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Water Vapour Absorption of Terry Fabrics with Linen and Hemp Pile Loop

Abstract
A textile material's ability to pass water vapour greatly affects the comfort of the wearer. Terry fabrics are characterised by their high absorption ability acquired by an increased absorbing surface of the pile structure. In this study we set out to elucidate the effects of textile structure and finishing technology on the vapour absorption of material. This paper presents an experimental investigation of the water vapour absorption of linen/cotton and hemp/cotton terry woven fabrics with respect to pile height and finishing procedures. The terry textiles used in the experimental work were made with a pile height of 6, 9, and 12 mm. The research demonstrated that the character of the water vapour absorption of terry woven fabrics depends on the fabric structure and finishing applied. It was found that various finishing operations such as washing in water, washing with detergent and softening as well as washing with detergent, softening, and tumbling processes had an influence on the water vapour absorption of terry fabrics. The uniformity of dispersions was proved for the variants investigated. High informativity of the experiment was found by analysing the data of water vapour absorption of tumbled linen/cotton terry fabric with a 12 mm pile height. The polynomial regression showed a match with experimental data with a regression of R^2 *= 0.7687. From this empiric model, the effect of the tumbling period can be understood.*

Key words: *water vapour absorption, finishing, pile height, terry woven fabric.*

Introduction

The creation of innovative textiles provides a wide spectra of new materials with different physical qualities, therefore the theoretical analysis of the influence of parameters on comfort conditions are of considerable value. Usually comfort is accepted as one of the very important factors for terry textiles used for sauna clothing, headgear, slippers, towels, etc. The material ability to pass water vapour or perspiration greatly affects the comfort feeling of the wearer. Besides this in many technological operations such as dyeing, finishing and end use characteristics, the water and water vapour absorbency of textiles is the key factor. The absorption feature is closely related to the textile composition. Natural fibres like flax, hemp, cotton, and their blends demonstrate high absorption ability. Some of the new filament constructions with improved absorption properties have special cross sections with micro channels or micro holes on their surface.

The aim of study [1] was to design and develop a novel filament that can absorb water vapour quickly but does not feel wet to the touch. Polypropylene (PP) was used as the outer surface and super absorbent polymer (SAP) as the filler placed into the cavity of the filament to absorb the excessive amount of water vapour. It is possible to change the absorption percentage of the filament by changing the amount and quality of SAP. A filament without SAP absorbs 0% water. The results indicated that vapour absorption of 8% was reached while providing a totally dry sense on the filament outer surface. The samples dried within 20 - 30 min after the first water vapour absorption test. It was pointed out that the vapour absorption capacity could be adjusted by changing filaments within the filament bundle i.e. the covering density of the filament bundle. It was seen that the effect of these parameters are statistically significant. The water absorbency [2] of jute nonwoven fabric was investigated using central composite rotatable experimental design. The extrinsic sorptive capacity of fabric is highly correlated with the bulk density, but there is a poor relationship between the extrinsic sorptive capacity and extrinsic rate of sorption as well as between the bulk density and extrinsic rate of sorption. Water absorbency tests were carried out on modal woven towels [3]. It was determined that the wicking height of terry fabrics increased by decreasing their weft density. The aim of the research [4] was to simulate water vapour transfer through knitted fabrics under different environmental conditions. The results indicated the influence of environmental conditions like temperature and relative humidity on the transfer of water vapour and the influence of the raw material on the rate of water vapour transfer under each pair of environmental conditions defined. Research [5] deals with the water vapour permeability of various types of knitted fabrics constructed of PP/cotton, PA/cotton, PES/cotton and other compositions. It was also found that there was a lack of surface porosity influence on water vapour permeability. In conditions of free convection, water vapour diffuses in the surface between fibres and clearances, and the general high capacity porosity of knitted fabric is conducive to this process. Moreover the sizes of water vapour molecules are disproportionately smaller than those of pores in the knitted fabric structure, which explains the distinct absence of any correlation between the water vapour permeability and thickness of the knitted fabrics investigated. Besides this the authors found that for plain knitted fabrics with a thickness in the range 1.11 - 1.13 mm, the highest water vapour permeability (903 g/m^2 for 24 h) was displayed by connecting cotton with PA.

The wetting phenomenon and liquid retention capacity of terry fabrics with respect to fabric characteristics and finishing was investigated in [6, 7]. It was determined that experimental results could be described by polynomial equations. It was found that the liquid retention capacity of pure linen and linen/cotton terry fabrics depends on the kind and intensity of the impact/finishing applied to the fabric [7]. However, there is no correlation [8] between the water vapour permeability and air permeability of double-layered knitted fabrics. Both physical and mathematical models of the coupled heat and water vapour transfer within multilayer structures were discussed in [9]. Mate-

Table 1. Characteristics of terry fabrics tested.

Code of sample	Linear density of yarns, tex			Yarn density, dm^{-1}		Pile height
	Warp		Weft			
	Pile	Ground	Ground	Pile and ground warp	Weft	
LCI	50, bleached linen yarn	25 x 2, plied cotton yarn	50, cotton yarn	250	200	6
LCII						9
LCIII						12
HCII	72 hemp yarn					9

*Table 2. Modes and conditions of finishing procedures; * The mode was applied to the LCI, LCIII, HCII variants.*

Mode	Finishing procedure and conditions
Without finishing	Grey (loom state) fabric was not affected by any impact or finishing procedure
Washing in water	Grey fabric was washed in water for 10, 30 or 60 min, then centrifuged and dried in air [14]
Washing with detergent, softening	Grey fabric was washed at 60 °C for 60 min using detergent, then softened at 40 °C for 60 min, centrifuged, and finally dried in air
Washing with detergent, softening, tumbling*	Grey fabric was washed at 60 °C for 60 min using detergent, then softened at 40 °C for 60 min, centrifuged and then tumble-dried for 30, 60, 90, 120 or 150 min

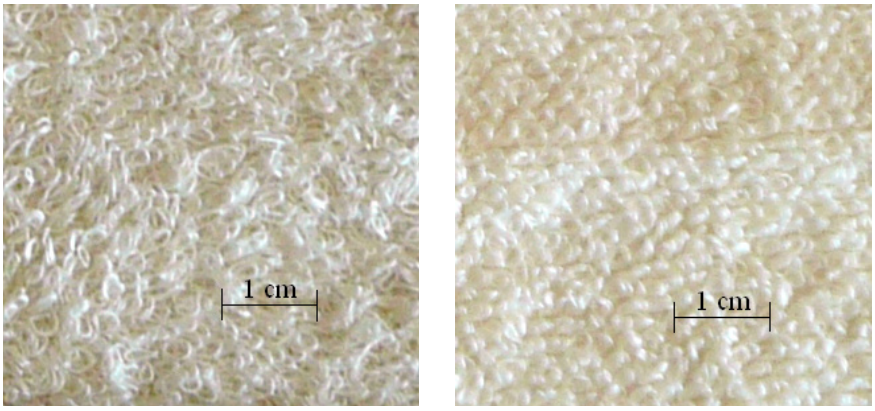

Figure 1. *Terry fabrics: a – LCII washed in water for 30 min, b – LCI tumbled.*

rial parameters should be determined for different numbers of layers, compositions of the raw material and thicknesses of the laminate with a membrane. The heat transfer resistance and resistance of the water vapour transfer were determined, which helped to design material for clothing that fulfils the user's thermal comfort. Moisture comfort [10] is important for protective clothing as well. It was found that the water vapour transmission rate decreased with the number of layers, and also when the thickness of the assembly increased. At the same time, each layer was relatively important for moisture transmission. The results of [11] strongly suggested that the hygroscopicity of connecting yarn which bridges the two layers of knitted double-layer fabric had a significant influence on the liquid water transfer and distribution ability of the fabric. Different mechanisms of liquid water absorption and the transfer properties of cotton and polyester fibre may lead to differences. The research in [12] presents a structural computation model developed for investigation of the heat and air-water vapour mass exchange between multilayer textile packages and the human body. The initial water-vapour resistance was measured and the water-vapour permeability of breathable-coated textiles investigated in [13].

Querying the literature proved that there is no research published concerning water vapour absorption within complex structure woven textiles like terry woven fabrics. Thus, to understand the significance of such a biophysical feature of textile like the water vapour effect on comfort, we conducted research with terry woven fabrics. The main goal of this study was to investigate the water vapour absorption of terry woven fabrics in relation to the raw material, pile height, and finishing operations, as well as to develop an empiric model suitable for evaluating and designing fabrics with the water vapour absorption ability required.

Object and methods of investigation

Various types of terry fabrics currently used as home textiles were manufactured as samples (see ***Table 1***) including linen/cotton and hemp/cotton. The samples were woven by joint-stock company "A Grupė" (in Jonava, Lithuania). The modes and conditions of finishing procedures are presented in ***Table 2***. Examples of some of the terry fabrics investigated are shown in ***Figure 1***.

The high absorption ability of flax and hemp fibre and the interest in such popular home textiles were the reasons for the choice of pile material. The detergent NOG CHT R. Beitlich GmbH (Germany) was used for washing and silicone conditioner Tubingal SMF CHT Beitlich GmbH (Germany) was used for softening. Washing with detergent and softening was performed in a rope bath. Tumble drying for different periods was done in an Airpress 15 tumbler (Germany).

The water vapour absorption was measured using EN 13515:2001 [15]. Samples of the fabrics with an area of 9.62 cm^2 were kept over a container which held distilled water with a temperature according to EN 12222. The duration of the test was 8.0 ± 0.1 hour. All the samples used for the tests were conditioned and water vapour absorption tests were carried out in a standard atmosphere: temperature 20 ± 2 °C and relative humidity 65 ± 2%. The water vapour absorption of the terry fabrics was determined by changes in the mass before and after the test, according to the following ***Equation 1*** [15]:

$$\text{WVA} = \frac{M_1 - M_0}{A}, \qquad (1)$$

where: WVA – water vapour absorption, M_1 – weight of sample after time of absorption, M_0 – initial weight of sample, A – area of sample.

The coefficient of variation (v) of WVA was calculated according to the equation:

$$v = \frac{S}{\bar{x}} 100, \qquad (2)$$

where: S – standard deviation, $\bar{x}$ – mean.

The relative error δ of WVA *was calculated according to the equation:*

$$\delta = \frac{\Delta}{\bar{x}} 100 \text{, in \%} \qquad (3)$$

where: Δ – absolute error, $\bar{x}$ – mean.

5 tests per fabric variant were performed.

Results and discussion

In this work the influence of the raw material, pile height, and finishing on the moisture transport property of linen/cotton and hemp/cotton terry fabrics was investigated. The water vapour absorption was determined. The wettability of linen and hemp fibre is good among all the long vegetable fibres. The terry woven structure is expected to improve the water vapour penetration capacity of the material. It is also assumed that the characteristics of the fabric and finishing applied may play a significant role in the water vapour absorption of such home textiles.

Figure 2 and ***Table 3*** show the WVA and its statistical indices in the analysis of grey and washed in water terry fabrics as well as those washed with detergent and softened. ***Table 4*** shows statistical results of the water vapour absorption of terry fabrics washed with detergent, softened and tumbled . The uniformity of dispersions of WVA was proved for variants LCI, LCIII, & HCII, and the informativity of the experiment was proved for variants LCI and LCIII (α = 0.95). These results are presented in ***Table 5***.Mathematical analysis of the WVA of terry fabrics washed with detergent, softened and then tumbled (for 30, 60, 90, 120, and 150 min) was performed with the aim of determining the regressions and interpret them later on.

The absorbency and permeability properties of linen fibre are good [16, 17]. Compared to cotton, they exhibit superior swellability under wet conditions [17]. Besides this, it was found that fabric woven in an oxford weave with a twist level varying from 16 to 18 dm^{-1} exhibited superior performance in terms of waterproofness, water vapour permeability and water retaining capability. In our experiment the porous bleached linen pile warps were expected to improve water vapour absorption. It was found that for the grey linen/cotton terry fabrics (see ***Figure 2***), with an increase in pile height, the water vapour absorption increased from 34.4 to 52.0 g/m^2, i.e. the WVA of the LCIII variant was even 51.2% and 30.0% higher compared with the LCI and LCII variants, respectively. The increase in pile height means a rise in the volume through which water vapour penetrates. The grey fabric was not affected by any liquid impact or finishing, as a result the loops are regular and range perpendicularly to the fabric base. For a grey terry fabric structure, with an increase in pile height, the WVA increased due to the yarn length in the higher loop. Moreover the orientation of loops is in a vertical direction, which facilitated the easy penetration of water vapour.

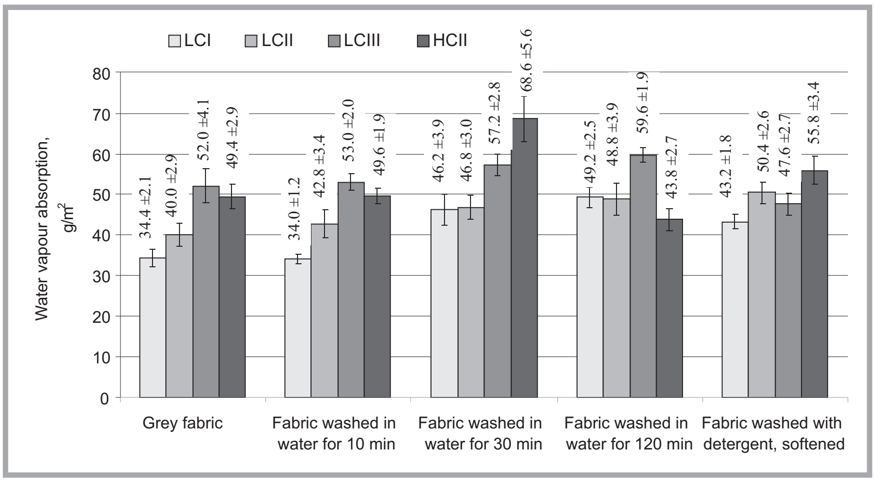

Figure 2. *Water vapour absorption of grey and washed terry fabrics.*

Table 3. *Statistical indices of water vapour absorption of grey and washed terry fabrics; v – coefficient of variation of WVA, δ – relative error of WVA.*

Fabric variant	Statistical indices of WVA, %	Grey fabric	Washed fabric			
			in water for, min			with detergent; softened
			10	30	120	
LCI	*v* δ	4.9 6.1	2.9 3.5	6.7 8.4	4.1 5.1	3.5 4.2
LCII	*v* δ	5.8 7.3	6.5 7.9	5.1 6.4	6.4 8.0	4.2 5.2
LCIII	*v* δ	6.3 7.9	3.0 3.8	3.5 4.9	2.5 3.2	4.6 5.7
HCII	*v* δ	4.7 5.9	3.0 3.8	6.6 8.2	5.0 6.2	5.0 6.1

Table 4. *Statistical results of water vapour absorption of terry fabrics washed with detergent, softened and tumbled; v – coefficient of variation of WVA, δ – relative error of WVA.*

Fabric variant	Statistical indices of WVA, %	Fabric washed with detergent, softened and tumbled for, min				
		30	60	90	120	150
LCI	*v* *δ*	4.2 5.1	3.4 4.4	3.6 4.3	5.5 6.9	2.1 2.6
LCIII	*v* *δ*	4.1 4.9	4.4 5.6	5.3 6.6	3.1 3.9	2.6 3.3
HCII	*v* *δ*	5.2 6.6	4.4 5.6	5.0 6.2	2.5 3.1	1.3 1.7

Linen/cotton and hemp/cotton terry fabrics can be used as grey because of their inherent flexural rigidity and inelastic nature, which offer a greater massage property. In other cases the use of linen and hemp, taking into consideration their toughness, could be employed after finishing procedures. The washing process is the first industrial finishing operation. We investigated two cases of washed fabrics: washed only in water without any chemical agents and washed using a detergent, then softened with a conditioner and tumble-dried. It was found that the washing procedure determined the loss of loop regularity even if there were not any washing agents, because water, heat and mechanical impacts during washing affected and transformed the structure of the textile. It was obtained that washing in water for different time periods, such as 10, 30, and 120 min, increased the WVA of linen/cotton terry fabrics from 34.0 to 49.2 g/m^2 for the LCI variant, from 42.8 to 48.8 g/m^2 for the LCII variant and from 53.0 to 59.6 g/m^2 for the LCIII variant, but the statistically significant increase in WVA for all washing periods was determined only for linen/cotton terry fabric with a 6 mm pile height for a 10 - 30 min period. Meanwhile the differences in WVA comparing grey fab-

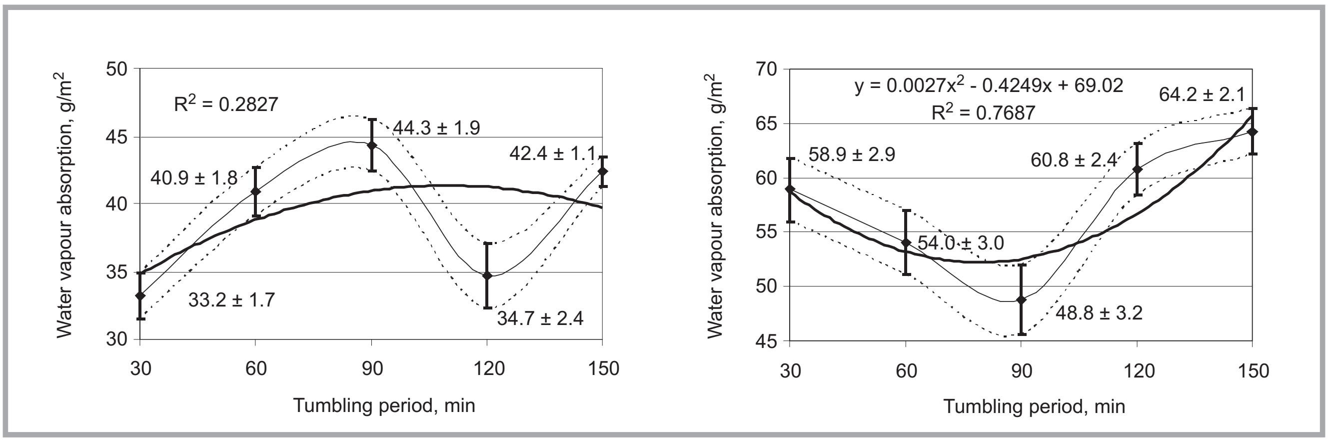

Figure 3. *Water vapour absorption of: a) LCI and b) LCIII fabric in relation to the tumbling period.*

rics and washed fabrics in water for 30 or 120 min were significant for nearly all variants investigated. It was found that the WVA of linen/cotton fabrics washed in water (for 30 min) increased by 10.0 – 34.3% compared with grey fabrics, while for hemp/cotton fabrics it was by even 38.9%.

When investigating all the linen/cotton variants washed in water, the highest water vapour absorption (59.6 ± 1.9 g/m^2) was found for the LCIII sample washed in water for 120 min, while for the hemp/cotton terry fabrics the highest water vapour absorption (68.6 ± 5.6 g/m^2) was determined for the sample washed in water for 30 min. The WVA of linen/cotton fabric washed in water for 30 min increased by 7.9 - 35.9% compared with the fabric washed for 10 min. The changes in water vapour absorption of these fabrics washed for 120 min were much more significant when compared with the samples washed for 10 min, i.e. the differences obtained were 12.5% (for LCIII variant) and 44.7% (for LCI variant). The washing in water of hemp/cotton fabrics changed the WVA from 43.8 to 68.6 g/m^2, i.e. by 56.6%, this difference being the largest among all fabrics investigated that were affected by such impacts. Thus these results confirmed the clearly noticeable effect of fabric structure and impacts applied like water/heat/mechanical on the water vapour absorption of the terry fabrics investigated.

For the grey terry fabrics the coefficient of variation of WVA varied from 4.7 to 6.3% and from 2.5 to 6.7% for those washed in water. Furthermore the relative error of the WVA of grey terry fabrics and those washed in water varied from 3.2 to 8.4%.

Washing with detergent and softening increased the WVA of the LCI, LCII and HCII variants by 13.0 – 26.0% compared with the grey ones, which could be explained by the fact that water vapour diffusion runs more smoothly in the increased surfaces between fibres and clearances. The general higher porosity of washed and softened terry fabric is conducive to this process.

After the analysis of the experiments of terry fabrics washed with detergent, softened and then tumbled , factorial designs were made. Results of the uniformity of dispersions using the G criterion (Cochran) and informativity using F criterion (Fisher) are presented in ***Table 5***. The experimental results of water vapour absorption were mathematically evaluated at a 95% confidence level and the uniformity of dispersions proved for all variants, while the informativity of the experiment was proved only for factorial designs of linen/cotton terry fabrics of variants LCI and LCIII. Moreover high informativity was determined by analysing LCI terry fabric: the F criterion calculated was 11.14 (F_T = 6.26).

The results expressed as a relationship between the water vapour absorption and tumbling period are presented in ***Figures 3*** and ***4***. The complex character of the relations is clearly visible. In ***Figure 3*** we observe a function (even concerning the dispersion of the results) of a distinct maximum and a minimum, whereas in ***Figure 4*** a dominant minimum characterises the curve. An attempt to express the relationships by polynomial functions leads to the conclusion that for the LCI variant presented in ***Figure 3*** it is impossible (R^2 = 0.2827), whereas for the LCIII variant (***Figure 4***) it is problematic as R^2 = 0.7687. The WVA of the HCII fabric in relation to the tumbling period is presented in ***Figure 5***, because the informativity of this experiment was not proved: $F_C = 0.29 < F_T = 4.05$. The large number of active finishing procedures like washing with detergent, softening, and tumbling affected the terry fabrics significantly. The tumbling operation changed the structure of the fabric by providing a fluffy handle surface, fuller volume and softness. Hence the structure of terry fabric is modified much more: one loop touches the other , the loops cover or interlace with each other, and sometimes a spiral loop geometry could be found. In addition the yarn in the loop becomes bulky and more hairy. Such intensive finishing apparently led to the ability to absorb water vapour into the depth of the fabric.

Table 5. *Results of the uniformity of dispersions of WVA and informativity of the experiment.*

Fabric variant	G criterion		Uniformity of dispersions	F criterion		Informativity of experiment
	Calculated G_C	Tabular G_T		Calculated F_C	Tabular F_T	
LCI	0.34	0.544	Proved (α = 0.95)	11.14	6.26	Proved (α = 0.95)
LCIII	0.27			7.31	6.26	Proved (α = 0.95)
HCII	0.35			0.29	4.05	Failed (α = 0.90)

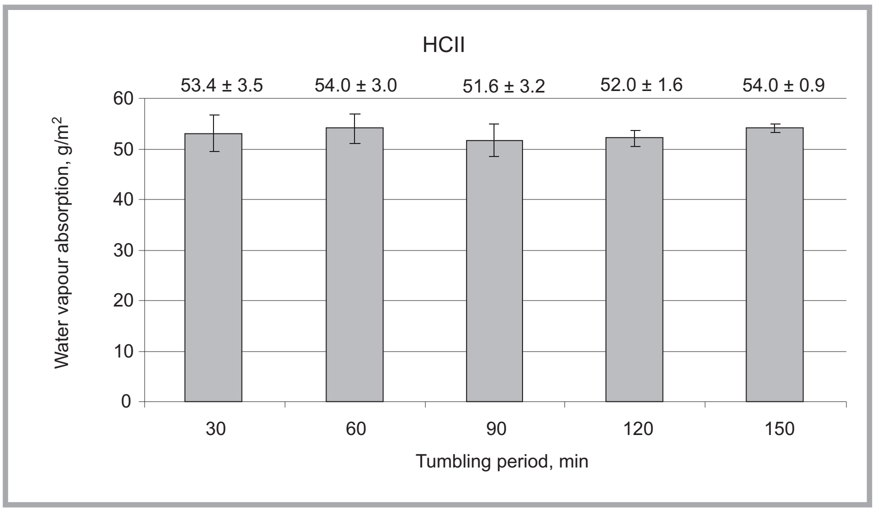

Figure 5. *Water vapour absorption of HCII fabric in relation to the tumbling period.*

It could be seen that the WVA of the fabrics in relation to the tumbling period was 33.2 – 44.3 g/m^2, 48.8 – 64.2 g/m^2 and 51.6 – 54.0 g/m^2 for variants LCI, LCIII and HCII, respectively.

The lowest value of WVA (33.2 ± 1.7 g/m^2) was determined for the LCI variant after 30 min of tumbling, while the highest value (64.2 ± 2.1 g/m^2) was determined for the LCIII variant after 150 min of tumbling. It was determined that there was a general tendency of an increase in the water vapour absorption with a rise in the tumbling period for the LCI variant. From the data presented in ***Figure 3*** it can be seen that tumbling for 90 min increased the WVA of the fabric by 33.4% compared with the result received for the fabric tumbled for 30 min. A decrease in WVA of 17.1% for the 30-90 min tumbling period and an increase of 31.6% for the 90 - 150 min tumbling period was determined for the LCIII variant (see ***Figure 4***). The data (see ***Figure 5***) show that the changes in WVA of the hemp/cotton fabric in relation to the tumbling period were not statistically significant for all contiguous tumbling periods. The role of pile height is evident when analysing the LCI and LCIII variants after the tumbling procedure: the water vapour absorption of terry fabrics with a 12 mm pile height was 10.2 – 77.4% higher compared with terry fabric with a 6 mm pile height. During the tumbling procedure the terry fabrics lose some flax fibres, and it can be assumed that this process runs more intensively for fabrics with a low pile height (6 mm), while high loops (12 mm) are an obstruction which brings about the loss of large amounts of such fibres from the fabric during a short-term tumbling period. But with an increase in the tumbling time, the loss of fibres also occurred in terry fabrics with a high loop pile. The influence of fabric shrinkage can also be found: with an increase in the tumbling period the shrinkage of the fabric increases and the penetration of water vapour between the loops and into the depth of the fabric becomes more difficult. Besides this, the increase in the WVA of tumbled terry fabrics compared with grey ones was determined by analysing the majority of tumbling periods. However, statistically significant increases were not determined for all cases investigated. In addition, statistical analysis of the tumbled terry fabrics showed that the coefficient of variation of WVA did not exceeded 5.5%; the relative error of WVA varied within the range of 1.7 – 6.9%.

Conclusion

- It is possible to change the water vapour absorption of linen/cotton and hemp/cotton terry woven fabrics by changing the fabric structure, the finishing procedures and their intensity.
- The pile height of terry woven fabrics had an effect on their water vapour absorption. The lowest water vapour absorption (33.2 – 49.2 g/m^2) was obtained for linen/cotton fabric with a 6 mm pile height, while the highest value of water vapour absorption was found for fabrics with a 12 mm pile height (47.6 – 64.2 g/m^2).
- The water vapour absorption of grey linen/cotton terry fabric with a 9 and 12 mm pile height was 16.3 and 51.2% higher compared with samples with a 6 mm pile height, respectively. Such results are determined by increasing the volume through which water vapour penetrates.
- The changes in water vapour absorption of terry fabrics were determined after their washing in water. It was noted that the duration of the impact is significant here: the water vapour absorption increased by 12.5 – 44.7% for linen/cotton fabrics washed in water for 10 min as compared with variants washed in water for 120 min. In many cases washing with detergent and softening increased the water vapour absorption of terry fabrics as compared with grey ones because after such finishing the structure of the terry fabric was modified: the yarn in the loop became softer and more cushiony.
- Washing with detergent, softening and tumbling caused changes in the water vapour absorption of the terry fabrics. Fabric shrinkage and the loss of some flax fibres from the fabric during intensive finishing procedures play a role here. The water vapour absorption of linen/cotton terry fabrics with respect to the tumbling period are expressed by complex relationships. Only for the fabric with a 12 mm pile height could the dependency be described by a polynomial equation, but with a regression of $R^2 = 0.7687$.
- The coefficient of variation of water vapour absorption of the terry fabrics investigated did not exceeded 6.7%, whereas the relative error varied within the range of 1.7 – 8.4%.

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