Katarzyna Ławińska*, Wioleta Serweta, Dorota Gendaszewska

Applications of Bamboo Textiles in Individualised Children's Footwear

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Institute of Leather Industry,
Zgierska 73, 91–462 Łódź, Poland
* e-mail : k.lawinska@ips.lodz.pl

Abstract
As part of the work, preliminary tests were made of textile materials with bamboo fibres for elements of children's footwear. The need to expand the range of materials which can be used in children's footwear is dictated by the specific anatomic structure of the child's foot during the first years of life. The research was focused on the area related to the mechanical and hygienic properties of the bamboo materials used. In order to make a qualitative analysis of the possibility of using bamboo materials in footwear elements, commonly used material like cotton was examined. The studies performed clearly indicate that the application of bamboo textiles as footwear materials is possible and show that they can be better than cotton materials as control samples. It is important to creating appropriate conditions conducive to the proper development of the foot.

Key words: *bamboo fibres, children's footwear, foot prevention, healthy footwear.*

Introduction

According to the latest economic studies available, the children's clothing and footwear segment is the largest and most dynamically developing area on the market for children's products. Along with the growing awareness of society, the aspect of safety of use may constitute one of the important criteria for the selection of a specific assortment [1]. With regard to physiology, a child's foot is not a miniaturised mirror reflection of an adult person's foot [2, 3]. Its evolution along with the growth of the whole organism is aimed at the development of a biomechanical support mechanism which makes it possible to implement the locomotion process [4]. The most important period in which the foot is shaped falls into the pre-school and early school age, until reaching the form of an adult foot between 12 and 14 years of age. An important aspect is also the fact of increased intensification of sweat production along with increased mobility following the accelerated development of the muscular system, especially in children between the second and third year of life, as well as between the seventh and twelfth year [4]. For this reason, children's footwear requires a certain specification of materials, as reflected in the literature [5-8]. What is more, it is postulated that it is necessary to include, at the design stage of the footwear, a set of parameters that can support the natural development and formation of soft tissues within the foot. In order to meet these requirements, it is assumed that the temperature range inside children's footwear should not exceed 21-33 °C, with a simultaneous CO_2 content in the air filling the volume of the footwear not greater than 0.8 per mille. During normal physical activity, the sweat rate stays at 3-6 grams per hour, which directly depends on the level of intensity of physical exertion and the conditions of the external environment, and in extreme cases it can increase up to 20 g per hour [5].

Correctly selected footwear should primarily ensure the possibility of bending the foot in possible directions, stimulating comprehensive muscle activation [8]. On the other hand, an equally important aspect is the production of an appropriate microclimate around the foot to ensure appropriate temperature and humidity conditions during the use of footwear. The microclimate of footwear is first of all affected by the hygienic property of the materials used for its production. Materials that adhere directly to the foot should have good hygroscopic properties, which include:

- sorption and desorption of water vapour,
- water vapour permeability,
- wetting with water,
- absorbency,
- water penetration.

The first three parameters determine the proper functioning of sweat removal from the skin surface mechanism. This mechanism can be classified according to several constituent processes: sorption of water vapour and then its desorption to the environment, diffusion of perspiration through the open pores of the material of the upper, the drying of materials, and then direct exchange of air with the environment as a result of walking. According to Foiasi [5], the material (or material package) intended for the upper should have a water vapor permeability of 1.25-2.5 mg/cm^2 per hour. In the case of the absorption of water vapour, comfortable conditions are ensured under conditions of less than 5 mg/cm^2. Parameters such as wettability, absorbency and water penetration determine the hydrophobicity or waterproofness of footwear materials. It is therefore desirable that the materials intended for the lining and insole have the ability to wet and have good water absorption.

In the case where the construction of the footwear does not ensure a proper microclimate, there is disturbance of sweat secretion as well as overheating or chilling of the foot inside the footwear, with the likelihood of the development of pathogenic microorganisms and fungi increasing. For this reason, the most optimal solution from the user's point of view is the use of material systems on the uppers and liners which have very good mechanical properties together with good hygienic properties.

The use of natural bamboo fabrics with high hygienic, antibacterial and bacteriostatic properties confirmed in literature reports is a solution close to optimal. Sekerden [9] in his work made a comparison of bamboo and cotton woven fabrics and their mixtures in terms of the air permeability of these fabrics. It was proven

Table 1. Characteristics of the materials with bamboo fibres tested.

Sample	Material type	Mass per square meter, g/m²	Thick-ness, mm	Yarn composition, %	Specification (from manufacturer's data sheet)
W1	Woven	170	0.40	100% bamboo	plain canvas
W2		500	1.74		frotte, in loop cover
W3		300	0.61	95% bamboo, 5% polyester	jacquard
W4		170	0.35	50% bamboo, 50% flax	plain canvas
W5		230	0.58	100% cotton	keper, raw fabrics
W6		145	0.37		diagonal canvas
K1	Knitwear	290	1.20	85% bamboo, 15% polyester	–
K2		220	0.38	95% bamboo, 5% elastane	–
K3		320	0.86	97% bamboo, 3% elastane	–

that the air permeability was the highest for a fabric woven from 100% bamboo. This is because the cross-section of the bamboo fibre is filled with many micro-gaps and micro-holes, which facilitate the flow of air. Similar conclusions can be found in the work of Kadapalayam *et al*. [10], in which it was confirmed that water vapour permeability and air permeability increase with the increasing share of bamboo fibre in a given fabric. Venkatesh and co-authors [11] introduced bamboo fibres into sisal fibres, which resulted in higher values of flexing, stretching and puncture resistance. In addition, increasing the share of bamboo fibres to 25% resulted in a significant increase in the moisture absorption coefficient. It is worth noting that natural bamboo fibres have the aforementioned properties without the need for additional chemical processes accompanying their processing, which is extremely important when designing children's footwear.

The aim of the work was to examine selected hygienic and mechanical properties of textile materials with the addition of bamboo fibres intended for children's footwear linings and uppers.

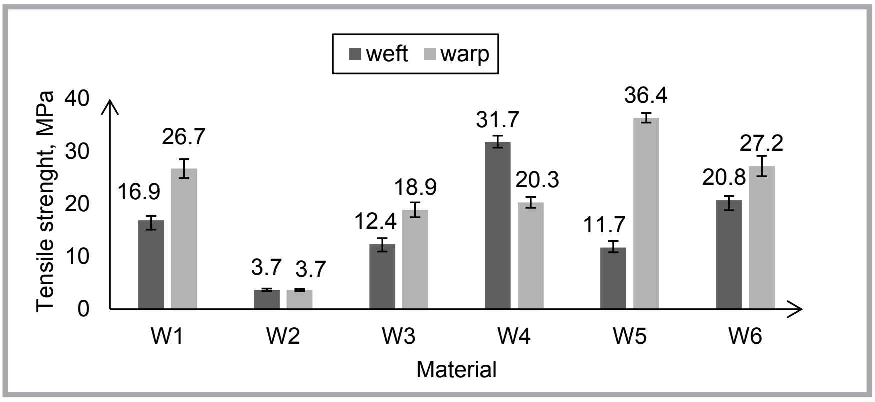

Figure 1. Tensile strength of woven fabrics (across the weft and warp) with bamboo (W1, W2 – 100%, W3 – 95%, W4 – 50%) and cotton (W5, W6 – 100%) fibre content.

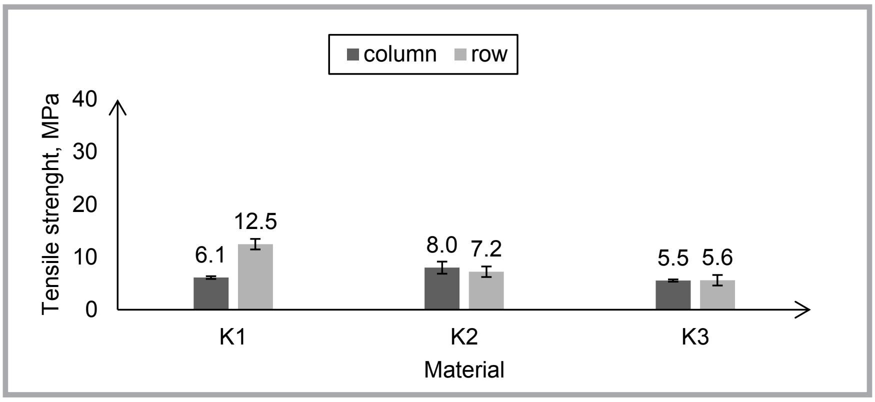

Figure 2. Tensile strength of knitted fabrics (across the columns and rows) with bamboo fibre content (K1 – 85%, K2 – 95%, K3 – 97%).

Materials and methods

Preliminary tests of selected materials based on regenerated cellulose bamboo fibres available on the market (woven fabrics W1 – W4 and knitted fabrics K1 – K3) were made as part of this study (***Table 1***). The research concerned the classification of these materials for mechanical and hygienic properties to assess the suitability of bamboo materials in the design of children's footwear, which ought to fulfill special requirements. In these studies the role of the control sample was played by cotton fabrics, which are the most common materials used for linings (W6) and uppers (W5) for children's footwear.

For the purpose of determining the mechanical properties of the materials, the following values were determined experimentally for each material tested: tensile strength, stress at maximum force and the strain value. Using these parameters, it is possible to make a comparison between individual materials to develop their qualitative assessment. The tensile strength T_s is the stress corresponding to the highest tensile force F_{max} obtained during the static tensile test with respect to the original cross-section S_0 of the sample [12] (product of sample thickness and width), i.e.

$$T_s = \frac{F_{\max}}{S_0} \cdot 10^6, [\mathrm{MPa}]. \qquad (1)$$

All material samples tested were subjected to static tensile tests on a Zwick/Roell Z010 strength machine. The dependence of the length increase of the material samples prepared on the amount of tensile force applied parallel to the axis of the sample was recorded. The fabrics were stretched across the weft and warp, while in the case of knitted fabrics the axis of the tensile force ran across the rows and columns. Each material was analysed with a view to tearing resistance (due to PN-EN ISO 4674–1: 2017:02 [3], method B) with use of a Matest material testing machine. The hygienic properties of the materials tested were based on two aspects: water vapor permeability and its absorption. Water vapour permeability (hereinafter referred to as W_{vp}) and water vapour absorption (W_{va}) were determined in accordance with the PN-EN ISO 20344: 2012 standard [14]. Also the water vapor permeability coefficient (VP_{coeff}), was determined, which links the water vapour permeability and water absorption as follows:

$$VP_{coeff} = t \cdot W_{vp} + W_{va}, \left[\frac{mg}{cm^2}\right] \quad (2)$$

where, t is the test time (t = 8 h).

Results and discussion

Mechanical properties

Footwear is a product normally used for a long time. It is therefore exposed to deformations, which are caused by forces, in particular by stretching, bending and abrasion, less by flexing (bending) forces. The behaviour of materials (or their systems) determines the durability and possibility of using a specific product under specific conditions of use, either outside or inside the three-dimensional volume of footwear. Quantitative classification of the strength values obtained for the textile materials tested (woven and knitted fabrics) is shown in ***Figures 1*** and ***2.***

The results make it possible to determine the range of tensile strength for fabrics. For woven bamboo these values are between 3.7 – 31.7 MPa measured across the weft and 3.7 – 36.4 MPa across the warp, whereas for cotton woven these values are consecutively 11.7 – 20.8 MPa and 27.2 – 36.4 MPa. For bamboo knitted fabrics, the values range between 5.5 and 8.0 MPa measured across the columns and between 5.6 and 12.5 MPa measured across the rows. This means that in most cases the knitted fabrics have a lower tensile strength compared to woven fabrics. These values are within the standard strength range of materials commonly used in footwear [15].

Another parameter which was taken into account was the flexibility of materials (***Figures 3*** and ***4***), measured by elongation obtained when the maximum breaking force was reached.

The smallest elongation was obtained for woven cotton fabrics W5, W6 (both weft and warp) and woven bamboo fabric W4 (across the weft), containing in its composition an addition of flax. The highest elongation values were obtained for the K2 knitted fabric. This is due to the fact that among all the materials tested, the K2 knitted fabric contained an addition of elastane, i.e. 5%. The results classify the materials tested in a elastic group, which is clearly demonstrated for knitted fabrics. The factor that is responsible for such high elongation at maximum force, exceeding two or three times the length of unloaded material, is primarily the addition of synthetic fibres (polyester, elastane), whose elastic properties increase the elasticity of the knitted fabrics to which they are added. It is also worth noting that in the case of woven fabrics, higher elongation values at break were obtained in the direction of the weft for all woven fabrics, with the exception of W5 (woven cotton). This proves that the W5 woven fabric was characterised by a weak threading of weft in this variant [16]. The ability to deform footwear materials plays an important role in shaping the active mechanism of maintaining the foot arch – both the longitudinal arch, supported by the brevis muscles, and the transverse arch, mainly in the interosseous muscles, causing the contraction of the metatarsal bones [17]. This is important in creating a resilience function of the foot, which plays an important role in making a stabile support mechanism for the whole human body.

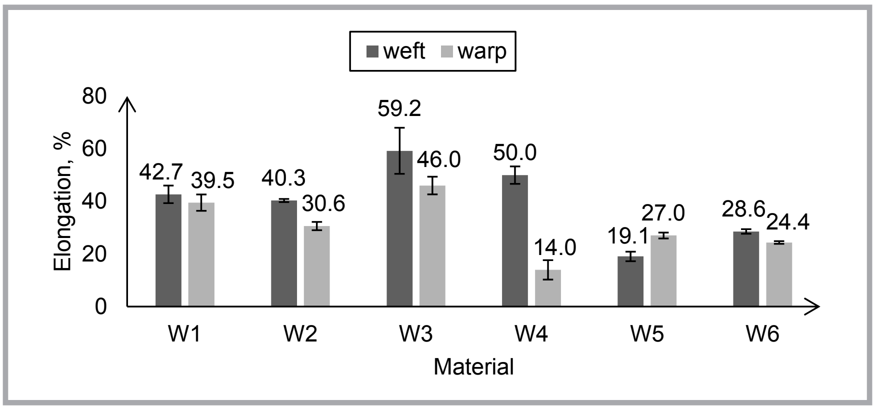

Figure 3. *Elongation at break of woven fabrics (across the weft and warp) with bamboo (W1, W2 –100%, W3 – 95%, W4 – 50%) and cotton (W5, W6 – 100%) fibre content.*

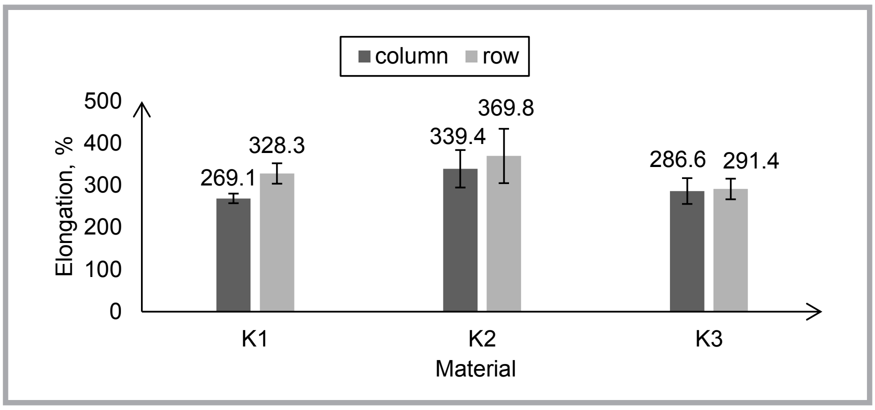

Figure 4. *Elongation at break of knitted fabrics (across the columns and rows) with bamboo fibre content (K1 – 85%, K2 – 95%, K3 – 97%).*

Tearing resistance measurement (***Figures 5*** and ***6***) showed that higher values were observed for bamboo material W3 (the value of tearing resistance is more than 200% higher than for woven cotton W5 (for weft) and more than 600% for W6 (for weft)). In most cases the knitted fabrics have lower tearing resistance than the wovens.

Hygienic properties

In order to provide footwear users with optimal microclimate conditions, the materials used should, on the one hand, have high water vapour permeability, but on the other also absorb vapour, to a large extent, in their mass. Thanks to this, footwear materials do not moisten. At the same time, processes of water desorption to the environment should proceed in an efficient and undisturbed manner. The test results (***Figures 7*** and ***8***) make it possible to classify the materials tested into a highly permeable class, characterised by very good water vapour absorption.

Analysis of the water vapour permeability value leads to the conclusion that the bamboo materials used are homogeneous in this respect. The coefficient of

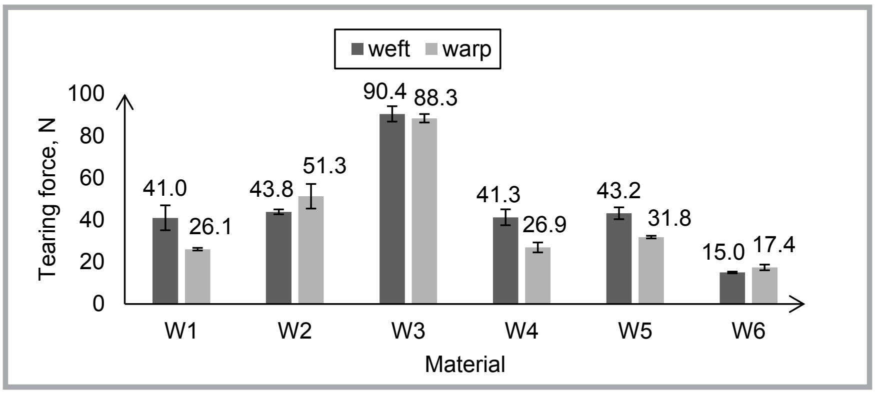

Figure 5. *Tearing force at break of woven fabrics (across the weft and warp) with bamboo (W1, W2 – 100%, W3 – 95%, W4 – 50%) and cotton (W5, W6 – 100%) fibre content.*

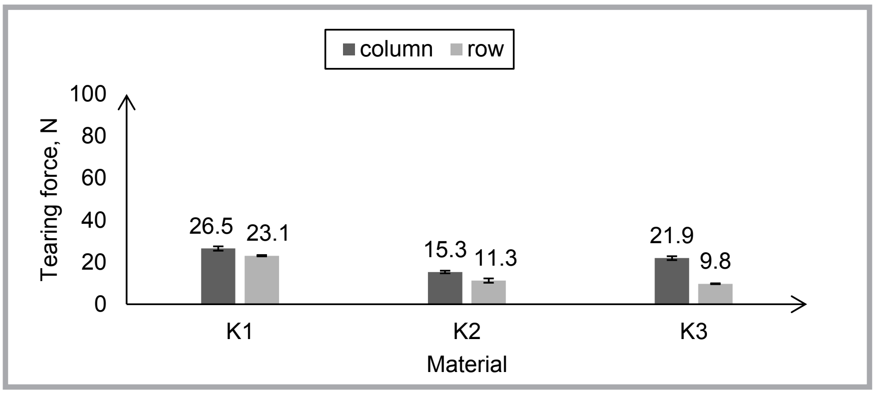

Figure 6. *Tearing force at break of knitted fabrics (across the columns and rows) with bamboo fibre content (K1 – 85%, K2 – 95%, K3 – 97%).*

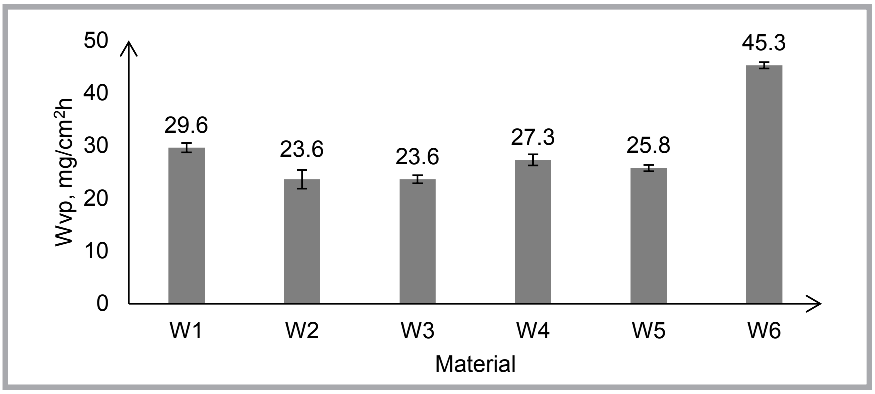

Figure 7. *Water vapour permeability for woven fabrics with bamboo (W1, W2 – 100%, W3 – 95%, W4 – 50%) and cotton (W5, W6 – 100%) fibre content.*

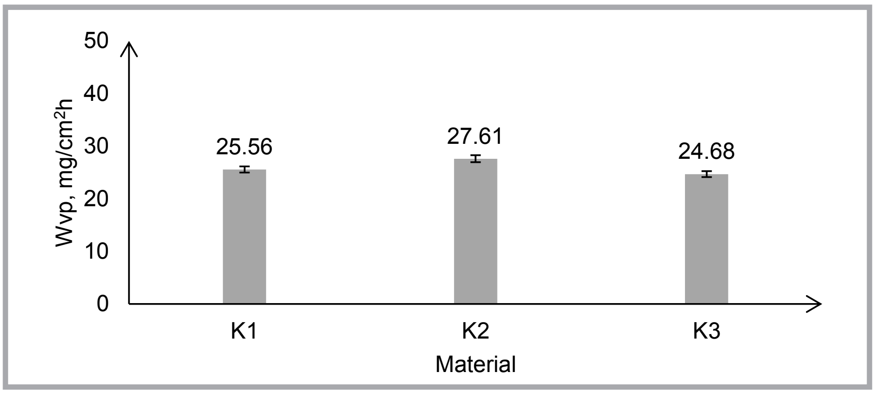

Figure 8. *Water vapour permeability for knitted fabrics with bamboo fibre content (K1 – 85%, K2 –95%, K3 – 97%).*

variation, determined as the ratio of the standard deviation to the arithmetic mean of the values obtained, is at a low level of 11% for woven fabrics W1 – W4 and 6% for knitted fabrics K1 – K3. Acceptable values of water vapour permeability of the PN-EN ISO 20344: 2012 standard should be at least 0.8 mg/cm^{2}h for the upper and 2 mg/cm^{2}h for the lining [14]. This means that the bamboo materials tested meet the requirements of the standard and can be used for the production of footwear.

Figures 9 and ***10*** show the results of water steam absorption (hereinafter referred to as W_{va}) for the bamboo fibre materials tested.

The results of the water vapour absorption coefficient classify the materials tested into a series of materials very well absorbing water in their structure. In the case of woven bamboo fabrics, the variability between materials, represented by the coefficient of variation, is approximately 32%, with woven fabrics W2 and W4 having the greatest influence on obtaining this value. This is because the difference in the absorption coefficient between them is around 43%, while between materials W3 and W1 it is about 4%. In the case of bamboo knitted fabrics K1 – K3, a similar situation takes place. The coefficient of variation for all materials is about 20%, but this value is mainly influenced by that obtained for the K3 material.

The level of water vapour permeability and its absorption is realised in the size of the water vapour permeability coefficient. In the case of the woven bamboo fabrics tested, it stood in the range of 191.84 – 239.96 mg/cm^2 and 200.61 – 227.98 mg/cm^2 for knitted fabrics. With reference to the PN-EN ISO 20344: 2012 standard, it can be noticed that the values obtained exceed the minimum acceptable values several times [14]. Thus the values determined allow the bamboo materials tested to be used in footwear (according to the standard: 15 mg/cm^2 for uppers and 20 mg/cm^2 for lining materials).

On the basis of research on the hygienic properties of bamboo materials for footwear, it is possible to postulate their very good properties which would predispose them to be used as elements of uppers systems, as well as for lining.

The analysis of mechanical and hygienic properties of selected and available on the market woven and knitted fabrics based on bamboo fibres confirms that their use as footwear materials can significantly affect the quality of use of the final product. Bamboo fibres are characterised by biodegradability, the source of which being in the high cellulose content [18, 19]. Due to this fact, they perfectly match contemporary global trends related to environmental protection. Until now, due to the specific properties of bamboo materials, mainly related to their antibacterial and bacteriostatic properties, they have been commonly used in hospital equipment (sheets, bathrobes, hospital protective clothing, protective masks, etc.). Other aspects, such as very good water vapour and air permeability properties, hygroscopicity as well as softness, equally important from the user's point of view, make bamboo products more and more often used as a material for the production of socks and underwear. With regard to materials used in the immediate vicinity of the foot, bamboo textiles have better hygienic properties than the commonly used cotton, viscose and chitosan fibres. According to the literature, under certain conditions bamboo materials are characterised by higher air and water vapour permeability as well as insulation than the aforementioned materials [20, 21]. From the user's point of view, the ability to accelerate drying out is also important, as it reduces the growth of mould and pathogenic fungi on the materials used [22].

The research of bamboo materials carried out in this work is an introduction to further work, the aim of which is to create a prototype of footwear with improved functional parameters, having a direct impact on footwear microclimate. As the microclimate is primarily determined by the hygienic properties [15], it is in this respect that the material systems for uppers and lining materials will be selected.

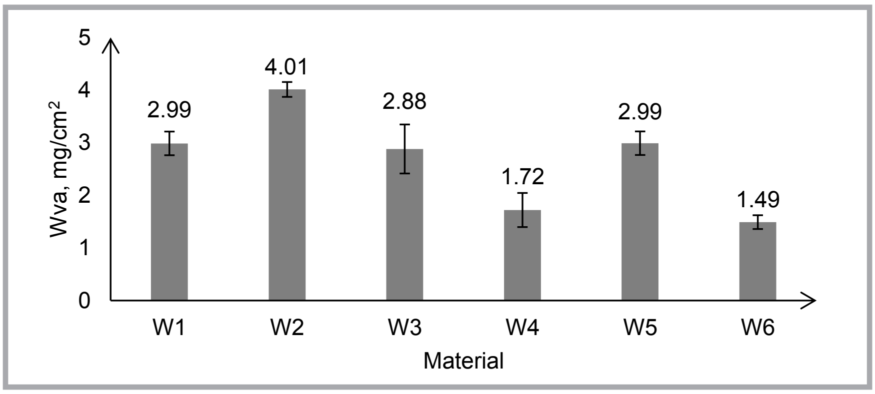

Figure 9. *Absorption of water vapour for woven fabrics with bamboo (W1, W2 – 100%, W3 – 95%, W4 – 50%) and cotton (W5, W6 – 100%) fibre content.*

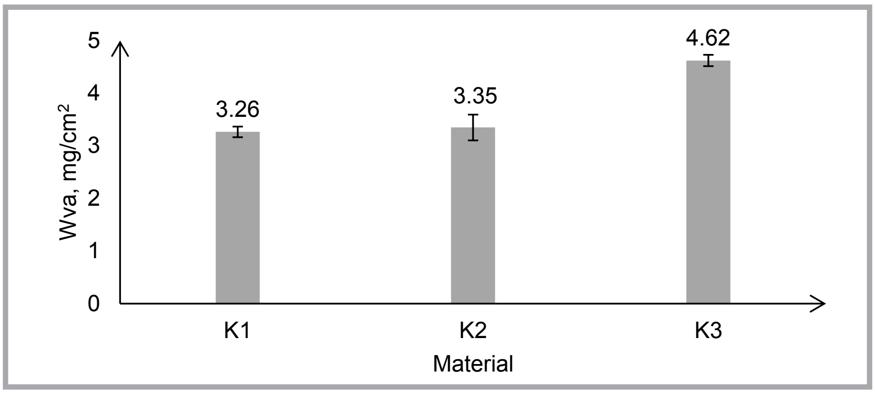

Figure 10. *Water vapor absorption for knitted fabrics with bamboo fibre content (K1 – 85%, K2 – 95%, K3 – 97%).*

Conclusions

- Woven and knitted fabrics based on bamboo fibres, which are available on the market, can be used as elements of children's footwear;
- In some cases they have better mechanical properties (more flexible or tougher) than commonly used cotton fabrics (for W1, W3, W4);
- In the majority of cases, bamboo textiles have better hygienic properties, as shown by higher values of water vapour absorption (W1, W2 compared to W5 and W1 – W4 compared to W6);
- Based on the preliminary studies, it is possible to predict that bamboo textiles can improve comfort sensations for footwear users in the spectrum of hygienic and mechanical properties.

Acknowledgment

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