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Hydrostatic Resistance and Mechanical Behaviours of Breathable Layered Waterproof Fabrics

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Abstract
Breathable layered waterproof fabrics have good applications in the fields of sportswear, protective clothing and construction industries. The properties of these fabrics in allowing water vapour to pass through while preventing liquid water from entering have made them unique. The mechanical properties of these fabrics are also very important for the satisfaction of the wearers. The layered constructions of these fabrics with different characteristic properties contribute to the influence on their hydrostatic resistance, mechanical properties and water vapour permeability. This study presents an experiment on eight different types of hydrophobic and hydrophilic membrane laminated layered fabrics used as sportswear during hot or cold weather. The hydrostatic resistance, tensile strength, stiffness and water vapour permeability of these fabrics were evaluated by varying different fabric parameters in the experiment. It was found from the test results that the fabric density, thickness and weight as well as types of membranes and layers have a significant effect on those properties of the layered fabrics.

Key words: *waterproof fabric, hydrostatic resistance, tensile strength, stiffness, breathability.*

Introduction

Breathability and waterproofing are two contradictory properties of fabrics. Breathability allows moisture vapour to flow from one side of a fabric to the other, and is determined by water vapour permeability [1]. Waterproofing resists water molecules from the outside to the inside of a fabric protecting the wearer from being wet under higher hydrostatic pressure. Waterproof fabric has fewer open pores; these are responsible for lower permeability of water vapour [2]. Hence it is a big challenge to maintain these two properties simultaneously in a fabric.

Again, clothing comfort is an integral part of the human body. The three main categories of clothing comfort are tactile comfort, thermal comfort and aesthetic comfort [3]. Besides these, it can be also categorised by mechanical comfort, which can be evaluated by fabric handle, rigidity and tensile properties. For sportswear, it should enable the release of sweat from the surface of skin in hot weather and prevent excessive heat loss in cold weather. Moreover, this fabric should have proper tensile strength and better stiffness for the satisfaction of the wearer.

However, different types of waterproof breathable fabrics can be developed from closely woven fabrics, micro-porous membranes and coating, hydrophilic membranes and coating, a combination of micro-porous and hydrophilic membranes and coating, retroreflective microbeads, smart breathable fabrics and fabrics based on biomimetics [4-6]. Micro-porous membranes have holes that are much smaller than the size of the smallest raindrops, but much larger than the water vapour molecular size. For this reason, water vapor molecules can enter but water cannot penetrate the fabric. On the other hand, nano-porous hydrophilic membranes allow water vapour to pass in a different way. By the chemical adsorption process, water vapour is transmitted here. An amorphous region is developed in the main polymer system of the hydrophilic part. This amorphous region acts as intermolecular pores that allow water vapour molecules to pass, while liquid water penetration is prevented due to the membrane's solid nature [7-8]. In this research work, different types of layered waterproof breathable polyester (PES) laminated fabrics used as sports clothing were investigated. Two different types of membranes were used to develop these laminated layered fabrics. One was a polytetrafluorothylene (PTFE) micro-porous hydrophobic membrane and another was a polyurethane (PU) nano-porous hydrophilic membrane. Different characteristic properties of these fabrics were analysed. It was found from the analysis of test results that there are significant influences of fabric density, fabric thickness and fabric weight along with membrane hydrophobic and hydrophilic characteristics and layer types on their different properties, like hydrostatic resistance, mechanical properties and water vapour permeability.

Experimental

Materials

Eight different types of laminated fabrics with a micro-porous PTFE hydrophobic membrane and nano-porous PU hydrophilic membrane were developed and investigated in the experiment. The first six samples were PTFE membrane laminated and the last two were PU membrane laminated. Among the six PTFE membrane laminated samples, the first four were three-layered fabrics, the fifth and sixth – two-layered fabrics, and the seventh and eighth PU membrane laminated fabrics were two-layered. The outer layers of all eight samples were with PES plain woven structures. PTFE and PU membranes in the fabric samples were after PES plain structures as the middle layers for three-layered fabrics and as the inner layers for two-layered fabrics. Out of the four three-layered PTFE membrane laminated samples, the inner layers of the first two samples were with PES knitted structures, and the inner layers of the third and fourth samples were with PES fleece knitted structures. Cross-sectional images of one three-layered sample and one two-layered sample are shown in ***Figure 1***. Characteristics of the samples are shown in ***Table 1***.

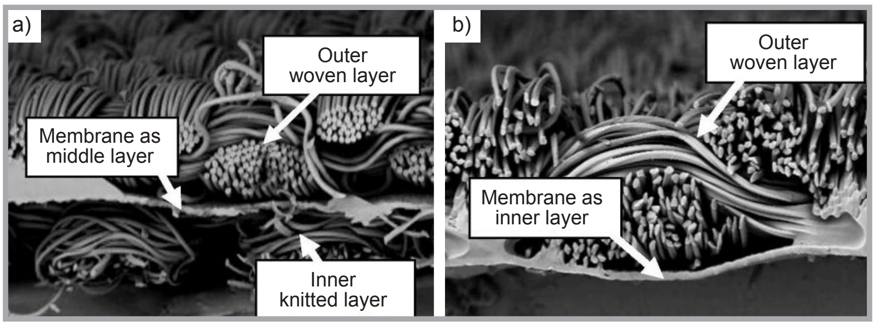

Figure 1. *Cross-sectional images of (a) three-layered and (b) two-layered samples.*

Methods

Different characteristics of the laminated fabric samples, like the cover factor of the outer woven part, stitch density of the inner knitted part and fabric density of the whole laminated fabric sample, as shown in ***Table 1***, were established under standard atmospheric conditions.

Cover factor

The warp and weft cover factor of the outer woven layer part of the laminated fabric were measured using the Peirce equation [9]:

$$K_1 = n_1 / (N_1)^{½} \text{ and } K_2 = n_2 / (N_2)^{½} \quad (1)$$

Here, K_1 = warp cover factor, K_2 = weft cover factor, n_1 = warp yarn density/inch, n_2 = weft yarn density/inch, N_1 = English count of warp yarn, and N_2 = English count of weft yarn.

Stitch density

The stitch density of the inner knitted layer part of the laminated fabric was calculated by the multiplication of wales/cm and courses/cm with the help of an optical microscope.

Fabric density

The fabric density of the whole laminated sample was calculated by the following ***Equation (2)*** [10]:

$$\text{Fabric density} = \frac{W}{t} \text{ Kg/m}^3 \quad (2)$$

Here, 'W' is the fabric mass per unit area, which was measured using the electronic weighing scale according to

Table 1. *Characteristics of laminated fabrics.*

Fabric sample code	Fabric construction (outer part to inner part)	Warp and weft cover factor of outer woven layer (K_1 & K_2)	Stitch density of inner knitted layer, stitches/cm^2	Fabric mass per unit area, g/m^2	Fabric thickness, mm	Fabric density, Kg/m^3
WMK-1	PES plain + PTFE + PES Knitting	(10 & 7)	273	89	0.21	423.81
WMK-2	PES plain + PTFE + PES Knitting	(19 & 14)	925	167	0.35	477.14
WMF-3	PES plain + PTFE + PES fleece knitting	(15 & 12)	192	314	1.20	261.67
WMF-4	PES plain + PTFE + PES fleece knitting	(15 & 13)	221	389	1.27	306.30
WM-5	PES plain + PTFE	(18 & 12)	–	86	0.19	452.63
WM-6	PES plain + PTFE	(18 & 14)	–	112	0.24	466.67
WM-7	PES plain + PU	(22 & 16)	–	139	0.26	534.62
WM-8	PES plain + PU	(23 & 17)	–	158	0.29	544.83

Table 2. *Different properties of laminated fabrics.*

Properties		WMK-1	WMK-2	WMF-3	WMF-4	WM-5	WM-6	WM-7	WM-8
Hydrostatic resistance, cmH_2O	Mean	1464	1522	1087	1114	1481	1505	1578	1597
	SD	6.55	6.13	4.55	4.11	6.65	4.78	5.73	4.55
Breaking force, N	Mean	410	478	356	379	428	444	501	513
	SD	5.50	7.69	7.94	9.44	7.86	5.99	5.78	3.50
Bending rigidity, 10^{-6} Nm	Mean	7.56	13.58	27.19	28.10	6.49	8.16	10.94	12.88
	SD	0.17	0.12	0.15	0.12	0.12	0.26	0.07	0.21
Relative water vapour permeability, RWVP, %	Mean	47.60	42.74	33.58	30.64	48.32	45.60	40.14	38.52
	SD	0.37	0.23	0.28	0.29	0.24	0.30	0.21	0.20
Evaporative resistance, R_{et}, m^{2}Pa/W	Mean	6.44	8.42	11.64	12.76	6.16	7.86	9.44	9.92
	SD	0.21	0.27	0.22	0.21	0.10	0.19	0.24	0.12

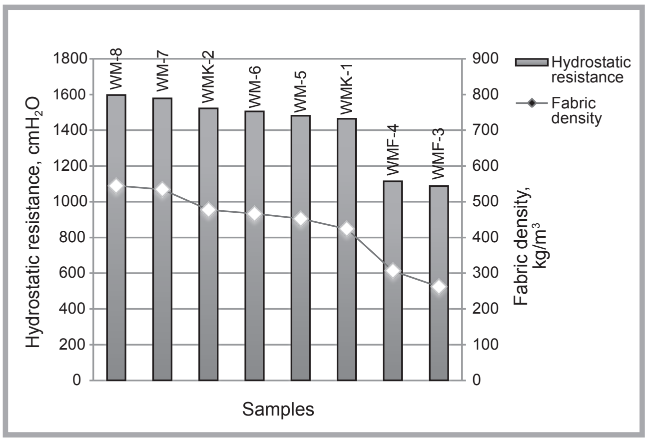

Figure 2. Effect of fabric density on hydrostatic resistance.

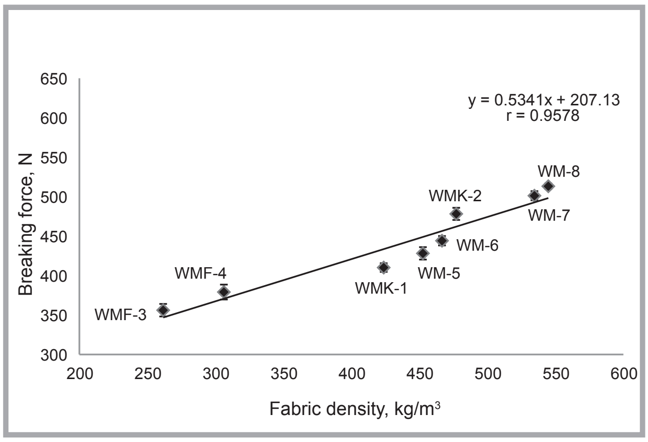

Figure 3. Effect of fabric density on breaking force.

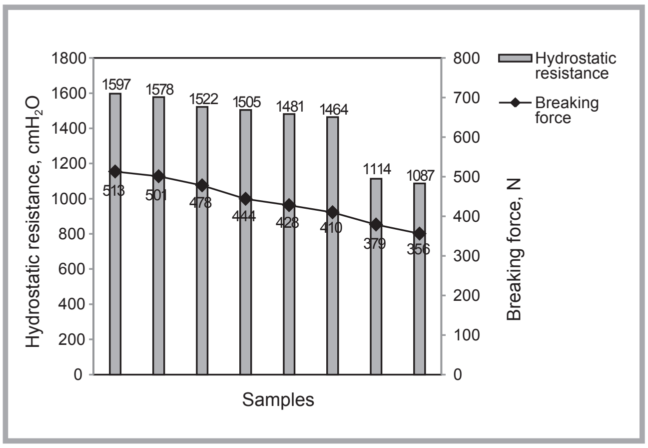

Figure 4. Relationship between hydrostatic resistance and breaking force.

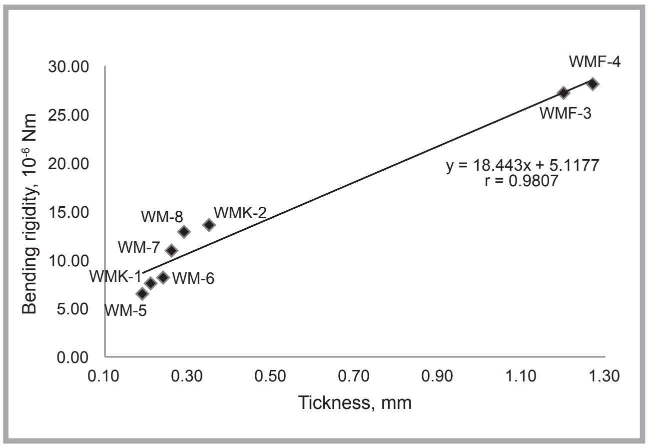

Figure 5. Effect of fabric thickness on bending rigidity.

the EN 12127 standard. Fabric thickness 't' was measured according to the EN ISO 5084 standard at a pressure of 100 Pa with a Louis Schopper Automatic Micrometer (Germany).

Hydrostatic resistance test

An SDL ATLAS Hydrostatic Head Tester Model MO18 (USA) was used at 20±2 °C for hydrostatic resistance testing according to CSN EN 20811 [11]. The rate of increase in water pressure was 60±3 cmH_2O/min. The maximum compressor pressure of 80 PSI was used. Water pressure was recorded at the point where water penetrated from the outer to inner layer. Here the unit was expressed as cmH_2O; test results are given in ***Table 2***.

Tensile strength test

For the tensile strength of the samples, a Testometric M350-5CT machine (UK) was used at room temperature according to the CSN EN ISO 13934-1 standard. The tensile testing speed was 100 mm/ min and the specimen size was kept at 20 cm x 5 cm. The result was expressed as the breaking force in Newtons (N). Five sets of experiments were performed, the average results of which with standard deviations are shown in ***Table 2***.

Measurement of bending rigidity

The bending force of the fabric was directly measured by a TH-7 instrument (Technical University of Liberec, Czech Republic) [12]. The bending rigidity was calculated by multiplication of the bending force value with a constant value obtained (0.7×10^{-6}), and the unit was expressed as Nm. Test results are given in ***Table 2***.

Determination of water vapour permeability

PERMETEST apparatus (Senzora, Czech Republic) was used to determine the water vapour permeability according to the ISO 11092 standard without any destruction of the laminated fabric samples. The sample was placed on a measuring head over a semi-permeable foil and exposed to parallel air flow at a velocity of 1 m/s [13]. The temperature of the measuring head was maintained at room temperature for isothermal conditions. A computer monitor connected to this instrument expressed the relative water vapour permeability (RWVP) in % and evaporative resistance (R_{et}) in m^2Pa/W. The results obtained are shown in ***Table 2***.

Results and discussion

Comparison of hydrostatic resistance

Eight different types of fabric samples of various fabric density were examined. From ***Figure 2***, it is found that there is a significant effect of fabric density on the hydrostatic resistance property. Among all the samples, WM-8 and WM-7 have higher hydrostatic resistance than the others due to their higher fabric density. Moreover their PU nano-porous mem-

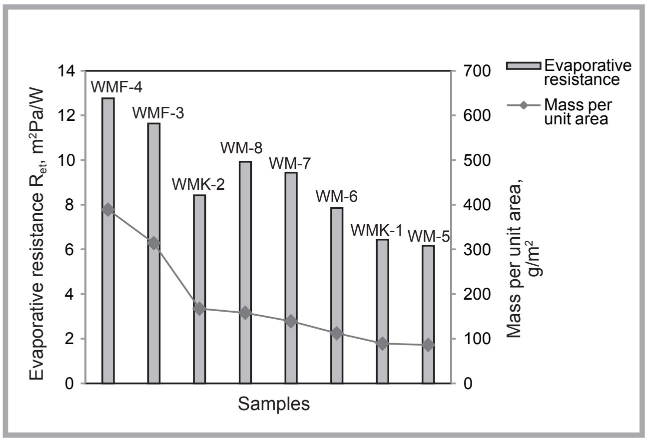

***Figure 6.** Effect of fabric weight on R_{et} value.*

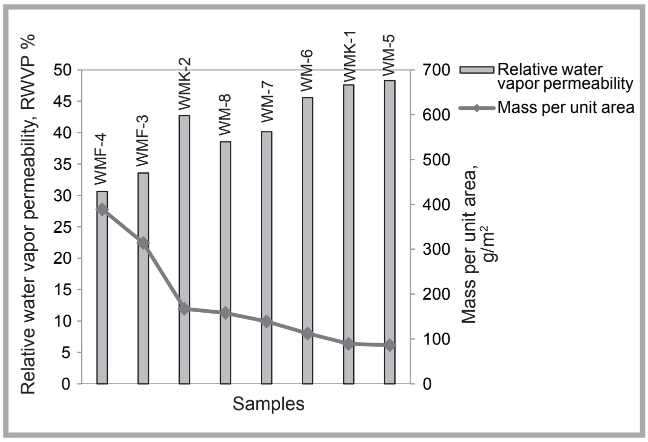

***Figure 7.** Effect of fabric weight on RWVP%*

branes also affect this property because the PU membrane is less porous than the PTFE micro-porous membrane. Comparing the remaining six PTFE membrane laminated samples, hydrostatic resistance is higher for WMK-2 than for the others. Here also the reason is the higher fabric density than for the others. In addition, the cover factor of the outer woven layer and stitch density of the inner knitted layer of this fabric are also higher than for the others. On the other hand, WMF-3 and WMF-4 have lower hydrostatic resistance due to their lower fabric density. Moreover their inner fleece knitted parts are also responsible for the lower values, as fleece knitted parts cannot resist water properly. However, it is noticeable that all the values are above 1000 cmH_2O. Thus all the fabrics can be used as outdoor sports clothing of good quality, because values ranging from 1000 cmH_2O to 3000 cmH_2O are used as the outdoor industry standard for waterproof fabrics. Again, hydrostatic resistance values of 500 cmH_2O for high quality products and 130 cmH_2O for lower grade products have been reported [14].

Comparison of tensile strength

A tensile strength test was performed to evaluate the mechanical properties of the sample fabrics. From the test results and ***Figure 3,*** it is obvious that the fabric density of the laminated layered samples influences their tensile strength significantly. Here the correlation coefficient is 0.9578, and there is a positive relationship between the fabric density and breaking force of the samples. The breaking force increases with an increase in fabric density. The highest breaking force is obtained for the WM-8 sample due to its highest fabric density, and the lowest breaking force is for WMF-3 due to its lowest fabric density. And there is a same positive trend for the rest of the samples when a comparison is made between the fabric density and breaking force.

Relationship between hydrostatic resistance and tensile strength

When the hydrostatic resistance and tensile strength of different samples are compared to each other, a positive relationship between these two properties is found from ***Figure 4***. Hydrostatic resistance increases with an increase in the breaking force and decreases with a decrease in the breaking force. Higher hydrostatic reistance is obtained in the case of samples with a higher breaking force and a lower hydrostatic resistance for samples with a lower breaking force. The hydrostatic resistance value is measured under water pressure, and the value at which water penetrates from the outer part of the fabric to the inner part is considered. This water pressure is also the force applied on the fabric until water penetrates. That is why hydrostatic resistance correlates with the breaking force of the samples.

Comparison of stiffness

The stiffness test result represents the rigidity of the fabric, determined by the bending rigidity. The bending rigidity of a fabric is an important comfort parameter. Very stiff fabric can be uncomfortable and unfit for use. From ***Figure 5***, it is evident that thickness is the vital determining factor which influences the bending rigidity of the layered laminated fabric samples. Here the correlation coefficient is 0.9807, which determines the positive significant influence of fabric thickness on bending rigidity. However, the thickness of WMF-4 and WMF-3 are higher than for the other six samples. Similarly the bending rigidity of these two samples is also higher than for the rest due to their higher thickness. Among the other six samples, WMK-2, WM-8 and WM-7 have higher rigidity than the other three due to their higher thickness. And the lowest bending rigidty is obtained in the case of sample WM-5 due to its lowest thickness property.

Comparison of water vapour permeability

Evaporative resistance (R_{et}) and RWVP% indicate the water vapour permeability of the fabric samples. Water vapour permeability is higher when the R_{et} value decreases or RWVP% increases. In ***Figures 6*** and ***7***, the effect of fabric weight (mass per unit area) on water vapour permeability is shown. The R_{et} value of the laminated fabric increases with an increase in fabric weight, as shown in ***Figure 6***, and here the correlation coefficient obtained is 0.9296. On the other hand, the RWVP% of the laminated fabric decreases with an increase in fabric weight, as shown in ***Figure 7***, and here the correlation coefficient is – 0.9404.

Among all the samples, WMF-4 and WMF-3 have the lowest water vapour permeability due to their higher fabric weight. Moreover their inner knitted fleece structures and higher thickness properties cause more air entrapment, which lowers the diffusion rate of water vapour. As a result, the release of sweat from the body in the form of water vapour is not easy for these samples. Hence these two types of fabrics are less suitable as sports fabrics, but can still be used as winter sports fabrics. On the other hand, samples WM-5 and WMK-1 show better water vapour permeability than the other fabrics due to their lower fabric weight than the others. These fabrics can provide better thermal comfort during sports activities in the summer season, releasing the increased sweating. However, water vapour permeability is lower for samples WM-8 and WM-7 than for WMK-2, although WMK-2 has higher fabric weight than these two samples. The reason is their PU nano-porous membranes reducing the diffusion rate of water vapour, which results in less water vapour permeability.

Conslusions

In the experiment, different properties of membrane laminated layered fabrics, like hydrostatic resistance, tensile strength, bending rigidity and water vapour permeability were analyzed. From the test results, it is clear that fabric density and compactness influence the hydrostatic resistance and tensile strength properties significantly. Fabric thickness greatly affects the bending rigidity of the fabrics, whereas water vapour permeability is impacted by the fabric weight as well as fabric compactness and the hydrophobic or hydrophilic nature of the membrane. Moreover there is a positive relationship between the hydrostatic resistance and tensile strength properties.

Laminated layered fabrics with higher hydrostatic resistance and better breathability are considered for outdoor sports clothing. Moreover better tensile strength along with low bending rigidity is preferable for users. Fabrics with better water vapour permeability are suitable for summer sports clothing, whereas those with less water vapour permeability can be used for winter sports clothing. Among all the samples investigated, WM-8 has the highest hydrostatic resistance and tensile strength properties. WM-5 and WMK-1 are more water vapour permeable and also have less bending rigidity; moreover their hydrostatic resistance and tensile strength are also quite satisfactory. As a result, these two types of fabrics should be more preferred by users as summer sports outdoor clothing. WMF-3 and WMF-4 fabric samples are suitable as winter sports clothing due to their lower water vapour permeability. However, two layered fabrics can be used as winter sports clothing, adding sufficient lining materials.

Finally it can be said that during the designing of summer or winter sports waterproof breathable laminated fabrics, hydrostatic resistance, mechanical properties and water vapour permeability should be considered to be of great importance for the comfortability of the wearers.

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