarn Pull-out of Linen/cotton Terry Fabrics" (A. Veličkienė, S. Petrulytė, D. Petrulis). August 27-31, 2013, Palanga, Lithuania.

National conferences

1. Conference of young scholars "Pramonės inžinerija 2014" (Industrial Engineering): presentation "Lininių ir puslininių kilpinių audinių vandens garų absorbcinių savybių tyrimas" (Asta Veličkienė, Salvinija Petrulytė, Roberta Samuson). May 8, 2014, Kaunas, Lithuania.
2. National student conference "Inovacijų taikymas technologijose 2014" - presentation "Ramės kilpinių audinių sandaros tyrimas" (Asta Veličkienė, Salvinija Petrulytė, Eglė Bagdonaitė). April 29, 2014, Kaunas, Kaunas University of Applied Sciences, Lithuania.
3. Kaunas University of Technology conference "Gaminių technologijos ir dizainas" (Technologies and Design of Products): presentation "Dilgėlinių/lininių/medvilninių kilpinių audinių kilpos ištraukimo elgsenos tyrimas" (D. Dapšauskaitė, A. Veličkienė, S. Petrulytė). April 26, 2013, Kaunas, Lithuania.
4. Kaunas University of Technology conference "Gaminių technologijos ir dizainas" (Technologies and Design of Products): presentations "Kilpinių audinių apdailos ir kilpos aukščio įtakos skysčio išgarinimo procesui tyrimas" (L. Kiviliūtė, A. Veličkienė, S. Petrulytė) and "Audinių su balintais ir nebalintais lininiais kilpiniais metmenimis džiūvimo tyrimas"

(M. Skripkiūnaitė, A. Veličkienė, S. Petrulytė). April 27, 2012, Kaunas, Lithuania.

5. Conference "Gaminių technologijos ir dizainas" (Technologies and Design of Products): presentation "Skysčio išgarinimo proceso kilpiniuose audiniuose tyrimas" (A. Veličkienė, S. Petrulytė). April 23, 2010, Kaunas, Lithuania.

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REZIUMĖ

Tiriamos problemos pagrindimas ir darbo aktualumas. Kilpiniai audiniai yra vieni iš populiariausių audinių, naudojamų namų tekstilėje, vonios, saunos, pirties gaminiams – tai rankšluosčiai, chalatai, šlepetės, vonios kilimėliai, pirties prijuostės, saunos krepšiai, kosmetinės kempinėlės, gobtuvai, plaušinės, pirštinės ir kt. Kilpiniai audiniai gali būti pritaikomi įvairių poreikių vartotojams. Naudojant tinkamas technologijas ir modernius apdailos metodus, įmanoma sukurti norimą gaminio kokybę.

Siekiant pagaminti kokybiškus kilpinius audinius, pirmiausia būtina gerai žinoti kilpinio audinio sandarą. Kilpinio audinio sandarą apibūdina sudėtingas pynimas, kuris gaunamas perpinant dvi metmenų ir vieną ataudų sistemą. Vadinasi, kilpinį audinį sudaro: kilpinio audinio pagrindas (pagrindo metmenys ir ataudai) ir kilpos (kilpiniai metmenys). Kilpa yra vienas iš svarbiausių kilpinio audinio sandaros elementų, nes nuo audinio paviršiuje sudarytų kilpų priklauso gaminio išvaizda ir daugelis kitų savybių. Kilpinio audinio kilpos sudaromos iš skirtingų ilginių tankių, pluoštinės sudėties siūlų ir gali būti įvairaus aukščio.

Augant gamintojų ir vartotojų sąmoningumui, šiandieninėje tekstilėje ypatingas dėmesys skirtas ekologiškiems natūraliems pluoštams. Ekologiškas turi būti ne tik gaminys, bet ir jo gamybos procesas. Disertacijoje yra nagrinėjami kilpiniai audiniai, pagaminti iš natūralių verpalų: medvilninių, lininių, kanapinių ir ramės. Šie natūraliųjų pluoštų verpalai gali būti iš ekologiškų pluoštų. Taip pat minėtų pluoštų panaudojimas gaminant kilpinius audinius yra perspektyvus dėl didelio kilpinių audinių panaudojimo buityje, kūdikių drabužių asortimente, gaminant medicinos, higienos priemones.

Norint pagaminti kokybiškus kilpinius audinius, būtina gerai žinoti ne tik audinio sandarą, bet ir kilpinio audinio fizikines bei mechanines savybes. Fizikinės audinio savybės nulemia gaminio patogumą. Kilpiniams audiniams svarbios sorbcinės savybės, todėl ši savybė yra dažnai tyrinėjama. Taigi šiame darbe ištirta kilpinių audinių vandens garų absorbcija ir vandens išgarinimas. Kita labai svarbi kilpinių audinių fizikinė savybė yra laidumas. Nuo laidumo orui priklauso audinio absorbcinės ir desorbcinės savybės.

Tekstilės medžiagų mechaninės savybės yra vienos iš svarbiausių charakteristikų, nulemiančių gaminių vartojamąją vertę; nuo pluošto stiprumo priklauso ne tik gaminio ilgaamžiškumas, bet ir gamybos procesas. Kitas kilpinių audinių dėvėjimosi įvertinimo būdas yra audinio mechaninių savybių pakitimo po dilinimo nustatymas. Šis tyrimas yra svarbus tuo, kad kai kurios verpalo ar audinio gamybos klaidos gali pabloginti eksploatacijos savybes, kurios išryškėja tik jį dėvint.

Kilpinių audinių apdailos būdais ne tik siekiama pagerinti jų išvaizdą ar suteikti papildomų funkcinių savybių, bet ir padidinti kilpinių audinių paklausą. Tačiau netinkamai parinktas apdorojimo režimas gali pabloginti gaminio išvaizdą ir eksploatacijos savybes. Todėl, siekiant įvertinti vandens, šilumos, mechaninių ir cheminių medžiagų poveikį, buvo atliekamas vilgymas arba skalbimas vandenyje, nenaudojant jokių cheminių medžiagų arba su apdaila.

Tyrimas taip pat apima audinių kokybės prognozavimą: rodiklių priklausomybės nuo vandens, šilumos, mechaninio, cheminio poveikio / apdailos procedūrų sudarymą. Taip pat atlikta įvairia apdaila paveiktų skirtingos sandaros ir įvairios pluoštinės sudėties kilpinių audinių sandaros, fizikinių, mechaninių savybių lyginamoji analizė. Nustatyti matematiniai ryšiai leidžia prognozuoti rodiklius, kuriais remiantis galima sukurti aukštos kokybės kilpinius audinius.

Darbo tikslas. Nustatyti ir įvertinti įvairios pluoštinės sudėties žalių (be apdailos) įvairiais poveikiais ir apdaila paveiktų kilpinių audinių sandaros, fizikines ir mechanines savybes; prognozuoti šių audinių sandaros, fizikinius, mechaninius rodiklius, ryšius aprašant matematinėmis priklausomybėmis, leidžiančiomis kurti naujus kilpinius audinius.

Darbo uždaviniai:

1. Ištirti kilpinių audinių sandaros ir apdailos įtaką kilpinių audinių siūlų sistemų procentinei sudėčiai ir audinių paviršiniam tankiui.
2. Nustatyti kilpinių audinių pluoštinės sudėties, sandaros ir apdailos įtaką audinių vandens garų absorbcijai ir vandens išgarinimui.
3. Ištirti kilpinių audinių, turinčių skirtingą kilpų aukštį, paveiktų įvairiais poveikiais / apdaila, kilpos atsparumą ištraukimui ir išnagrinėti kilpinio siūlo strigimą ir slydimą audiniuose.
4. Išanalizuoti kilpinių audinių atsparumą dilinimui, masės nuostolius dilinimo metu ir ištirti, kaip kinta dėvimų audinių laidumas orui.
5. Matematinėmis priklausomybėmis aprašyti kilpinių audinių sandaros, fizikinius, mechaninius rodiklius ir juos prognozuoti. Atlikti kilpinių audinių kokybės rodiklių lyginamąją analizę.

Darbo naujumas ir jo reikšmė. Literatūros šaltiniuose nagrinėjami kilpiniai audiniai dažniausiai yra iš medvilninių verpalų, o kilpinių audinių iš lininių verpalų tyrimų stokojama, nors lietuviškas grynas lininis audinys yra sulaukęs didelio populiarumo. Taip pat šioje disertacijoje nagrinėjami kilpiniai audiniai iš retai naudojamų natūralių augalinių pluoštų – kanapės ir ramės (dilgėlių). Kanapės pluoštas pasižymi geromis fizikinėmis ir mechaninėmis savybėmis, o po apdailos audiniai iš kanapių pluošto tampa minkšti ir švelnūs (malonaus grifo). Gaminiai iš ramės pluošto taip pat pasižymi geromis absorbcinėmis savybėmis, yra lengvi, todėl patogūs dėvėti. Pluoštas yra natūralios baltos spalvos, todėl jo nereikia balinti. Literatūros apie ramės audinių savybes beveik nėra, taip pat eksperimentinių tyrimų atlikta vienas kitas, ir tai tik su drobinio pynimo audiniais. Apie sudėtingos konstrukcijos ramės audinius, tokius kaip kilpiniai, literatūros neaptikta. Taigi ypač aktualu ištirti naujų kilpinių audinių su ramės, lininiais ir kanapiniais kilpiniais metmenimis sandaros, fizikines ir mechanines savybes, jų tarpusavio priklausomybes, taip pat išanalizuoti galimybes šių pluoštų verpalus panaudoti kilpiniams audiniams gaminti.

Kilpinio audinio išvaizda priklauso ne tik nuo audinio sandaros ir savybių, bet ir nuo eksploatavimo sąlygų. Geros audinio eksploatacijos savybės pirmiausia priklauso nuo jų stiprumo. Dauguma tyrėjų analizuoja fizikines kilpinių audinių savybes, tačiau mechaninių savybių tyrimų atlikta labai mažai. Disertaciniame darbe atlikti mechaniniai tyrimai, kurie nulemia gaminio dėvėjimosi charakteristikas. Kilpiniai audiniai dėvėti dilinant, įvertintas gaminio suirimas ir masės nuostoliai. Šio tyrimo metu taip pat nustatytas kilpinių audinių laidumas orui dėvėjimo metu, nustatant ribą, iki kurios audinys tinkamas eksploatuoti. Literatūros apie tokio pobūdžio kilpinių audinių tyrimus nerasta.

Pūko kilpos atsparumo ištraukimui nustatymo tyrimai yra svarbūs ir aktualūs kilpinių audinių mechanikos požiūriu ir vertinant gaminio estetiką. Literatūros apie siūlų atsparumo ištraukimui tyrimus nedaug, o ir esantys tyrimai yra skirti ne kilpiniams audiniams; dažniausia nagrinėjami techninės tekstilės audiniai, kurie yra elementarių pynimų. Taip pat disertaciniame darbe atlikta kilpinių audinių pūko kilpos atsparumo ištraukimui analizė, išnagrinėtas kilpinio siūlo strigimo ir slydimo reiškinys, aktualus dėvint.

Ginamieji disertacijos teiginiai:

1. Ramės / medvilninių kilpinių audinių ataudų tankumas turi didesnę įtaką audinių sandaros ir geometriniams rodikliams, taip pat fizikinėms ir mechaninėms savybėms nei kilpos aukštis.
2. Ramės / medvilninių, lininių / medvilninių, kanapinių / medvilninių ir lininių kilpinių audinių vandens išgarinimui turi įtakos audinio gebėjimas absorbuoti skystį; vandens garų absorbcijai turi įtakos paviršinis tankis. O kilpinių audinių mechaninėms savybėms didelę įtaką daro audinio sandara ir geometrinės ypatybės: paviršinis tankis, ataudų tankumas ir pluoštinė sudėtis.
3. Lininių / medvilninių, kanapinių / medvilninių ir lininių kilpinių audinių apdaila pagerina jų fizikines bei mechanines savybes, tačiau pernelyg ilga apdailos operacijų trukmė, ypač kai šių operacijų skaičius yra labai didelis, gali turėti neigiamos įtakos audinių kokybei.
4. Siūlo strigimas ir slydimas traukiant iš kilpinių audinių pūko kilpą priklauso ne tik nuo kilpinio audinio sandaros – didelę įtaką turi ir verpalų nevienodumas.
5. Ramės / medvilninių, lininių / medvilninių, kanapinių / medvilninių ir lininių kilpinių audinių tyrimai leidžia prognozuoti audinių kokybės ir ekonominiu požiūriu svarbius audinių žaliavos sąnaudų rodiklius, o gauti rezultatai leidžia projektuoti naujus natūralių pluoštų aukštos kokybės kilpinius audinius, kurie pasižymėtų norimomis fizikinėmis, mechaninėmis savybėmis, taip pat ekonominėmis pluoštų sąnaudomis.

Darbo aprobacija. Disertacijos tema yra pateikta 17 – mokslinių publikacijų, iš jų 4 straipsniai *Thomson Reuters Web of Knowledge* bazės leidiniuose, turinčiuose citavimo indeksą (IF / AIF > 0,2). Tyrimų rezultatai pristatyti 12 konferencijose – 7 tarptautinėse ir 5 respublikinėse. Iš viso konferencijose pristatyta 14 pranešimų.

Darbo sandara ir apimtis. Disertaciją sudaro įvadas, 3 skyriai, išvados, literatūros sąrašas (214 įrašai) ir mokslinių darbų sąrašas. Disertacijos medžiaga pateikta 123 puslapiuose, kuriuose yra 5 lentelės, 48 pav. ir 17 formulės.

IŠVADOS

1. Ramės / medvilninio kilpinio audinio paviršiniam tankiui didelę įtaką turi audinio sandara: didinant kilpos aukštį nuo 4,5 iki 10,5 mm, audinių paviršinis tankis padidėjo nuo 274,8 iki 441,9 g/m^2, o, didinant ataudų tankumą nuo 8 iki 16 cm^{-1}, paviršinis tankis padidėjo nuo 230,4 iki 574,2 g/m^2. Nustatyta, kad egzistuoja stiprus ryšys tarp audinio sandaros rodiklio ir paviršinio tankio: aprašant priklausomybes tiesinėmis lygtimis, apibrėžties koeficientas R^2 = 0,9393 – 0,9755.
2. Nustatyta, kad kilpinių audinių su ramės kilpiniais metmenimis kilpiniai metmenys sudaro nuo 54,8 iki 74,4 proc. Be to, didėjant kilpos aukščiui ir ataudų tankumui, didėja ramės kilpinių metmenų procentinis kiekis. Audinių su lininiais ir kanapiniais kilpiniais metmenimis kilpiniai metmenys sudaro nuo 60,1 iki 76,9 proc. Nustatyta, kad, esant didesniam kilpos aukščiui ir mažesniam apdailos veiksmų skaičiui, didėja lininių ir kanapinių kilpinių metmenų siūlų sistemos procentinė sudėtis.
3. Tiriant ramės / medvilninius kilpinius audinius nustatyta, kad ataudų tankumas turi didesnę įtaką vandens garų absorbcijai nei kilpos aukštis. Rezultatai rodo, kad vandens garų absorbcija didėja nuo 21,4 iki 61,5 g/m^2, didinant ataudų tankumą, o, didinant kilpos aukštį, vandens garų absorbcija padidėjo tik nuo 24,5 iki 29,1 g/m^2. Taip pat nustatyta, kad egzistuoja stiprus ryšys tarp audinio sandaros ir vandens garų absorbcijos: aprašant priklausomybes logaritminėmis lygtimis, apibrėžties koeficientas yra R^2 = 0,9699.
4. Nagrinėjant lininių / medvilninių, kanapinių / medvilninių ir lininių kilpinių audinių vandens garų absorbciją nustatyta, kad kuo daugiau kilpiniai audiniai patiria vandens, šilumos, mechaninių ir cheminių poveikių, tuo daugiau absorbuoja vandens garų. Itin ryškus vandens garų absorbcijos skirtumas nustatytas tiriant žalius (be apdailos) ir vilgytus kilpinius audinius. Taip pat didesne vandens garų absorbcija pasižymi audiniai, kurių kilpos aukštis yra maksimalus – 12 mm.
5. Nustatyta, kad, ilgėjant skalbimo vandenyje trukmei (nuo 10 iki 120 min.), taip pat ir šlapią apdailą patyrusių audinių tumbleravimo trukmei (nuo 30 iki 150 min.), kilpiniai audiniai geba daugiau absorbuoti vandens garų, tačiau pernelyg ilgas audinių skalbimas vandenyje ar tumbleravimas mažina vandens garų absorbcijos gebą. Tai paaiškinama tuo, kad palaipsniui trupa pluoštai ir prarandami verpalai.
6. Vandens išgarinimo trukmei reikšmingą įtaką turi kilpinio audinio sandara. Ramės / medvilninių kilpinių audinių vandens išgarinimo trukmė tęsėsi iki 90–140 min. esant skirtingam ataudų tankumui (8–16 cm^{-1}). O lininiai / medvilniniai kilpiniai audiniai vandenį išgarina per 90–180 min., bet greičiausiai šis procesas vyko audiniuose, kurių kilpos aukštis yra 9

mm. Nustatyta, kad egzistuoja labai stiprus ryšys tarp vandens išgarinimo trukmės ir vandens likučio koeficiento: aprašant priklausomybes empirinėmis lygtimis, kurių apibrėžties koeficientai siekia iki 0,9999.

7. Nustatyta, kad kilpiniai audiniai vandenį išgarina nevienodu intensyvumu, t. y. kilpiniuose audiniuose, kurių vandens išgarinimo laikas buvo trumpesnis – apie 80–120 min., vandens išgarinimo procesas intensyviausiai vyko nuo pat pirmųjų minučių. O kilpiniai audiniai, kurių vandens išgarinimo laikas tęsėsi ilgiau – apie 120–180 min., intensyviausiai vandenį garindavo tik nuo 20 iki 60 minučių.
8. Nustatyta, kad skalbimas vandeniu skirtingais laiko intervalais kilpinių audinių vandens išgarinimo trukmei neturi įtakos arba ji labai menka, tačiau po šlapios apdailos vykstantis tumbleravimas skirtingais laiko intervalais turi įtakos vandens išgarinimo trukmei: greičiausiai vandenį išgarindavo kilpiniai audiniai, kurie buvo tumbleruoti 30, 60 arba 150 minučių.
9. Nustatyta, kad ramės / medvilninių kilpinių audinių pūko kilpos atsparumas ištraukimui yra nuo 99,0 iki 1728,3 mN esant 5–25 mm ištįsai. Gauta, kad pūko kilpos atsparumo ištraukimui jėga yra didesnė esant mažesnėms audinio kilpoms ir didesniam ataudų tankumui.
10. Ištyrus lininius / medvilninius kilpinius audinius, kurie buvo skalbti su plovikliu / minkštikliu / tumbleruoti ir kurių kilpiniai metmenys – nebalinti lininiai verpalai, nustatyta, kad didžiausia kilpos pūko ištraukimo jėga reikalinga audiniams, kurie po šlapios apdailos buvo tumbleruoti ilgiau, t. y. 90, 120 arba 150 minučių. O tiriant kilpinius audinius su balintais lininiais kilpiniais metmenimis gauta, kad pūko kilpos ištraukimo jėga yra didesnė tais atvejais, kai audinys buvo tumbleruotas trumpiau (30–90 min.).
11. Tiriant lininių / medvilninių, kanapinių / medvilninių ir lininių kilpinių audinių kilpos atsparumą ištraukimui, verpalas dažnai stringa, o tiriant ramės / medvilninius audinius nustatyta, kad ramės verpalas slysta ir beveik visai nestringa. Šie rezultatai patvirtina gana didelius kilpos atsparumo ištraukimui nevienodumo rodiklius. Nustatytas daugumos ramės / medvilninių kilpinių audinių stiprus ryšys tarp ištįsos ir tempimo jėgos (R^2 = 0,9807–0,9967).
12. Ramės / medvilninių kilpinių audinių atsparumas dilinimui yra didžiausias iki suyrant (50 000 ciklų) iš visų kilpinių audinių, o ramės / medvilninių audinių masės nuostoliai: nuo 0,97 iki 32,24 proc., priklausomai nuo dilinimo ciklo skaičiaus (5000–50 000 sūkių). Didžiausiu atsparumu dilinimui pasižymėjo kilpiniai audiniai, kurių kilpos aukštis yra 10,5 mm, o ataudų tankumas – didžiausias (16 cm^{-1}).

13. Analizuojant ramės / medvilninių kilpinių audinių laidumo orui priklausomybę nuo dilinimo ciklų skaičiaus nustatyta didelė audinio sandaros įtaka. Rasta, kad laidumas orui sumažėjo 8,5 kartų keičiant ataudų tankumą visame eksperimento intervale: nuo 8–16 cm^{-1} ir 1,4 kartus, keičiant kilpos aukštį visame eksperimento intervale: nuo 4,5–10,5 mm. Didėjant dilinimo ciklų skaičiui, iš pradžių laidumas orui sumažėja, o po tam tikro ciklų skaičiaus ima didėti.
14. Prognozavimo tikslumo analizė parodė, kad ramės / medvilninių kilpinių audinių apskaičiuotosios paviršinio tankio, kilpinių metmenų siūlų procentinės dalies ir pūko kilpos atsparumo ištraukimui reikšmės yra artimiausios eksperimentinėms ir neviršija 7,1 proc., išskyrus pavienius atvejus, kai šis rodiklis buvo didesnis. Taip pat nustatytas reikšmingas skirtumas tarp paviršinio tankio ir vandens garų abstrakcijos, vandens išgarinimo, laidumo orui bei tarp masės nuostolio ir paviršinio tankio rodiklių. Dažnai koreliacijos koeficientai rodo, kad egzistuoja koreliacinė priklausomybė.

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