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Evaluation of Hydrostatic Resistance and Comfort Properties of Breathable Laminated Fabrics

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SUMMARY OF THE THESIS

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ABSTRACT

Waterproof breathable laminated fabrics allow water vapour passing through, but prevent liquid water to pass. This ability of the fabrics to protect rain and snow water while allowing sweat vapour to evaporate from inside to outside atmosphere, leads them to be used as outdoor sportswear or protective clothing. The challenge of enhanced hydrostatic resistance of these fabrics with proper breathability and other comfort properties has widened the research scope.

In the first part of the thesis, waterproof breathable laminated fabrics were prepared which could be used as outdoor sports fabrics. For this purpose, firstly, 20 GSM (g/m^2) microporous polyurethane (PU) membranes were laminated with three different types of polyester plain woven fabrics whose fabric weights and cover factors were different. Here, three different types of two-layered fabrics were prepared where polyester woven fabrics acted as outer layers and membranes acted as inner layers. And secondly, polyurethane membranes were laminated with those three different types of polyester plain woven fabrics and a one type of single jersey polyester knitted fabric to prepare three-layered fabrics. Here, three different types of three-layered fabrics were prepared where polyester woven fabrics acted as outer layers, membranes acted as middle layers and knitted fabrics acted as inner layers. All the newly produced six layered sample fabrics were characterized. Then this work investigated the influence of different parameters of these laminated fabrics, i.e., fabric weight, fabric thickness, fabric density, layered structures, warp and weft cover factors of outer woven layers on their different properties, i.e., hydrostatic resistance and other thermal and mechanical comfort properties, i.e., water vapour permeability, thermal resistance, air permeability, breaking strength and stiffness. It has been found from the test results and statistical analysis that there are significant influences of different fabric parameters on their different properties and these findings are important for designing and preparing waterproof breathable laminated fabrics for using as outdoor sports fabrics.

In the second part of the research work, a novel approach was applied for coating four different types of microporous polytetrafluoroethylene (PTFE) membrane laminated three-layered waterproof breathable fabrics. Here, eco-friendly C_6-based fluorocarbon water-repellent chemical and silicone based polysiloxane hydrophobic softening agent were used to prepare the coating solution in order to enhance the existing hydrostatic resistance and mechanical performance of the fabrics while keeping their water vapour permeability and air permeability in mind. From different test results and statistical analysis, it has been found that hydrostatic resistance and breaking strength have been significantly increased after coating while there are no significant changes in the results of water vapour permeability and air permeability. Furthermore, all the coated fabrics show good water-repellent property which is important for outdoor sports fabrics.

Keywords: Waterproof fabrics; breathability; hydrostatic resistance; water vapour permeability; water-repellent; thermal resistance; breaking strength; stiffness;

ABSTRAKT

Nepromokavé prodyšné vrstvené textilie umožňují průchod vodní páry, ale zabraňují průchodu kapalné vody. Tato schopnost textilií chránit před dešťovou a sněhovou vodou a současně umožnit, aby se pára odpařovala zevnitř ven, vede k použití pro venkovní sportovní oblečení nebo ochranné oděvy. Cílem práce je rozšíření klasifikace tkanin se zvýšenou hydrostatickou odolností s vhodnou prodyšností a dalšími komfortními vlastnostmi.

V první části práce byly připraveny nové vodotěsné prodyšné vrstvené tkaniny, které by mohly být použity na venkovní sportovní oděvy. Za tímto účelem bylo nejprve laminováno 20 mikroporézních polyurethanových (PU) membrán GSM (g/m^2) se třemi různými typy polyesterových hladkých tkanin, jejichž hmotnost a krycí faktory byly odlišné. Byly připraveny tři různé typy dvouvrstvých tkanin, kde polyesterové tkaniny působily jako vnější vrstvy a membrány působily jako vnitřní vrstvy. A za druhé, polyurethanové membrány byly laminovány těmito třemi různými typy polyesterových hladkých tkanin a jedním typem zátažného jednolícního polyesterového pleteného materiálu pro výrobu třívrstvých tkanin. Byly připraveny tři různé typy třívrstvých tkanin, kde polyesterové tkaniny působily jako vnější vrstvy, membrány působily jako střední vrstvy a pletené látky působily jako vnitřní vrstvy. Byly charakterizovány všechny nově vyrobené vrstvené textilie. Tato práce zkoumala vliv různých parametrů těchto laminovaných textilií, tj. hmotnosti, tloušťky, plošné hmotnosti, krycího faktoru atd., na jejich různé vlastnosti, tj. hydrostatickou odolnost a jiné tepelné, mechanické a komfortní vlastnosti, tj. propustnost pro vodní páru, propustnost vzduchu, pevnost v tahu a tuhost. Z výsledků testů a statistických analýz bylo zjištěno, že existují významné vlivy různých parametrů tkaniny na některé vlastnosti a tyto nálezy jsou důležité pro navrhování a přípravu nepromokavých prodyšných laminovaných textilií určených k použití pro sportovní oděvy.

V druhé části práce byl aplikován nový přístup s použitím potahovacího roztoku připraveného ekologicky optimalizovaným hydrofobním změkčovadlem na bázi fluoruhlovodíkové hydrofobní chemikálie a na bázi silikonu pro povlékání čtyř různých typů mikroporézních polytetrafluorethylenových (PTFE) vrstvených nepromokavých prodyšných sportovních tkanin pomocí metody suché vulkanizace, aby se zvýšila stávající hydrostatická odolnost a mechanická účinnost těchto tkanin při zachování jejich prodyšnosti a vzduchové propustnosti. Z různých výsledků testů a statistické analýzy bylo zjištěno, že hydrostatickou odolnost a pevnost v tahu se po povrstvení výrazně zvýšily, zatímco nedošlo k významným změnám ve výsledcích propustnosti vodní páry a propustnosti pro vzduch. Navíc všechny textilie vykazují správnou vodoodpudivou vlastnost, která je důležitá pro venkovní sportovní oblečení.

Klíčová slova: Voděodolné textilie; prodyšnost; hydrostatický odpor; propustnost vodních par; vodoodpudivost; teplotní odolnost; pevnost v tahu; tuhost;

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1 Introduction

Water vapour permeability and waterproofing are two contradictory properties of fabrics. Water vapour permeability of a fabric is the ability of clothing to allow moisture vapour transmission from inside to outside atmosphere by diffusion and therefore facilitate evaporative cooling [1, 2, 3]. On the other hand, waterproofing is a term that can be described as the impermeability to water. It is measured by hydrostatic resistance. Waterproof fabrics are resistant to the penetration of water even under pressure. These fabrics have fewer open pores and are less permeable to the passage of air and water vapour [4]. The resistance of a fabric to water depends on the nature of the fiber surface and the dynamic force behind the impacting water spray [5].

Waterproof breathable fabric is one of the harsh weather fabrics. In severe environmental conditions, waterproof breathable fabrics should protect the human body from external heat, wind and water, but at the same time they should let moisture vapour to be transmitted from inside to outside. These properties of the fabrics help to provide the wearer with a great level of comfort in many unpleasant situations. As a result, there are significant uses of waterproof breathable fabrics in the fields of sportswear and protective clothing [6, 7]. Waterproof breathable fabrics are of different types, i.e., closely woven fabrics, hydrophilic membranes and coating, microporous membranes and coating, combination of hydrophilic and microporous membranes and coating, smart breathable fabrics, retroreflective microbeads, and fabrics based on biomimetics [8-12]. Multi-layered waterproof breathable textile-polymeric fabrics are produced from various types of water-tight and wind-tight polymeric membranes that are permeable to water vapour. These membranes are of two basic types, like, microporous membranes that are mostly of hydrophobic character and hydrophilic membranes with compact structure [13-16]. Laminated microporous fabrics have holes that are much smaller than the size of the smallest raindrop, yet are much larger than the size of a water vapour molecule [17]. As a result, water droplets cannot penetrate the fabric, but water vapour molecules can penetrate. On the other hand, water-repellent fabrics resist being wetted by water. In this case, water drops roll off the fabrics [5]. By depositing hydrophobic materials on the fiber's surface, this type of fabric can be prepared. They have open pores and are permeable to air and water vapour. They still increase the water resistance property, but permit the passage of liquid water under higher hydrostatic pressure [4].

Again, comfort is a basic requirement during selection of clothing [18] and it is an integral part of the human body. It is one of the most essential attributes that a fabric should possess [19]. Comfort is associated with the ability of the body to maintain a constant core temperature under different environmental conditions, like cold or hot weather as well as under different physical or sports activities. Core temperature of the human body is approximately 37°C. When core body temperature exceeds 37°C under different conditions, perspiration is produced in order to balance the core temperature by secretion of sweat. It is important for clothing to play a role for keeping the body comfortable by removing sweat as water vapour [20]. So, water vapour permeability of a fabric which allows transmission of moisture and heat from the surface of human body into the environment is one of the most important factors. Because clothing comfort sensation is determined mainly by a balanced process of moisture and heat exchange between human body and environment through clothing system [21]. Sports apparels should prevent excessive heat loss in cold weather and enable the release of sweat from the surface of skin in hot weather. Three main categories of clothing comfort are tactile comfort, thermal comfort and aesthetic comfort [22]. Thermal property, air permeability, water vapour permeability and liquid water permeability have been suggested as critical properties for thermal comfort of the clothed body [23]. Besides, bending rigidity and breaking strength as mechanical properties are also important for the wearers.

Firstly, this research study prepared waterproof breathable laminated fabrics with microporous polyurethane (PU) membrane for the users of outdoor sports fabrics and focused on assessing the effect of different fabric characteristic parameters on their different properties, like, hydrostatic resistance along with thermal and mechanical comfort properties. Secondly, this research study applied a novel approach for coating four different types of microporous polytetrafluoroethylene (PTFE) membrane laminated three-layered waterproof breathable fabrics in order to enhance their existing hydrostatic resistance and mechanical performance.

2 Purpose and the aim of the thesis

The aim of this study was to newly develop waterproof breathable laminated fabrics and to characterize these fabrics in order to evaluate their hydrostatic resistance and other comfort properties which are very important for the users of outdoor sports fabrics as well as this research work was performed to enhance the hydrostatic resistance and mechanical performance of multi-layered breathable waterproof fabrics that are also useful for the users. The specific objectives are given as below:

To prepare waterproof breathable fabrics
This study was performed to design and prepare waterproof breathable membrane laminated fabrics. Firstly, two-layered waterproof breathable fabrics were prepared using polyurethane (PU) membrane and three different types of polyester plain woven fabrics and secondly, three-layered waterproof breathable fabrics were prepared with those three different types of polyester plain woven fabrics, PU membrane and a one type of single jersey polyester knitted fabric.

Analysis of hydrostatic resistance of the prepared samples
In this study, the influences of different structural characteristics of the prepared PU membrane laminated two-layered and three-layered fabrics on their water resistance property were determined. Statistical evaluation with regression analysis was used to analyze the influences of different factors of the fabrics on their hydrostatic resistance property.

Study of thermo-physiological and mechanical behaviors of the prepared samples
This study was performed to determine the influences of different characteristics of the prepared PU membrane laminated fabrics on their thermo-physiological and mechanical behaviors. The thermal behavior was evaluated with the help of thermal resistance evaluation. Water vapour permeability was measured and analyzed in order to study the breathability performance of the sample fabrics as well as air permeability was evaluated. Mechanical behavior, i.e., breaking strength was identified

with the result analysis of the breaking force of the fabrics and bending rigidity of the sample fabrics was analyzed. The influences of various factors on desired properties were statistically analyzed.

Application of a novel approach for coating

A novel approach for coating was applied on four different types of polytetrafluoroethylene (PTFE) membrane laminated three-layered waterproof breathable fabrics using eco-friendly C_6-based fluorocarbon water-repellent chemical and silicone based polysiloxane hydrophobic softening agent in order to enhance their existing hydrostatic resistance and mechanical performance while considering their water vapour permeability and air permeability. Water-repellent property of these four sample fabrics was also analyzed after coating. Statistical analysis of variance was used to describe the significant or non-significant increases of different properties of these four different three-layered fabrics after coating.

3 Overview of the current state of the problem

Waterproof breathable fabrics used for various protective clothing and sportswear should show the resistance to the penetration of water under pressure, while simultaneously should show a high possible permeability for water vapour. This permeability is of importance for the fabric's hygienic value, as it allows human perspiration to be carried away from the skin surface and secreted beyond the area between the clothing and the human body. This prevents the human body from overcooling or overheating and consequently protects them against a chill and ensures a good frame of mind and comfort [13-16, 24-29]. It is a big challenge to maintain hydrostatic resistance value and simultaneously water vapour permeability in the fabric. However, waterproof breathable fabrics had already been studied by some researchers. Kang et al. worked on waterproof breathable fabric prepared by electrospun polyurethane (PU) nanoweb to polyester and nylon blended fabric and discussed about its air and water vapour permeability with water resistance [6]. Ahn et al. studied on two-layered fabric laminated by electrospun PU nanoweb with water repellent nylon fabric and discussed about its waterproof and breathable properties [17]. Kim et al. explained thermal comfort and waterproof breathable properties for polyester fabrics with aluminum coated polyurethane nanoweb [30]. Ozen tried to develop waterproof breathable fabrics using plain and twill woven fabrics of cotton and polyester yarns and it was revealed from the study that waterproofing was increased when water repellent fabrics were laminated with breathable linear low density polyethylene films [4].

But, this research study newly designed and prepared microporous polyurethane (PU) membrane laminated waterproof breathable fabrics that could be used as outdoor sports fabrics. For this purpose, firstly, polyurethane membranes were laminated with three different types of polyester plain woven fabrics whose fabric weights as well as warp and weft cover factors were different in order to produce two-layered fabrics. Here, three different types of two-layered fabrics were prepared. Polyester woven fabrics acted as outer layers and membranes acted as inner layers. And secondly, polyurethane membranes were laminated with those three different types of polyester plain woven fabrics and a one type of single jersey polyester knitted fabric to prepare three-layered fabrics. Here, three different types of three-layered fabrics were prepared. Polyurethane membrane acted as a middle layer and knitted fabric acted as an inner layer for each of three different types of three-layered fabrics. But, outer layers of these three different laminated three-layered sample fabrics were three different types of polyester woven fabrics. Then all the newly produced layered six sample fabrics were characterized and evaluated statistically in order to analyze the influences of different fabric characteristic parameters on their different properties, like, hydrostatic resistance, thermo-physiological behaviors, i.e., thermal property with air and water vapour permeability as well as mechanical properties, i.e., bending rigidity and breaking strength.

In the second part of the research work, a novel approach was applied for coating four different types of microporous polytetrafluoroethylene (PTFE) membrane laminated three-layered waterproof breathable fabrics. For this purpose, water-repellent coating solution was prepared by ecologically optimized C_6-based fluorocarbon chemical instead of conventional C_8-based fluorocarbon chemical. C_6-based fluorocarbon chemical produces perfluorohexanoic acid (PFHA) that is supposed to be 40 times less bio accumulative than perfluorooctanoic acid (PFOA) [31]. Polysiloxane hydrophobic chemical was used as a softening agent with C_6-based fluorocarbon chemical in the coating solution to get advantageous functions of both water- repellent property as well as softening property. At first, different mixing ratios of C_6-based fluorocarbon chemical and polysiloxane hydrophobic softening agent were applied on one of the four PTFE laminated fabrics and then the best ratio on which the best results were obtained for this sample was selected for coating the rest three other PTFE laminated sample fabrics. After coating all four PTFE laminated three-layered fabrics, different test results were statistically analyzed in order to determine the significant or non-significant increases in the results of hydrostatic resistance, breaking strength, bending rigidity as well as water vapour permeability and air permeability. Water-repellent property of these fabrics was also evaluated after coating for its importance in outdoor sports clothing.

4 Methods used, studied material

4.1 Methodology for investigation of hydrostatic resistance and comfort properties of PU membrane laminated fabrics

4.1.1 Materials

In order to produce two-layered and three-layered laminated fabrics, three different types of polyester plain woven fabrics with different fabric weights and different warp and weft cover factors were used as outer layers. Warp yarn and weft yarn of the woven fabrics were with the fineness of 150 Denier. One type of single jersey polyester knitted fabric with 127 GSM (g/m^2) was applied as an inner layer for preparation of each three-layered laminated fabric. 20 GSM (g/m^2) microporous polyurethane (PU) membrane was used as an inner layer for each two-layered fabric lamination and as a middle layer for each three-layered fabric lamination. Polyester woven and polyester knitted fabrics were purchased from Hira Mukta Design & Fashion of Bangladesh. PU membrane was obtained from Nanotex Group in Czech Republic. Particulars of three different types of woven fabrics and one type of knitted fabric are given in Table-1.

Table 1. Particulars of woven and knitted fabrics

Fabric code	Type of fabric	Fabric weight (g/m^2)	Warp density (yarn/cm)	Weft density (yarn/cm)	Warp and weft cover factor of woven fabric (K_1 & K_2)	Stitch density of knitted fabric ($stitches/cm^2$)
F-1	Polyester plain woven fabric	139	33	28	(14 & 12)	------
F-2	Polyester plain woven fabric	128	30	24	(13 & 10)	------
F-3	Polyester plain woven fabric	122	26	24	(11 & 10)	------
K	Polyester single jersey knitted fabric	127	------	------	------	208

4.1.2 Methods

4.1.2.1 Lamination process

Comel PL/T 1250 Heat and Press Machine was used for producing six different types of laminated fabrics. Two-layered three samples were prepared placing one upon another in the order of PU membrane and each of three different polyester woven fabrics separately. And three-layered three samples were prepared laying one upon another in the order of each of three different polyester woven fabrics separately, PU membrane and polyester knitted fabric. Then fabrics were laminated under heat and pressure treatment of the machine at 160°C temperature with 2 bar pressure for 15 seconds. Characteristics of produced six laminated sample fabrics are shown in Table-2.

Figure 1. Lamination by Comel PL/T 1250 Heat and Press Machine.

Table 2. Characteristics of PU membrane laminated sample fabrics

Sample Fabric code	Layered structure of fabric (outer layer to inner layer)	Areal density of sample fabric (g/m^2)	Thickness of sample fabric (mm)	Density of sample fabric (kg/m^3)
		(Mean ± SD)	(Mean ± SD)	(Mean ± SD)
FM-1	F-1 + PU membrane	158 ± 1.01	0.42 ± 0.01	376.19 ± 1.16
FM-2	F-2 + PU membrane	147 ± 1.29	0.40 ± 0.01	367.50 ± 1.26
FM-3	F-3 + PU membrane	141 ± 1.12	0.39 ± 0.01	361.53 ± 1.18
FMK-4	F-1 + PU membrane + K	283 ± 1.77	0.69 ± 0.01	410.14 ± 1.55
FMK-5	F-2 + PU membrane + K	271 ± 1.42	0.68 ± 0.01	398.53 ± 1.61
FMK-6	F-3 + PU membrane + K	263 ± 1.26	0.67 ± 0.01	392.54 ± 1.85

4.1.2.2. Characterization of laminated fabrics

Cover factor

Warp cover factor and weft cover factor of outer woven layer part of the laminated fabric were measured using the Peirce equation [32]:

$$K_1 = n_1 / (N_1)^{1/2} \text{ and } K_2 = n_2 / (N_2)^{1/2} \qquad (1)$$

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

Stitch density

Stitch density of inner knitted layer part of the laminated fabric was calculated by the multiplication of courses/cm and wales/cm using optical microscope [33].

Fabric weight

Fabric weight per unit area was measured using electronic weighing scale according to CSN EN 12127 [34].

Fabric thickness

Fabric thickness was measured according to EN ISO 5084 [35] at a pressure of 100 Pa with Louis Schopper Automatic Micrometer.

Fabric density

Fabric density of the laminated sample fabric was calculated by the following equation [36]:

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

Here, 'W' is fabric mass per unit area and 't' is fabric thickness.

4.1.2.3 Morphology

The morphological cross-sections of the laminated samples show the layered structures of the fabrics. This morphology was examined using high resolution of scanning electron microscope VEGA TS 5130- TESCAN. To increase the surface conductivity, the samples were sputter coated with gold.

4.1.2.4 Hydrostatic resistance

Hydrostatic resistance tests were carried out by SDL ATLAS Hydrostatic Head Tester Model MO18 according to AATCC 127 [37] at 20±2ºC. The rate of increase of water pressure per minute was kept at 60±3 cmH_2O. Water pressure was recorded at the point when water penetrated from outer layer to inner layer showing three drops of water or crack of sample or constant fall of water pressure. The unit was expressed as cmH_2O and this unit was converted into Pascal (Pa) = N/m^2. Obtained test results are reported in Table-3.

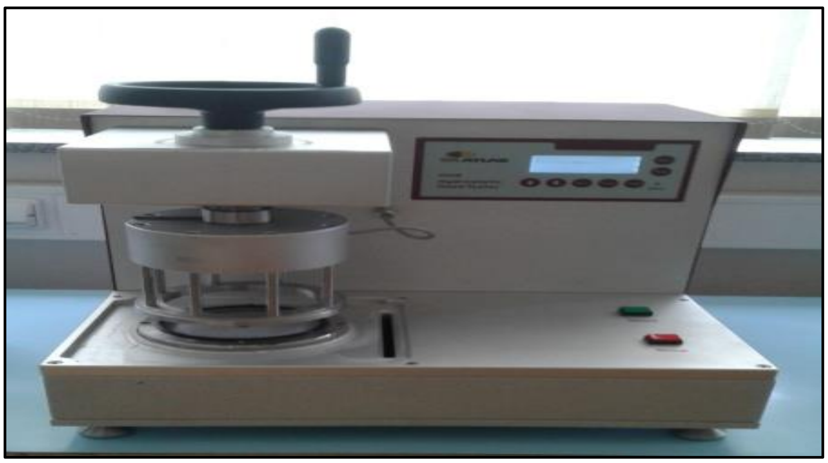

Figure 2. MO18 Hydrostatic Head Tester.

4.1.2.5 Water vapour permeability

The water vapour permeability of the sample fabric was measured by PERMETEST instrument. This instrument is able to determine non-destructive measurement of the samples according to ISO 11092 standard [38] and it works on the principle of heat flux sensing. The fabric 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. The measurement was carried out at room temperature for isothermal conditions following the skin model [39]. When water flows into the measuring head, some amount of heat is lost and the instrument measures the heat loss from the measuring head due to evaporation of water without fabric and with fabric. The relative water vapour permeability (RWVP) of the sample is calculated by the ratio of heat loss from the measuring head with fabric (q_s) and heat loss from the measuring head without fabric (q_o) as below equation [40, 41].

$$RWVP = (q_s / q_o) \times 100\% \tag{3}$$

PERMETEST enables to determine water vapour transmission of the fabric by measuring the two parameters as RWVP% and evaporative resistance (R_{et}) in the unit of m^2Pa/W. Five tests for each sample were done and the mean test results are presented in Table-3.

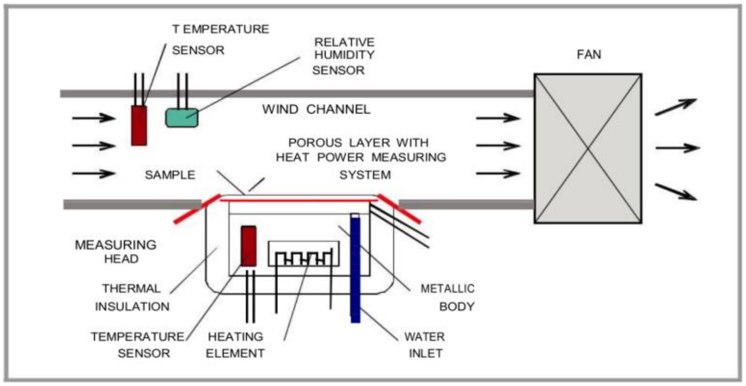

Figure 3. PERMETEST skin model.

Table 3. Properties of PU membrane laminated sample fabrics

Properties		FM-1	FM-2	FM-3	FMK-4	FMK-5	FMK-6
Hydrostatic resistance (N/m^2)	Mean	66195	62664	60311	81297	77080	74334
	SD	244	212	240	288	257	303
Evaporative resistance, R_{et} (m^2Pa / W)	Mean	7.44	6.82	6.40	9.18	8.68	8.22
	SD	0.16	0.12	0.11	0.18	0.10	0.12
Relative water vapour permeability, RWVP (%)	Mean	45.42	47.34	48.62	39.42	41.02	42.92
	SD	0.27	0.28	0.23	0.25	0.29	0.22
Air permeability ($l/m^2/s$)	Mean	1.97	2.38	2.59	1.42	1.73	1.85
	SD	0.03	0.04	0.06	0.03	0.04	0.05
Thermal resistance ($x10^{-3}$ Km^2/W)	Mean	13.84	12.20	10.94	19.36	17.54	16.56
	SD	0.17	0.21	0.19	0.22	0.27	0.16
Bending rigidity ($x10^{-6}$ Nm)	Mean	12.67	12.08	11.79	21.31	20.91	20.57
	SD	0.07	0.10	0.06	0.07	0.04	0.04
Breaking force (N)	Mean	373	354	342	451	423	405
	SD	4.32	4.67	3.92	4.94	5.31	4.63

4.1.2.6 Air permeability

The air flow rate that passes perpendicularly under a prescribed air pressure through a known area between the two surfaces of a material is considered as air permeability. Textest FX-3300 air permeability tester was used to measure air permeability of the samples according to standard EN ISO 9237 [42]. Test area of the sample was 20 cm^2 and air pressure difference between the two surfaces was kept at 200 Pa because of the layered structures of the sample fabrics. Average value of ten measurements was taken for each sample in the unit of $l/m^2/s$ and the results are shown in Table-3.

4.1.2.7 Thermal resistance

Thermal property, like, thermal resistance was measured by ALAMBETA apparatus which is a computer controlled instrument for measuring the basic static and dynamic thermal characteristics of textiles. The contact pressure was 200 Pa in all cases, and the CV (coefficient of variation) values of all the samples were lower than 4% as like as used in other experiment [43]. The values of thermal resistance of the laminated fabrics were determined from the instrument and test results are given in Table-3. Measurement of thermal property by ALAMBETA is standardized in the Internal Standard of Textile Faculty of Technical University of Liberec [44].

4.1.2.8 Bending rigidity

By TH-7 instrument, bending force of the sample fabric was directly obtained. Bending rigidity was calculated by the multiplication of this bending force value with a constant value of (0.7 x 10^{-6}). Here, unit was expressed as Nm. The device TH-7 was developed in the Department of Textile Evaluation at Technical University of Liberec. It was developed by means of innovation of device TH-5 on which only rectangle samples sized 2.5x5 cm could be measured. The following features give the differences between the model of device TH-5 and TH-7 [45]:

- The clamping and sensor jaw has been extended so that the device can be used for measuring rectangular, square and circular samples.
- The revolving clamping jaw has been designed so that it can turn in both directions, which enables one to draw the whole hysteresis loop of bending.
- The sensor jaw has been adjusted so that the bending power can be scanned in both directions: face– face and back–back. The sensor jaw is of shape U.
- Teflon tubes on the sensor jaw reduce the coefficient of friction between the tube and the bent fabric.
- New software has been developed in order to control the device and store the measured data.
- To set 10 cycles of automatic bending at maximum is possible. The values of every cycle as well as the final average value are recorded.

4.1.2.9 Breaking strength

Testometric M350-5CT machine (UK) was used at room temperature according to CSN EN ISO 13934-1 [46] for breaking strength test of the samples. Specimen size was kept at 20cm x 5cm and testing speed was 100 mm/ min. The unit was expressed as breaking force in Newton (N) and the test results are given in Table-3.

4.2 Methodology for enhancement of hydrostatic resistance and mechanical performance of PTFE membrane laminated fabrics

4.2.1 Materials

4.2.1.1 Waterproof breathable laminated fabrics

Four different types of polytetrafluoroethylene (PTFE) hydrophobic microporous membrane laminated waterproof breathable fabrics were used in this part of the experiment. The fabrics were purchased from Hira Mukta Design & Fashion of Bangladesh. All the samples were three-layered fabrics. Outer layers of all four samples were with polyester plain woven structures. Inner layers of first two samples were with polyester knitted structures and inner layers of third and fourth samples were with polyester fleece knitted structures. PTFE membrane was laminated as a middle layer for each sample. Particulars of the laminated sample fabrics are shown in Table-4.

Table 4. Particulars of PTFE membrane laminated sample fabrics

Fabric sample code	Fabric construction (outer layer to inner layer)	Warp and weft cover factor of outer woven part of fabric (K_1 & K_2)	Stitch density of inner knitted part of fabric (stitches/cm^2)
WMK-1	Polyester plain woven + PTFE membrane + polyester knitting	(10 & 7)	273
WMK-2	Polyester plain woven + PTFE membrane + polyester knitting	(19 & 14)	925
WMF-3	Polyester plain woven + PTFE membrane + polyester fleece knitting	(15 & 12)	192
WMF-4	Polyester plain woven + PTFE membrane + polyester fleece knitting	(15 & 13)	221

4.2.1.2 Coating chemicals

®RUCOSTAR EEE6 with density of 1.03 g/cm^3 at 20°C was used as a water-repellent chemical. This chemical is a C_6-based fluorocarbon chemical which is different from conventional C_8-based fluorocarbon chemical. It is ecologically optimized agent for water and free from perfluorooctanoic acid (PFOA), perfluorooctanesulfonate (PFOS) and alkylphenol ethoxylate (APEO). ®RUCOFIN HSF polysiloxane hydrophobic softening agent was added with ®RUCOSTAR EEE6 in the coating solution. This chemical is easily diluted with water and its density is 1.10 g/cm^3 at 20°C. Both of the chemicals were purchased from Rudolf GmbH, Germany.

4.2.2 Methods

4.2.2.1 Coating process

At first, WMK-2 sample was considered as a standard sample among these four samples and this sample was coated with different mixing ratios of C_6-based fluorocarbon resin (®RUCOSTAR EEE6) and polysiloxane hydrophobic softening agent (®RUCOFIN HSF) according to T-2, T-3, T-4, T-5, T-6 and T-7. Characteristics of WMK-2 sample fabric coated with different ratios of ®RUCOSTAR EEE6 and ®RUCOFIN HSF are shown in Table-5. And properties of WMK-2 sample fabric coated with different ratios of ®RUCOSTAR EEE6 and ®RUCOFIN HSF are shown in Table-6. Then the best ratio, from which the best results were obtained, was selected and applied for coating the rest three sample fabrics, like, WMK-1, WMF-3 and WMF-4 samples. However, pad-dry-cure method was used for coating using Rapid Padding Mangle. The homogeneous coating solution was made by ordinary manual stirring and put into the coating bath. Material-liquor ratio of 1:15 was used for coating. The waterproof fabrics were impregnated in the coating bath at room temperature. The coating fluid was agitated by glass rod to have uniform coating on the fabrics. After impregnation, the fabrics were passed through the squeezing rollers. Then the fabrics were dried under usual condition and finally cured at 160°C for 1 minute.

Figure 4. Rapid Padding Mangle.

Table 5. Characteristics of WMK-2 sample fabric coated with different ratios of ®RUCOSTAR EEE6 and ®RUCOFIN HSF

Fabric sample		Areal density of Fabric (g / m^2)	Fabric thickness (mm)	Fabric density (Kg / m^3)	Increase in areal density after coating (%)
T-1 (uncoated)	Mean	167	0.350	477.14	-----
	SD	2.29	0.01	2.20	
T-2 (40 g/L ®RUCOSTAR EEE6 with 15 g/L ®RUCOFIN HSF)	Mean	182	0.377	482.76	8.98
	SD	2.06	0.01	2.05	
T-3 (50 g/L ®RUCOSTAR EEE6 with 15 g/L ®RUCOFIN HSF)	Mean	185	0.380	486.84	10.78
	SD	2.19	0.01	3.15	
T-4 (60 g/L ®RUCOSTAR EEE6 with 15 g/L ®RUCOFIN HSF)	Mean	177	0.370	478.38	5.99
	SD	2.03	0.01	3.30	
T-5 (40 g/L ®RUCOSTAR EEE6 with 20 g/L ®RUCOFIN HSF)	Mean	183	0.378	484.13	9.58
	SD	2.35	0.01	3.47	
T-6 (50 g/L ®RUCOSTAR EEE6 with 20 g/L ®RUCOFIN HSF)	Mean	180	0.374	481.28	7.78
	SD	2.37	0.01	3.28	
T-7 (60 g/L ®RUCOSTAR EEE6 with 20 g/L ®RUCOFIN HSF)	Mean	176	0.368	478.26	5.39
	SD	2.39	0.01	3.33	

Table 6. Properties of WMK-2 sample fabric coated with different ratios of ®RUCOSTAR EEE6 and ®RUCOFIN HSF

Properties		T-1	T-2	T-3	T-4	T-5	T-6	T-7
Hydrostatic resistance (N/m^2)	Mean	149257	163967	167890	160143	165340	162202	159260
	SD	601	667	722	642	727	622	635
Breaking force (N)	Mean	478	559	572	514	562	535	504
	SD	7.69	8.27	8.36	8.09	8.47	7.82	8.26
Bending rigidity ($x10^{-6}$ Nm)	Mean	13.58	14.51	14.63	14.16	14.48	14.19	14.04
	SD	0.12	0.11	0.13	0.22	0.14	0.21	0.16
Evaporative resistance, R_{et} (m^2Pa / W)	Mean	8.42	8.74	8.84	8.54	8.78	8.66	8.52
	SD	0.27	0.21	0.31	0.22	0.25	0.23	0.24
Relative water vapour permeability, RWVP (%)	Mean	42.74	42.46	42.40	42.56	42.44	42.50	42.58
	SD	0.23	0.29	0.36	0.31	0.38	0.32	0.33
Air permeability ($l/m^2/s$)	Mean	0.72	0.69	0.68	0.70	0.68	0.69	0.70
	SD	0.05	0.04	0.05	0.03	0.04	0.05	0.04

After coating WMK-1, WMK-2, WMF-3 and WMF-4 samples on the basis of best ratio of ®RUCOSTAR EEE6 and ®RUCOFIN HSF, all the four samples were characterized before and after coating and their properties were analyzed. Characteristics of four different sample fabrics before and after coating are presented in Table-7 and properties of four different sample fabrics before and after coating are shown in Table-8.

Table 7. Characteristics of PTFE membrane laminated samples before and after coating

Fabric sample		Areal density of uncoated fabric (g/m^2)	Areal density of coated fabric (g/m^2)	Increase in areal density after coating (%)	Thickness of uncoated fabric (mm)	Thickness of coated fabric (mm)	Density of uncoated fabric (Kg/m^3)	Density of coated fabric (Kg/m^3)
WMK-1	Mean	89	99	11.24	0.21	0.23	423.81	430.43
	SD	2.24	2.31		0.01	0.01	2.21	4.85
WMK-2	Mean	167	185	10.78	0.35	0.38	477.14	486.84
	SD	2.29	2.19		0.01	0.01	2.20	3.15
WMF-3	Mean	314	339	7.96	1.20	1.25	261.67	271.20
	SD	1.62	3.74		0.01	0.02	1.45	2.01
WMF-4	Mean	389	418	7.46	1.27	1.32	306.30	316.67
	SD	1.22	3.56		0.01	0.02	2.25	1.74

Table 8. Properties of PTFE membrane laminated samples before and after coating

Properties		Uncoated				Coated			
		WMK-1	WMK-2	WMF-3	WMF-4	WMK-1	WMK-2	WMF-3	WMF-4
Hydrostatic resistance (N/m^2)	Mean	143569	149257	106598	109246	158475	167890	116895	119249
	SD	642	601	446	403	764	722	635	612
Breaking force (N)	Mean	410	478	356	379	477	572	412	435
	SD	5.50	7.69	7.94	9.44	8.47	8.36	9.58	10.38
Bending rigidity ($x10^{-6}$ Nm)	Mean	7.56	13.58	27.19	28.10	8.01	14.63	28.62	29.53
	SD	0.17	0.12	0.15	0.12	0.18	0.13	0.16	0.12
Evaporative resistance, R_{et} (m^2Pa / W)	Mean	6.44	8.42	11.64	12.76	6.74	8.84	11.92	13.00
	SD	0.21	0.27	0.22	0.21	0.29	0.31	0.25	0.28
RWVP (%)	Mean	47.60	42.74	33.58	30.64	47.28	42.40	33.26	30.30
	SD	0.37	0.23	0.28	0.29	0.41	0.36	0.33	0.30
Air permeability ($l/m^2/s$)	Mean	1.07	0.72	1.51	1.32	1.04	0.68	1.45	1.26
	SD	0.04	0.05	0.06	0.07	0.04	0.05	0.07	0.07

4.2.2.2 Spray test

To determine the resistance of a fabric to wetting by water, spray test method is used. It is usually used to determine the water-repellent effect of finishes applied to fabrics. Pro-ser Spray Rating Tester was used in the experiment for conducting spray test according to AATCC 22 [47]. The coated samples were conditioned at 21°±1°C for 24 hours under a relative humidity of 65±2% before testing. The samples were stretched on a hoop which was held at an angle of 45° and 250 mL water was poured through a spray nozzle. Any wetting or spotted pattern was observed and compared with the photographic rating chart [48].

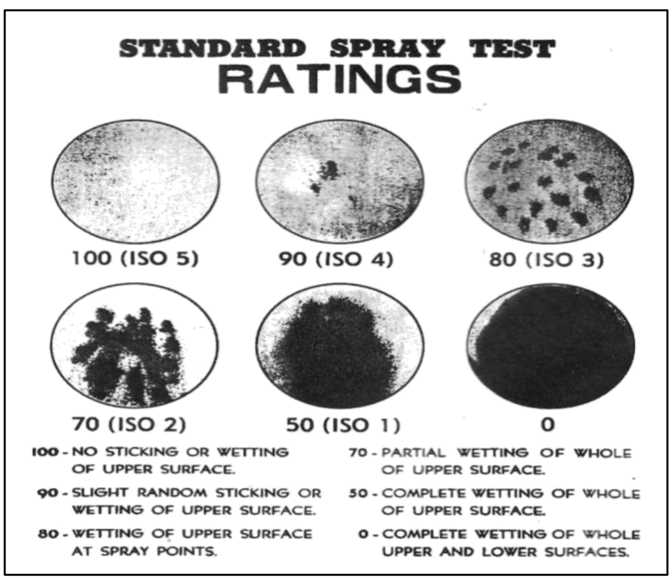

Figure 5. Spray test rating chart

4.2.2.3 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) was used to determine the statistical significance of variations. To deduce whether the variations of different properties before and after coating for the samples were either significant or not, P-value was examined. It was considered as a statistical significant change in the result if P-value was found less than 0.05 ($p < 0.05$), otherwise, there was no significant change.

5 Summary of the results achieved

5.1 Results and discussion for evaluation of different test results of PU membrane laminated fabrics

5.1.1 Morphological cross-section

Figure-6 shows the images of two-layered and three-layered samples obtained from scanning electron microscope (SEM). It gives a proper idea about the morphological cross-sections of six different types of PU membrane laminated sample fabrics prepared in the experiment. From the images, it is evident that FM-1, FM-2 and FM-3 are two-layered fabrics, where upper layers of all these three samples are outer polyester plain woven fabrics and lower layers are polyurethane membranes. On the other hand, FMK-4, FMK-5 and FMK-6 samples from the images are three-layered laminated fabrics. Here, upper layers of these samples are polyester plain woven fabrics, middle layers are polyurethane membranes and lower layers of these sample fabrics are inner polyester knitted fabrics.

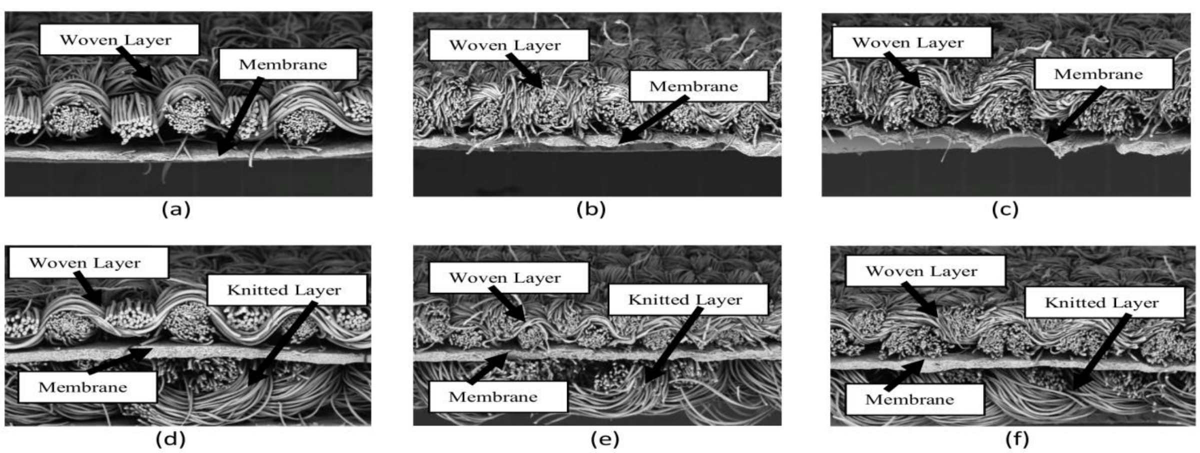

Figure 6. SEM images (x 200) of two-layered samples: (a) FM-1 (b) FM-2 (c) FM-3 and three-layered samples: (d) FMK-4 (e) FMK-5 (f) FMK-6.

5.1.2 Analysis of hydrostatic resistance

Breathability is meaningless without proper hydrostatic resistance. It is evident from the test results of hydrostatic resistance (Table-3), that all PU membrane laminated sample fabrics prepared in the experiment show the values more than 50000 N/m^2. These fabrics can be considered as good quality products and can be used as outdoor sports clothing. However, Pearson correlation coefficient (r) values during considering fabric weight and hydrostatic resistance are obtained +0.9985 and +0.9999 for two-layered and three-layered samples respectively from Table-9. This represents a strong positive relation between fabric weight and hydrostatic resistance of the sample fabrics which indicates that hydrostatic resistance of the sample is increased with the increase of fabric weight. Here, coefficient of determination (R^2) values are 0.9972 and 0.9999 for two-layered and three-layered samples respectively which denotes a good strength linear association between fabric weight and hydrostatic resistance of different samples. Again, in case of relation between fabric density and hydrostatic resistance, r-values are +0.9999 and +0.9981 for two-layered and three-layered samples respectively, whereas, R^2-values are obtained 0.9999 for two-layered samples and 0.9963 for three-layered samples from Table-10. This also indicates a strong positive relation between fabric density and hydrostatic resistance. However, r-value and R^2-value of three-layered samples are little bit higher than r-value and R^2-value of two-layered samples in case of relation between fabric weight and hydrostatic resistance. But, r-value and R^2-value are little bit higher for two-layered samples than r-value and R^2-value of three-layered samples in case of relation between fabric density and hydrostatic resistance.

Here, all three-layered samples show better hydrostatic resistance property than all two-layered samples. Because there are increases of fabric weight and fabric density for all three-layered samples when knitted fabrics are added as inner layers during their lamination process resulting in the increases of hydrostatic resistance values (Figure-7, 8, 9 & 10). Among the six samples, highest hydrostatic resistance property is obtained for FMK-4 sample due to its highest fabric weight and fabric density and lowest is found for FM-3 sample due to its lowest fabric weight and fabric density. When compared only two-layered three samples to each other, the best hydrostatic resistance is obtained for FM-1 sample and when compared only three-layered three samples to each other, the highest hydrostatic resistance is found for FMK-4 sample. The reason is that outer woven layer parts of FM-1 and FMK-4 samples are prepared by F-1 polyester woven fabric whose warp density and weft density as well as warp cover factor and weft cover factor are more than those of F-2 and F-3 polyester woven fabrics. These factors of outer woven layers of FM-1 and FMK-4 samples influence in resulting more hydrostatic resistance property.

Table 9. Correlation between fabric weight and hydrostatic resistance

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	HR=343.02FW + 12061 HR= Hydrostatic resistance FW= Fabric weight	+ 0.9985	0.9972
Three-layered samples	HR=348.41FW - 17313 HR= Hydrostatic resistance FW= Fabric weight	+ 0.9999	0.9999

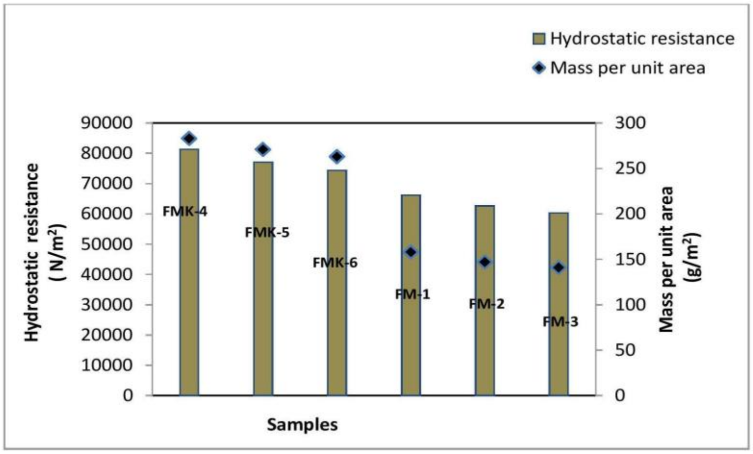

Figure 7. Fabric weight vs. hydrostatic resistance.

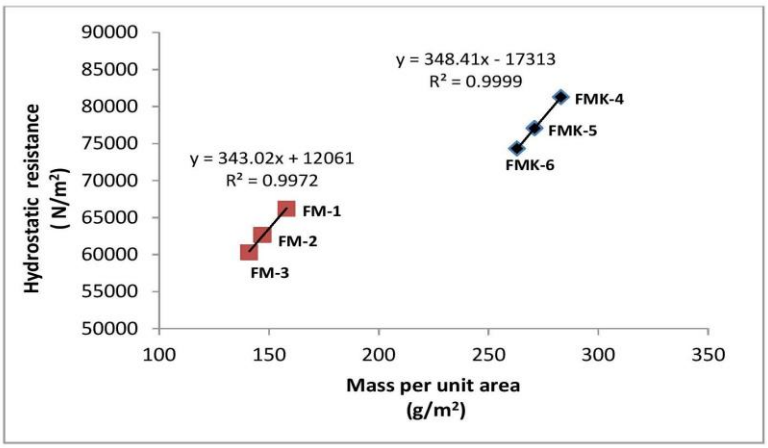

Figure 8. Effect of fabric weight on hydrostatic resistance for two-layered and three-layered samples.

Table 10. Correlation between fabric density and hydrostatic resistance

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	HR=401.72FD - 84941 HR= Hydrostatic resistance FD= Fabric density	+ 0.9999	0.9999
Three-layered samples	HR=391.22FD - 79077 HR= Hydrostatic resistance FD= Fabric density	+ 0.9981	0.9963

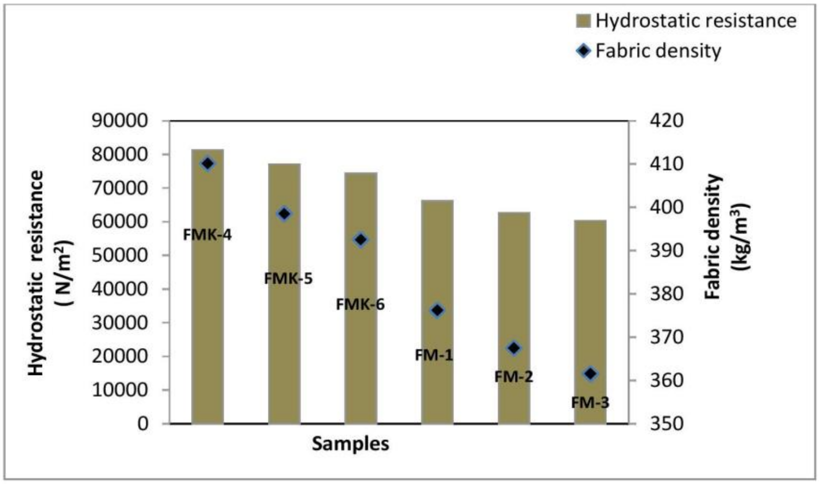

Figure 9. Fabric density vs. hydrostatic resistance.

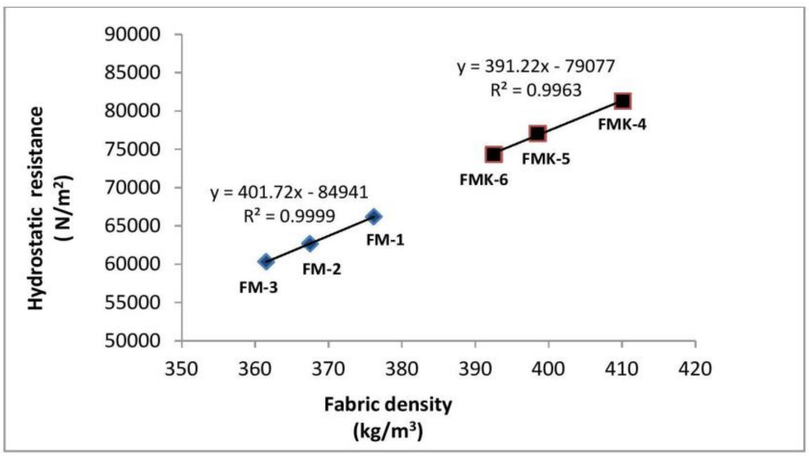

Figure 10. Effect of fabric density on hydrostatic resistance for two-layered and three-layered samples.

5.1.3 Analysis of water vapour permeability

Water vapour permeability of a fabric is obtained by measuring relative water vapour permeability (RWVP) and evaporative resistance (R_{et}). Increased RWVP and decreased R_{et} values determine the higher water vapour transmission of the measuring samples. R_{et} represents the water vapour pressure difference between the two sides of the specimen divided by the resultant evaporative heat flux per unit area in the direction of the gradient as the unit of m^2Pa/W. The obtained R_{et} values of all prepared PU membrane laminated samples are between 6-10 m^2Pa/W (Table-3). This means that all the prepared samples are good breathable fabrics. From Table-11, r-value and R^2-value are -0.9985 and 0.9972 respectively for two-layered samples, whereas, r-value and R^2-value are -0.9865 and 0.9732 respectively for three-layered samples when correlation between fabric weight and RWVP is considered. This represents a negative strong relationship between fabric weight and RWVP as well as denotes a good linear relationship between them. On the other hand, from Table-13, r-value and R^2-value are +0.9983 and 0.9967 respectively for two-layered samples, whereas, r-value and R^2-value are +0.9958 and 0.9918 respectively for three-layered samples when correlation between fabric weight and evaporative resistance is considered. This represents a positive strong linear relationship between fabric weight and evaporative resistance. Laminated sample fabric becomes more comfortable when the fabric weight is lower, as there is an increase of RWVP or a decrease of evaporative resistance with the decrease of fabric weight.

Again, from Table-12, r-value and R^2-value are found -0.9972 and 0.9944 respectively for two-layered samples, whereas, r-value and R^2-value are obtained -0.9987 and 0.9976 respectively for three-layered samples which indicates a good negative relationship between fabric thickness and RWVP. But, from Table-14, r-value and R^2-value are +0.9968 and 0.9937 respectively for two-layered samples, whereas, r-value and R^2-value are +0.9997 and 0.9994 respectively for three-layered samples that expresses a positive good relationship between fabric thickness and evaporative resistance. Here, laminated sample fabric becomes more comfortable with the decrease of fabric thickness, as there is an increase of RWVP and a decrease of evaporative resistance with the decrease of fabric thickness.

Table 11. Correlation between fabric weight and relative water vapour permeability

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	RWVP= -0.1865FW + 74.86 RWVP= Relative water vapour permeability FW= Fabric weight	- 0.9985	0.9972
Three-layered samples	RWVP= -0.1717FW + 87.88 RWVP= Relative water vapour permeability FW= Fabric weight	- 0.9865	0.9732

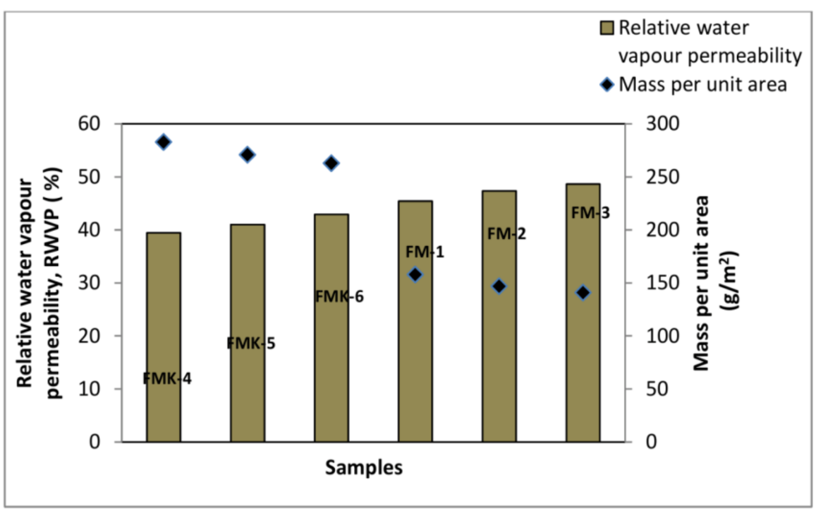

Figure 11. Fabric weight vs. relative water vapour permeability.

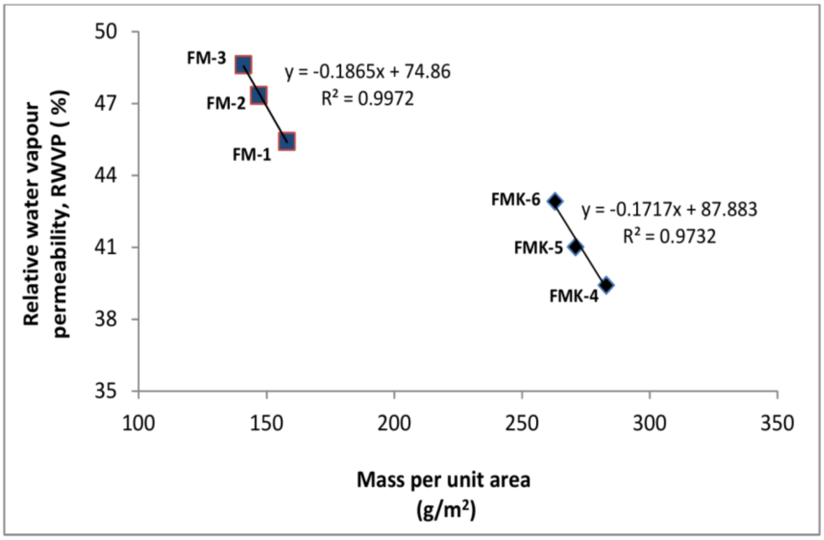

Figure 12. Effect of fabric weight on relative water vapour permeability for two-layered and three-layered samples.

Table 12. Correlation between fabric thickness and relative water vapour permeability

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	RWVP= -105.14FT + 89.53 RWVP= Relative water vapour permeability FT= Fabric thickness	- 0.9972	0.9944
Three-layered samples	RWVP= -175FT + 160.12 RWVP= Relative water vapour permeability FT= Fabric thickness	- 0.9987	0.9976

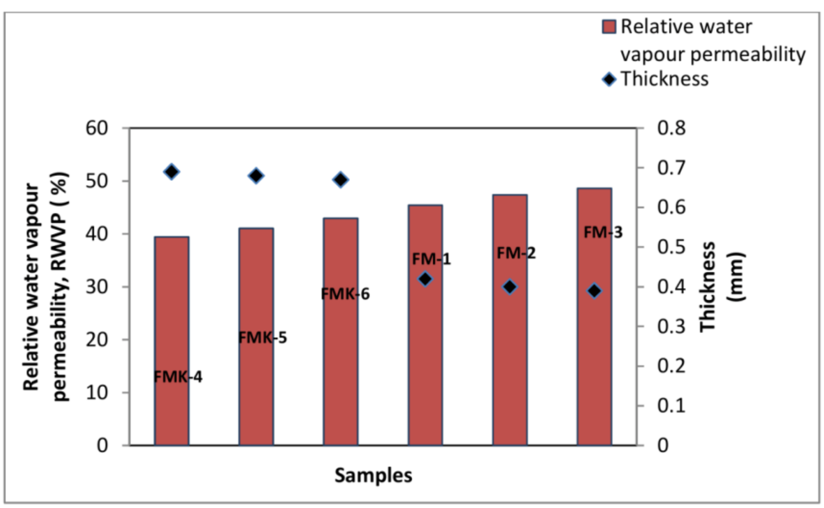

Figure 13. Fabric thickness vs. relative water vapour permeability.

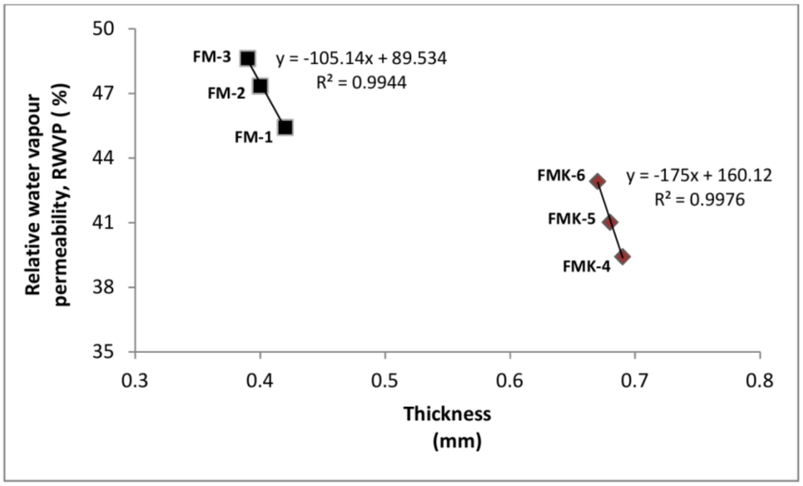

Figure 14. Effect of fabric thickness on relative water vapour permeability for two-layered and three-layered samples.

Table 13. Correlation between fabric weight and evaporative resistance

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	ER= 0.0606FW – 2.12 ER= Evaporative resistance FW= Fabric weight	+ 0.9983	0.9967
Three-layered samples	ER= 0.0475FW – 4.24 ER= Evaporative resistance FW= Fabric weight	+ 0.9958	0.9918

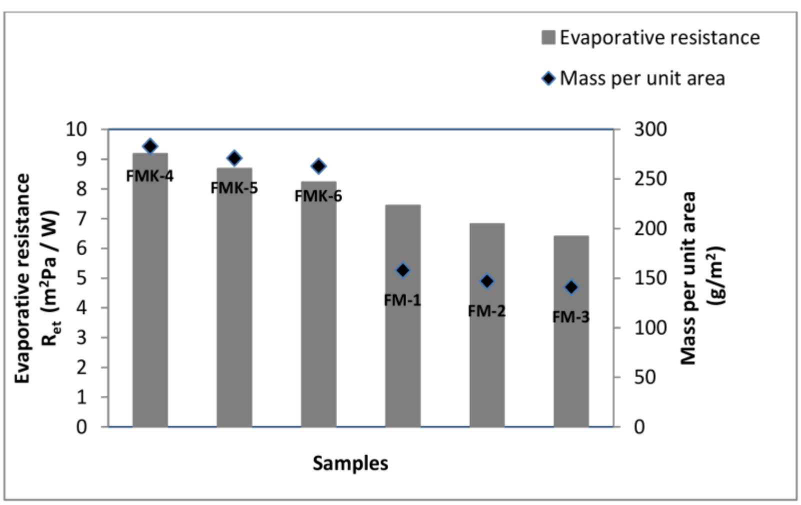

Figure 15. Fabric weight vs. evaporative resistance.

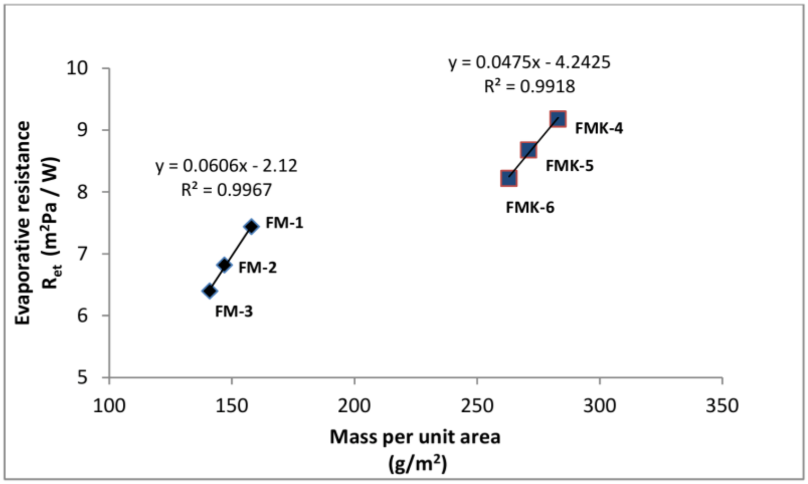

Figure 16. Effect of fabric weight on evaporative resistance for two-layered and three-layered samples.

Table 14. Correlation between fabric thickness and evaporative resistance

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	ER= 34.143FT – 6.884 ER= Evaporative resistance FT= Fabric thickness	+ 0.9968	0.9937
Three-layered samples	ER= 48FT – 23.947 ER= Evaporative resistance FT= Fabric thickness	+ 0.9997	0.9994

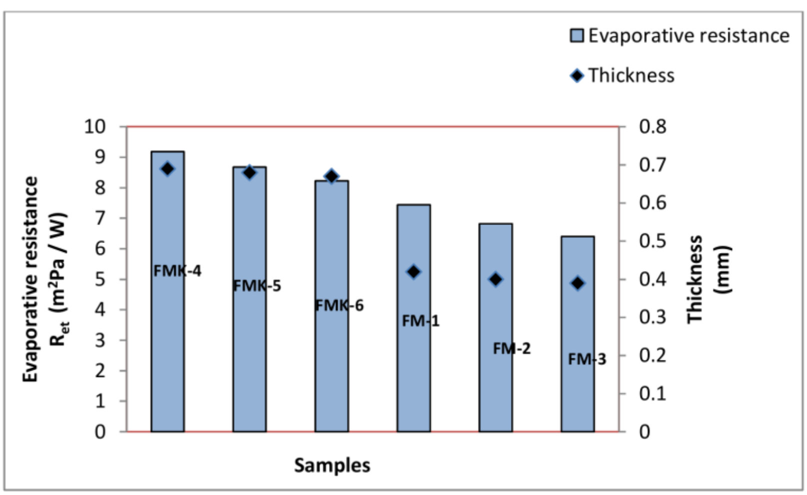

Figure 17. Fabric thickness vs. evaporative resistance.

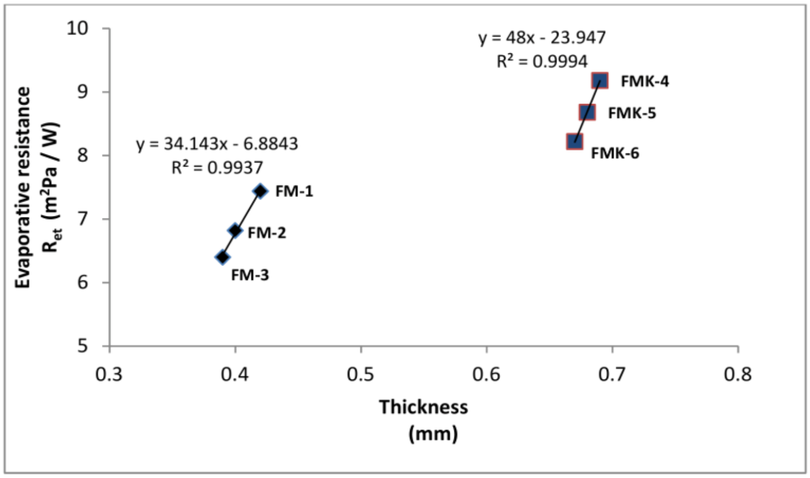

Figure 18. Effect of fabric thickness on evaporative resistance for two-layered and three-layered samples.

From the Figures (11, 12, 13 & 14), it is evident that relative water vapour permeability of the two-layered sample fabrics are higher than relative water vapour permeability of the three-layered fabrics. And from the Figures (15, 16, 17 & 18), it is clear that evaporative resistance of three-layered samples are higher than evaporative resistance of two-layered samples. Because, when polyester knitted fabrics are added as inner layers in all three-layered samples, then fabric weight and fabric thickness of these samples are also increased resulting in less relative water vapour permeability and more evaporative resistance during comparison with two-layered samples. However, among all the samples, highest relative water vapour permeability and lowest evaporative resistance are obtained in case of sample FM-3 with lowest fabric weight and thickness. This sample is prepared with F-3 polyester woven fabric as an outer layer whose fabric weight is also lower than the fabric weights of F-1 and F-2 polyester woven fabrics due to its lower warp and weft cover factor. On the other hand, lowest relative water vapour permeability and highest evaporative resistance are obtained for the sample FMK-4 due to its highest fabric weight and thickness among all fabrics. Moreover, this sample is produced by F-1 polyester woven fabric as an outer layer whose weight is higher than the weights of F-2 and F-3 polyester woven fabrics due to its higher warp and weft cover factor.

5.1.4 Analysis of air permeability

From Table-15, in case of correlation between fabric thickness and air permeability, r-value and R^2-value are -0.9999 and 0.9999 respectively for two-layered samples, whereas, r-value and R^2-value are -0.9689 and 0.9389 respectively for three-layered samples which indicates that there is a good negative linear relationship between fabric thickness of the laminated samples and their air permeability. Again, from Table-16, r-value is -0.9970 and R^2-value is 0.9940 for two-layered samples, whereas, r-value is -0.9977 and R^2-value is 0.9955 for three-layered samples in case of correlation between fabric density and air permeability. This indicates that there is a good negative linear relationship between fabric density and air permeability of the sample fabrics. From the result analysis, it can be said that air permeability of the laminated samples here decreases with the increase of fabric thickness and fabric density, but air permeability increases with the decrease of fabric thickness and fabric density of the samples.

Table 15. Correlation between fabric thickness and air permeability

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	AP= -20.643FT + 10.639 AP= Air permeability FT= Fabric thickness	- 0.9999	0.9999
Three-layered samples	AP= -21.5FT + 16.287 AP= Air permeability FT= Fabric thickness	- 0.9689	0.9389

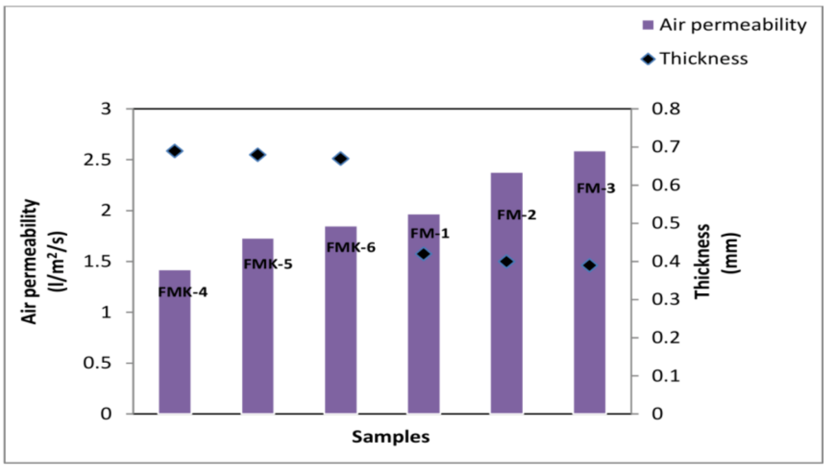

Figure 19. Fabric thickness vs. air permeability.

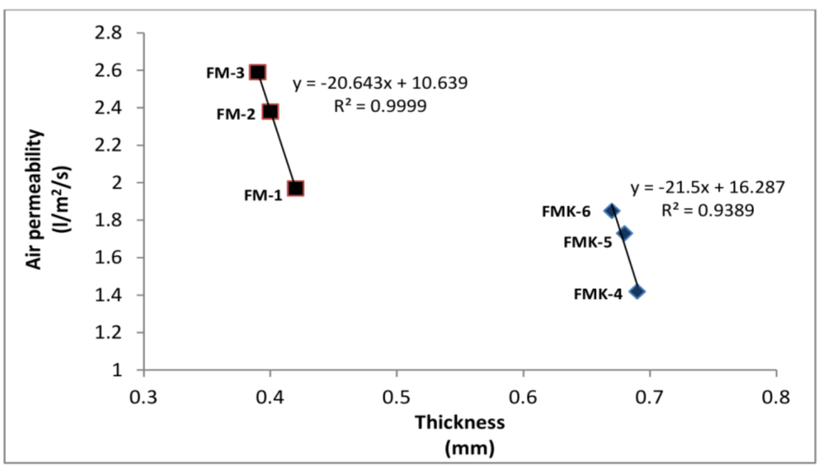

Figure 20. Effect of fabric thickness on air permeability for two-layered and three-layered samples.

Table 16. Correlation between fabric density and air permeability

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	AP= -0.0426FD + 18.025 AP= Air permeability FD= Fabric density	- 0.9970	0.9940
Three-layered samples	AP= -0.0247FD + 11.573 AP= Air permeability FD= Fabric density	- 0.9977	0.9955

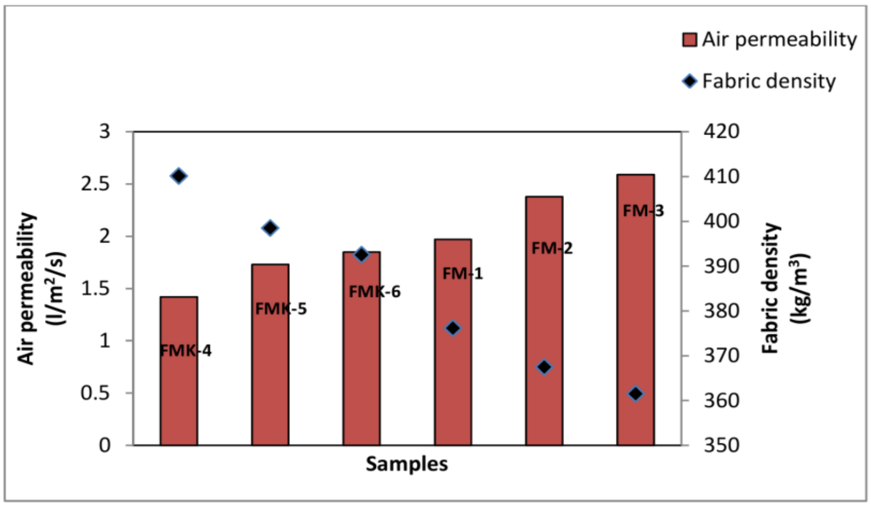

Figure 21. Fabric density vs. air permeability.

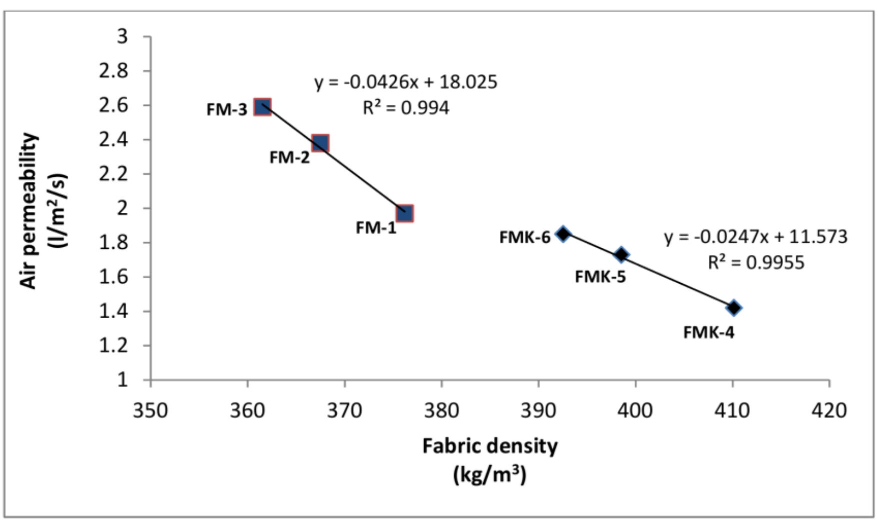

Figure 22. Effect of fabric density on air permeability for two-layered and three-layered samples.

Among all the samples, two-layered samples have more air permeability than three-layered samples. The reason is when knitted layer is added as an inner layer for each of three-layered samples then, both fabric thickness and fabric density also increase resulting in less air permeability than two-layered laminated sample fabrics. Moreover, due to use of knitted layer for each three-layered sample, there is more air entrapment that also causes less air permeability. So, fabric air permeability with membrane is attributed here due to higher compactness and air entrapment that offer resistance to the passage of air. From the Figures (19, 20, 21 & 22), it can be observed that FM-3 sample has the highest air permeability value among all the samples for its lowest fabric thickness and density. Moreover, its outer woven layer part is F-3 polyester woven fabric whose warp cover factor and weft cover factor are lower than the cover factors of F-1 and F-2 polyester woven fabrics. On the other hand, lowest air permeability is obtained for FMK-4 sample due to its highest fabric thickness and density as well as its outer woven layer part is F-1 polyester woven fabric whose warp cover factor and weft cover factor are more than the cover factors of F-2 and F-3 polyester woven fabrics. Outer layer parts of two-layered FM-1 sample and three-layered FMK-4 sample are prepared with F-1 polyester woven fabric, but air permeability value for FM-1 is higher than FMK-4 due to its lower fabric thickness and density.

5.1.5 Analysis of thermal resistance

Thermal resistance can be defined as a measure of the body's ability to prevent heat from flowing through it. Under a certain condition of climate, if the thermal resistance of clothing is low, the heat energy will gradually reduce with a sense of coolness [49]. Thermal conductivity and thermal resistance are opposite to each other. If thermal resistance of a fabric increases, thermal conductivity decreases. For ideal conditions, thermal resistance, $R = h / \lambda$, where h is thickness and λ is thermal conductivity of the fabric. However, from Table-17, r-value is +0.9934 and R^2-value is 0.9869 for two-layered samples, whereas, r-value and R^2-value are +0.9853 and 0.9709 respectively for three-layered samples in case of correlation between fabric thickness and thermal resistance. This indicates a good positive linear relationship between fabric thickness and thermal resistance property of the samples. It means that thermal resistance of the sample fabric increases with the increase of fabric thickness.

Table 17. Correlation between fabric thickness and thermal resistance

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	TR= 94.571FT – 25.817 TR= Thermal resistance FT= Fabric thickness	+ 0.9934	0.9869
Three-layered samples	TR= 140FT – 77.38 TR= Thermal resistance FT= Fabric thickness	+ 0.9853	0.9709

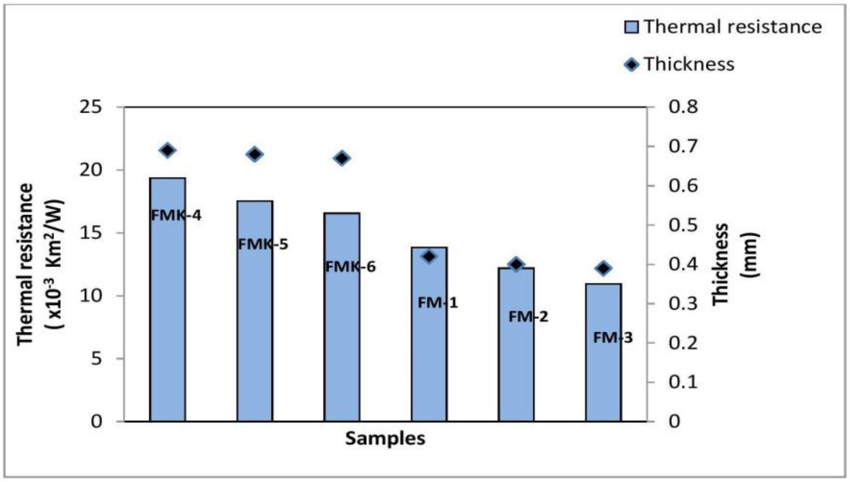

Figure 23. Fabric thickness vs. thermal resistance.

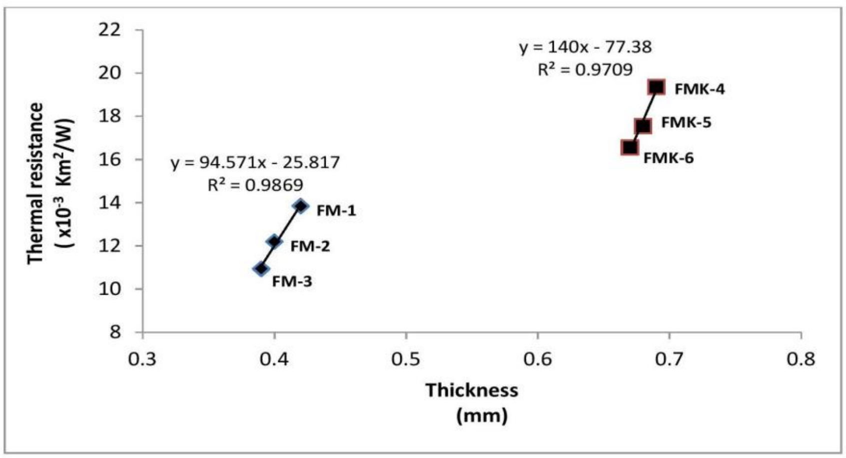

Figure 24. Effect of fabric thickness on thermal resistance for two-layered and three-layered samples.

Among all the six samples, highest thermal resistance is obtained for FMK-4 sample due to its highest thickness value and lowest thermal resistance value is obtained in case of sample FM-3 for its lowest thickness value obtained from Figure-23 and Figure-24. All three-layered samples have more thermal resistance than all two-layered samples. Because when knitted fabric is added during lamination process, thickness of the three-layered fabric also increases. Moreover, due to knitted part, there are more air gaps between fibers which decrease the heat transfer with increasing thermal resistance. So, these three-layered fabrics with better thermal resistance are more suitable than two-layered fabrics in comparatively cold condition.

5.1.6 Analysis of bending rigidity

Bending rigidity represents the fabric stiffness property. Very stiff fabric can be uncomfortable and unfit for use. It is evident from Figure-25 and Figure-26 that thickness is the determining factor which influences on bending rigidity of the layered laminated fabric samples. From Table-18, r-value is +0.9999 and R^2-value is 0.9999 for two-layered samples as well as r-value and R^2-value are

+0.9989 and 0.9978 respectively for three-layered samples when correlation between fabric thickness and bending rigidity is considered. This clearly determines a strong positive influence of thickness of the sample fabrics on their bending rigidity.

Table 18. Correlation between fabric thickness and bending rigidity

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	BR= 29.357FT + 0.3393 BR= Bending rigidity FT= Fabric thickness	+ 0.9999	0.9999
Three-layered samples	BR= 37FT – 4.23 BR= Bending rigidity FT= Fabric thickness	+ 0.9989	0.9978

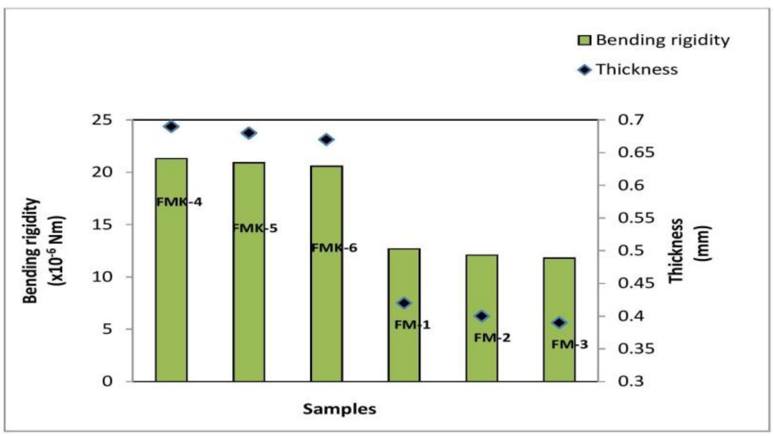

Figure 25. Fabric thickness vs. bending rigidity.

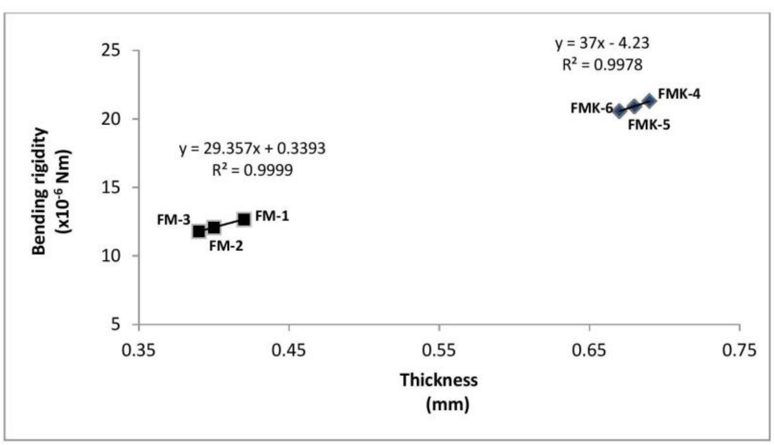

Figure 26. Effect of fabric thickness on bending rigidity for two-layered and three-layered samples.

However, bending rigidity values of two-layered samples are lower than bending rigidity values of three-layered samples due to their lower thickness values than three-layered samples. Among all the samples, highest bending rigidity is obtained in case of sample FMK-4 due to its highest fabric thickness property. And lowest bending rigidity is found for the sample fabric FM-3 due to its lowest thickness property. When only two-layered three samples are compared to each other, higher bending rigidity is obtained for FM-1 sample due to its higher thickness value than FM-2 and FM-3 samples. Again, when only three-layered three samples are compared to each other, lower bending rigidity is found in case of sample FMK-6 due to its lower thickness value than the rest two other samples FMK-4 and FMK-5.

5.1.7 Analysis of breaking strength

In the experiment, breaking force was measured to evaluate the breaking strength property of the sample fabrics because users are aware of this property. However, r-value and R^2-value are +0.9993 and 0.9985 respectively for two-layered samples, but r-value is +0.9999 and R^2-value is 0.9999 for three-layered samples when correlation between fabric weight and breaking force is considered in Table-19. These results represent a strong positive relation between fabric weight and breaking force of the laminated sample fabrics. Again, from Table-20, r-value and R^2-value are +0.9997 and 0.9995 respectively for two-layered samples, whereas, r-value and R^2-value are +0.9983 and 0.9967 respectively for three-layered samples in case of correlation between fabric density and breaking force. This also explains a strong positive linear relationship between fabric density and breaking force of the sample fabrics. So, it can be said from this statistical analysis that breaking strength of the laminated fabric increases with the increase of fabric weight and fabric density.

However, from the test results (Table-3) and Figures (27, 28, 29 & 30), it is clear that breaking forces for all three-layered samples are more than breaking forces of all two-layered samples. This is because of increasing fabric weight and fabric density of three-layered three samples after adding polyester knitted fabrics as their inner layers during lamination process. Among the all six samples, highest breaking force value is obtained for FMK-4 sample due to its highest fabric weight and density and lowest is obtained for FM-3 sample due to its lowest fabric weight and density. When only two-layered three samples are compared to each other, the best breaking force is obtained for FM-1 sample. Here the reason is not only the fabric weight and fabric density, but also the warp

Table 19. Correlation between fabric weight and breaking force

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	BF= 1.8117FW + 87 BF= Breaking force FW= Fabric weight	+ 0.9993	0.9985
Three-layered samples	BF= 2.3026FW – 200.75 BF= Breaking force FW= Fabric weight	+ 0.9999	0.9999

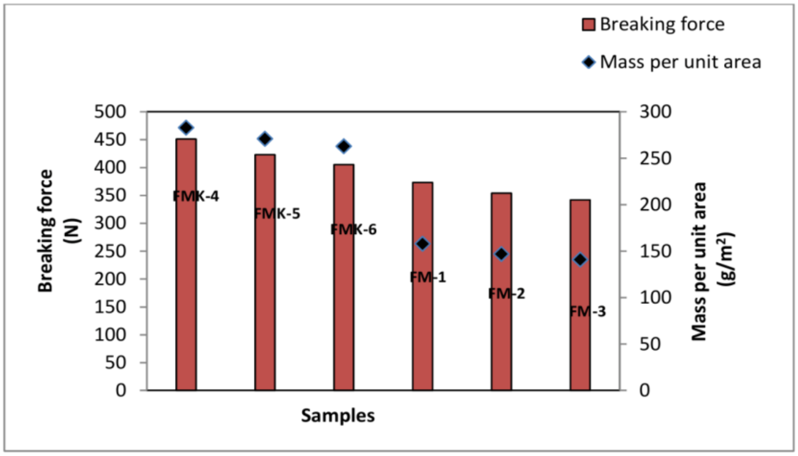

Figure 27. Fabric weight vs. breaking force.

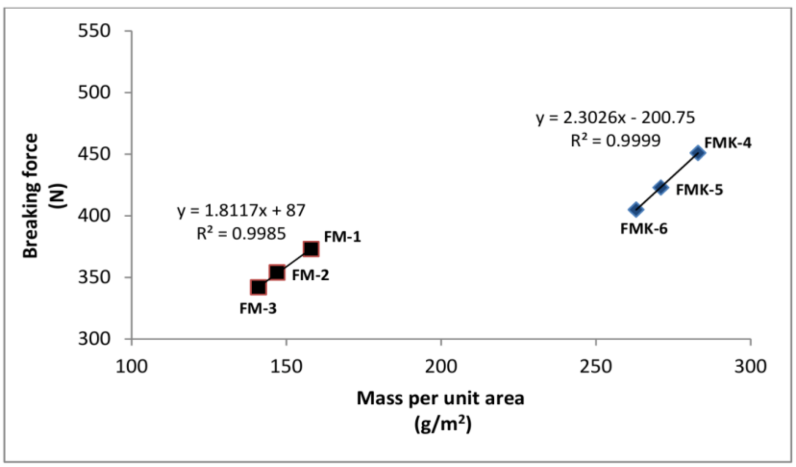

Figure 28. Effect of fabric weight on breaking force for two-layered and three-layered samples.

Table 20. Correlation between fabric density and breaking force

Type of samples	Correlation equation	Pearson correlation coefficient (r)	Coefficient of determination (R^2)
Two-layered samples	BF= 2.1198FD – 424.62 BF= Breaking force FD= Fabric density	+ 0.9997	0.9995
Three-layered samples	BF= 2.5862FD – 609.19 BF= Breaking force FD= Fabric density	+ 0.9983	0.9967

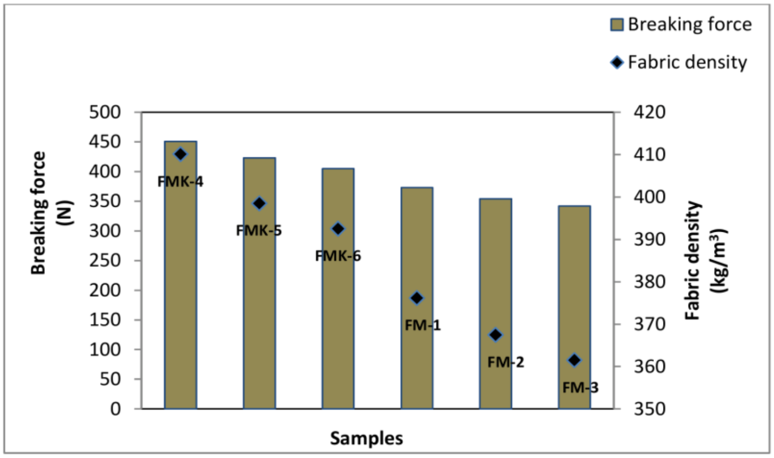

Figure 29. Fabric density vs. breaking force.

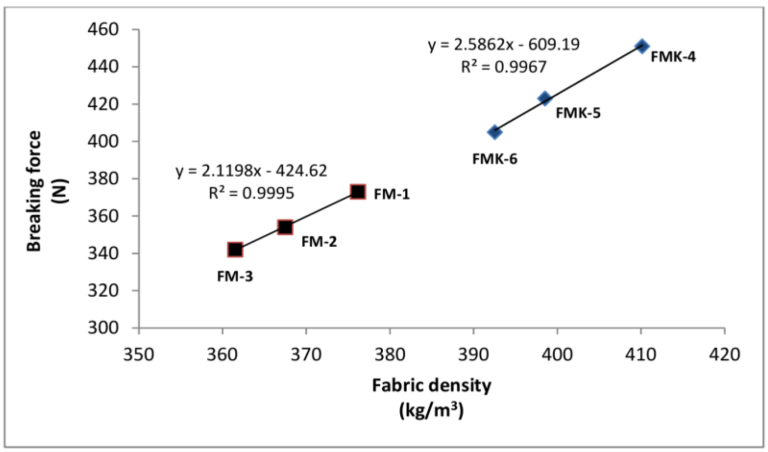

Figure 30. Effect of fabric density on breaking force for two-layered and three-layered samples.

cover factor and weft cover factor of outer layer woven part of FM-1 sample that are higher than the cover factors of outer layer parts of FM-2 and FM-3 samples. Again, when only three-layered three samples are compared to each other, the best breaking force is obtained for FMK-4 sample. The reason is also here not only the fabric weight and density, but also warp cover factor and weft cover factor of outer layer woven part of FMK-4 sample that are higher than the cover factors of outer layer woven parts of FMK-5 and FMK-6 samples.

5.2 Results and discussion for evaluation of enhanced hydrostatic resistance and mechanical performance of PTFE membrane laminated fabrics

5.2.1 Analysis of test results for WMK-2 sample fabric after coating

5.2.1.1 Analysis of coating for WMK-2 sample fabric

Table-5 shows the different characteristics of WMK-2 sample fabric which was coated under different mixing ratios of C_6-based fluorocarbon chemical (®RUCOSTAR EEE6) and polysiloxane hydrophobic softening agent (®RUCOFIN HSF) according to T-2, T-3, T-4, T-5, T-6 and T-7. In case of T-2, T-3 and T-4 samples, 40 g/L, 50 g/L and 60 g/L ®RUCOSTAR EEE6 are respectively added with 15 g/L ®RUCOFIN HSF. Here, fabric density and increase in percentage for areal density after coating are higher for T-3 sample than T-2 and T-4 samples. More liquor penetration for T-3 sample is the reason here. On the other hand, in case of T-5, T-6 and T-7 samples, 40 g/L, 50 g/L and 60 g/L ®RUCOSTAR EEE6 are respectively added with 20 g/L ®RUCOFIN HSF. Here, fabric density and increase in percentage for areal density after coating is higher for T-5 sample than T-6 and T-7 samples because of more liquor penetration for T-5 sample. Again, when 60 g/L ®RUCOSTAR EEE6 is added with 15 g/L ®RUCOFIN HSF (T-4 sample) and 60 g/L ®RUCOSTAR EEE6 is added with 20 g/L ®RUCOFIN HSF (T-7 sample), then increases in percentage for areal density after coating are 5.99% and 5.39% respectively due to their lower penetration of liquor than other samples. However, among all the samples, the highest increase in percentage for areal density after coating is obtained 10.78% for T-3 sample. Consequently, highest fabric density is also obtained for T-3 sample after coating.

5.2.1.2 Water-repellent property for coated WMK-2 sample fabric

Water repellent property is one of the important properties for outdoor sports fabrics. More water-repellent property of a fabric shows more resistant property against the wetting by water. In spray test results, there are six ratings shown in a photographic chart according to AATCC 22 method [47]. A specimen with complete wetting of the entire face is assigned by “0” rating, while a specimen with no sticking or wetting of the face is assigned by “100” rating. The rest four ratings are in between “0” to “100” ratings. After coating of WMK-2 sample with different mixing ratios, spray test ratings are obtained like the following:

Table 21. Spray test ratings of coated WMK-2 sample with different mixing ratios

Sample fabric	Spray rating
T-2 (40 g/L ®RUCOSTAR EEE6 with 15 g/L ®RUCOFIN HSF)	100
T-3 (50 g/L ®RUCOSTAR EEE6 with 15 g/L ®RUCOFIN HSF)	100
T-4 (60 g/L ®RUCOSTAR EEE6 with 15 g/L ®RUCOFIN HSF)	90
T-5 (40 g/L ®RUCOSTAR EEE6 with 20 g/L ®RUCOFIN HSF)	100
T-6 (50 g/L ®RUCOSTAR EEE6 with 20 g/L ®RUCOFIN HSF)	100
T-7 (60 g/L ®RUCOSTAR EEE6 with 20 g/L ®RUCOFIN HSF)	90

5.2.1.3 Analysis of other properties for WMK-2 sample fabric after coating with different mixing ratios

From the analysis of test results, the highest increase in percentage for areal density after coating is found for T-3 sample and consequently, highest fabric density is also obtained for T-3 sample after coating. As a result, highest increase of hydrostatic resistance is obtained in case of sample T-3 (Figure-31) and highest breaking force is also found for T-3 sample (Figure-32), when the test results of WMK-2 coated samples with different mixing ratios are compared. Here, T-4 sample has lower hydrostatic resistance and breaking force than T-3 sample. The reason is higher liquor penetration for T-3 sample than T-4 sample which results in higher areal density and higher fabric density for T-3 sample. Again, lower areal density and lower fabric density are obtained in case of samples T-4 and T-7 among all samples due to their lower liquor penetration when 60 g/L ®RUCOSTAR EEE6 is mixed with 15 g/L ®RUCOFIN HSF and 60 g/L ®RUCOSTAR EEE6 is mixed with 20 g/L ®RUCOFIN HSF respectively. However, after coating, bending rigidity is also found higher for T-3 sample (Figure-33), but not so big differences in values are found. On the other hand, after coating the evaporative resistance values range from 8.52 to 8.84 m^2Pa/W (Figure-34) and this indicates no big differences in evaporative resistance values after coating. And from Figure-35, no big differences are obtained in air permeability values for WMK-2 sample after coating with different mixing ratios.

After analysis of all above test results for coated WMK-2 sample fabric with different mixing ratios, it has been found that the mixing ratio of T-3 sample gives the best results. As a result, this ratio, i.e., 50 g/L ®RUCOSTAR EEE6 with 15 g/L ®RUCOFIN HSF was selected as a standard recipe for coating other three-layered PTFE membrane laminated waterproof breathable fabrics, like, WMK-1, WMF-3 and WMF-4 samples.

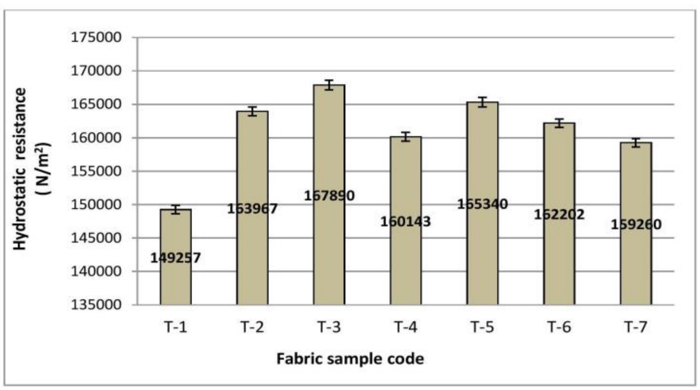

Figure 31. Hydrostatic resistance after coating with different ratios for WMK-2 sample.

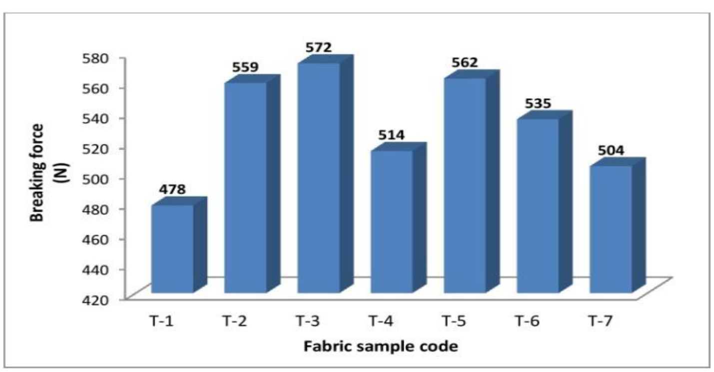

Figure 32. Breaking force after coating with different ratios for WMK-2 sample.

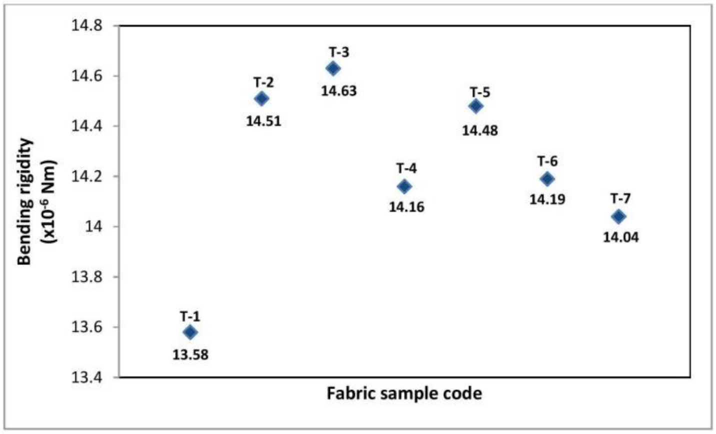

Figure 33. Bending rigidity after coating with different ratios for WMK-2 sample.

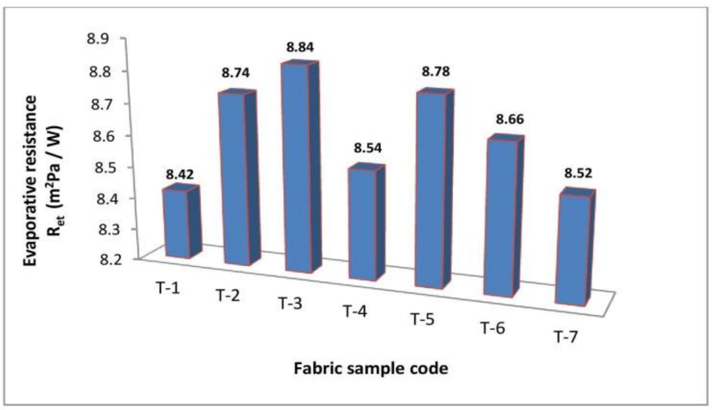

Figure 34. Evaporative resistance after coating with different ratios for WMK-2 sample.

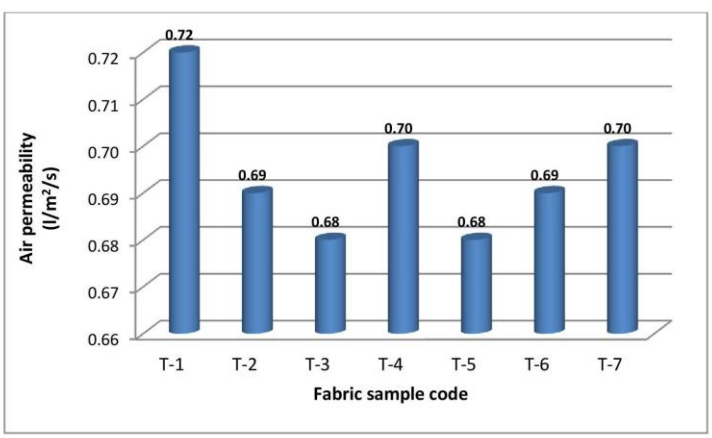

Figure 35. Air permeability after coating with different ratios for WMK-2 sample

5.2.2 Evaluation of test results for PTFE membrane laminated four different types of samples after coating

5.2.2.1 Analysis of applied coating

Coating solution that was applied on four different types of PTFE membrane laminated fabrics, was prepared with 50 g/L C_6-based fluorocarbon water-repellent chemical (®RUCOSTAR EEE6) and 15 g/L polysiloxane hydrophobic softening agent (®RUCOFIN HSF). Among the four samples, WMK-1 and WMK-2 are more densely fabrics. WMK-2 is more densely than WMK-1 due to its more densely outer woven layer and inner knitted layer. WMF-3 and WMF-4 are less densely due to their higher thickness and inner fleece knitted structures. Higher increases in areal density (g/m^2) after coating are obtained in case of WMK-1 and WMK-2 which are 11.24% and 10.78% increases respectively (Table-7). On the other hand, 7.96% and 7.46% increases are found for the samples of WMF-3 and WMF-4. The reason for less increase in this case may be due to their inner fleece knitted structures which cannot hold the coating solution as properly as the first two samples. However, fabric thickness values of all four fabrics also increase after coating and these values influence on their total fabric density values as well.

5.2.2.2 Morphology and water-repellent property

Scanning electron microscope (SEM) gives a proper idea about morphological cross-sectional images of four different laminated fabrics before and after coating. It is evident from the images that WMK-1, WMK-2, WMF-3 and WMF-4 have three layers and their membranes are between outer and inner layers (Figure-36). However, the coated samples show more regular and smooth surfaces under scanning electron microscope. This is due to the evenly deposition of coating materials on the fabric layers, as a result, individual yarns within the fabrics are more strongly attached to each other which can contribute to the higher resistance against water pressure as well as can increase their breaking strength.

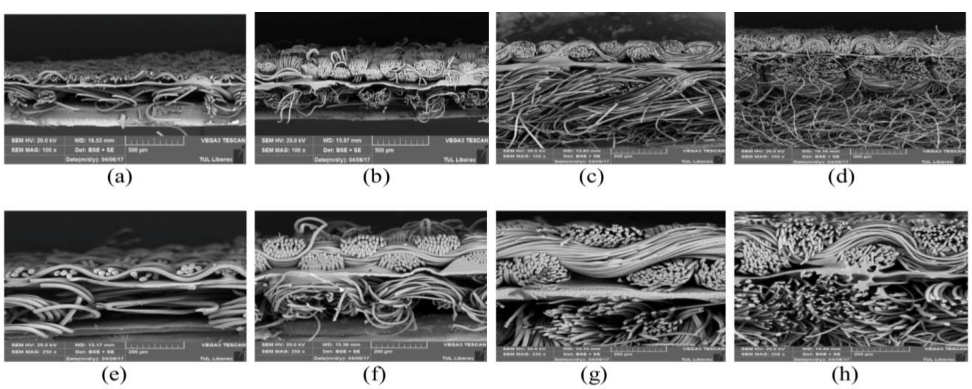

Figure 36. SEM images of uncoated samples: (a) WMK-1 (b) WMK-2 (c) WMF-3 (d) WMF-4 and coated samples: (e) WMK-1 (f) WMK-2 (g) WMF-3 (h) WMF-4.

Water-repellent property of four different types of laminated sample fabrics was measured by the evaluation of spray test results according to AATCC 22 method [47]. At first, all four coated samples showed "100" rating. Then all four coated samples were washed with 4 g/l detergent at 40°C for 1 hour. After five washes, water-repellent property was again evaluated by spray test results. Here also all the four samples showed "100" rating because of complete non-wetting property of the coated fabrics.

5.2.2.3 Comparison of hydrostatic resistance

From Figure-37, it is evident that there is a good positive relation between fabric density and hydrostatic resistance. Hydrostatic resistance increases with the increase of fabric density in case of both coated and uncoated fabrics. Highest hydrostatic resistance is obtained for WMK-2 sample in both cases (Table-8). This is due to its higher fabric density and more compact structure than any other sample. For example, warp cover factor and weft cover factor of its outer woven part and stitch density of its inner knitted part are denser than any other PTFE membrane laminated fabric sample. Hydrostatic resistance values of WMF-3 and WMF-4 are less than the hydrostatic resistance values of others. The reason is their lower fabric density. Moreover, their inner fleece knitted parts cannot make higher resistance against water pressure, though their thickness values are higher than others. So, hydrostatic resistance is attributed here to fabric density as well as compactness of fabric structure. However, the comparisons between coated and uncoated samples from ANOVA of Table-22 express that there are significant increases of hydrostatic resistance after coating for all samples. Because, P-values for all samples are less than 0.05 and F-ratios are clearly higher than F-critical values. Increases of hydrostatic resistance after coating for WMK-1 and WMK-2 samples are 14906 N/m^2 and 18633 N/m^2 respectively which are about 10.38% and 12.48% increases from uncoated samples. About 9.66% increase for WMF-3 and 9.16% increase for WMF-4 are found after coating from hydrostatic resistance test results of Table-8. These are also significant increases after coating. So, it can be said that there are significant enhancement of hydrostatic resistance for all laminated sample fabrics after coating.

Table 22. ANOVA for hydrostatic resistance of coated and uncoated sample fabrics

Compared pairs (coated and uncoated)	Source of Variation	SS	df	MS	F-ratio	P-value	F -critical
WMK-1	Between Groups	34504.17	1	34504.17	444.26	2.995E-05	7.709
	Within Groups	310.66	4	77.66			
	Total	34814.83	5				
WMK-2	Between Groups	54150	1	54150	786.68	9.613E-06	7.709
	Within Groups	275.33	4	68.83			
	Total	54425.33	5				
WMF-3	Between Groups	16537.50	1	16537.50	351.86	4.756E-05	7.709
	Within Groups	188	4	47			
	Total	16725.50	5				
WMF-4	Between Groups	15606	1	15606	373.05	4.235E-05	7.709
	Within Groups	167.33	4	41.83			
	Total	15773.33	5				

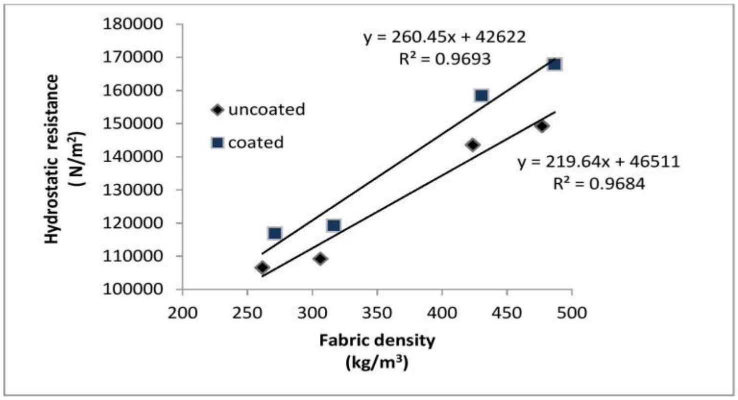

Figure 37. Hydrostatic resistance of coated and uncoated samples.

5.2.2.4 Comparison of breaking strength

Breaking strength test was performed to evaluate the mechanical property of the sample fabrics. Breaking strength was determined by breaking force. From the test results of Table-8, ANOVA of Table-23 and Figure-38, it is evident that there are significant increases of breaking strength of all samples after coating. Here, ANOVA table shows that F-ratios are higher than F-critical values and P-values are less than 0.05 in all fabrics when there are comparisons between coated and uncoated samples. The highest increase in breaking strength after coating among all samples is found for WMK-2 sample. Here, about 19.67% increase is obtained after coating because of its denser and more compact structure than others. About 16.34%, 15.73% and 14.78% increases are found in case of WMK-1, WMF-3 and WMF-4 samples respectively. From Figure-38, it is also clear that there is a positive relationship between fabric density and breaking strength. Breaking strength increases with the increase of fabric density and this trend is observed for both coated and uncoated samples. WMK-2 and WMK-1 samples show higher breaking strength property than WMF-3 and WMF-4 samples due to their higher fabric density values in both cases.

Table 23. ANOVA for breaking strength of coated and uncoated sample fabrics

Compared pairs (coated and uncoated)	Source of Variation	SS	df	MS	F-ratio	P-value	F -critical
WMK-1	Between Groups	11424.40	1	11424.40	179.21	9.27894E-07	5.318
	Within Groups	510	8	63.75			
	Total	11934.40	9				
WMK-2	Between Groups	21902.40	1	21902.40	271.57	1.85467E-07	5.318
	Within Groups	645.20	8	80.65			
	Total	22547.60	9				
WMF-3	Between Groups	8065.60	1	8065.60	83.32	1.67004E-05	5.318
	Within Groups	774.40	8	96.80			
	Total	8840	9				
WMF-4	Between Groups	8065.60	1	8065.60	65.55	4.00664E-05	5.318
	Within Groups	984.40	8	123.05			
	Total	9050	9				

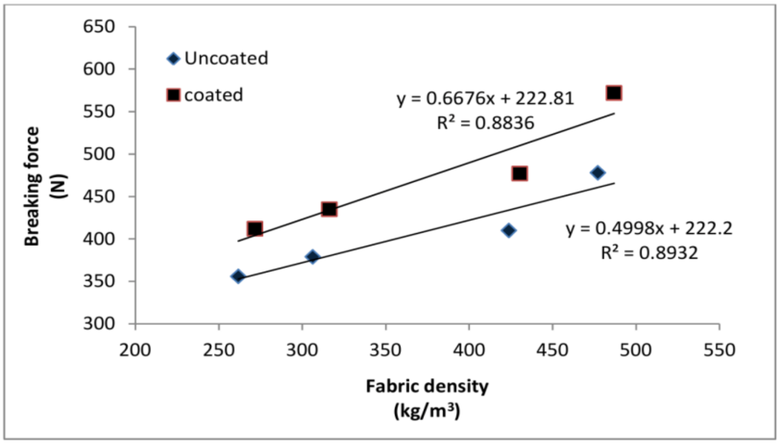

Figure 38. Breaking force of coated and uncoated samples.

5.2.2.5 Comparison of bending rigidity

Stiffness is a special property of a fabric to keep it standing without support. It is determined by bending rigidity which is an important comfort parameter. A fabric needs stiffness, but very stiff fabric can be uncomfortable and unfit for use. When coated and uncoated samples are compared, ANOVA from Table-24 shows that F-ratios are higher than F-critical values in case of all samples as well as P-values are less than 0.05. But, from bending rigidity test results of Table-8 and Figure-39, it can be said that increases of bending rigidity after coating are not as high as the increases of hydrostatic resistance and tensile strength after coating. Here, maximum increase is obtained 7.73% for WMK-2 sample after coating. 5.95%, 5.26% and 5.09% increases are found for WMK-1, WMF-3 and WMF-4 samples respectively. These results reveal that there are not much higher increases in stiffness property after coating because of using polysiloxane hydrophobic softening agent in the coating solution.

Table 24. ANOVA for bending rigidity of coated and uncoated sample fabrics

Compared pairs (coated and uncoated)	Source of Variation	SS	df	MS	F-ratio	P-value	F -critical
WMK-1	Between Groups	0.497	1	0.497	12.689	0.0073771	5.318
	Within Groups	0.314	8	0.039			
	Total	0.811	9				
WMK-2	Between Groups	2.809	1	2.809	138.682	2.474E-06	5.318
	Within Groups	0.162	8	0.020			
	Total	2.971	9				
WMF-3	Between Groups	5.169	1	5.169	175.063	1.015E-06	5.318
	Within Groups	0.236	8	0.029			
	Total	5.405	9				
WMF-4	Between Groups	5.127	1	5.127	292.112	1.396E-07	5.318
	Within Groups	0.140	8	0.018			
	Total	5.267	9				

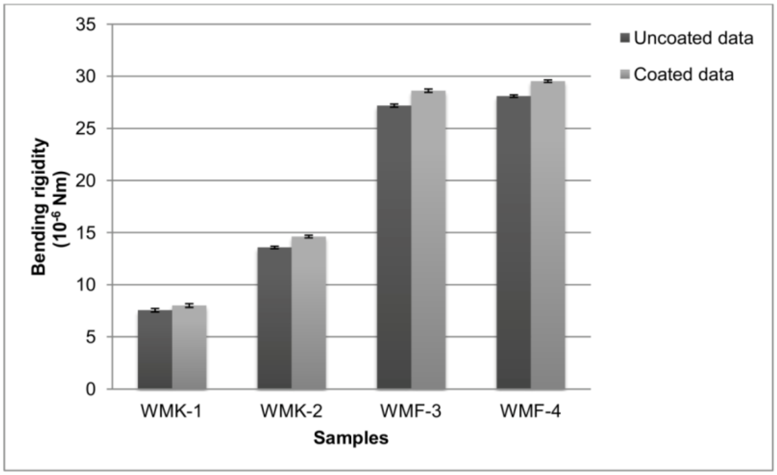

Figure 39. Bending rigidity of coated and uncoated samples

5.2.2.6 Comparison of water vapour permeability

By measuring evaporative resistance (R_{et}), water vapour permeability of a fabric is obtained. Higher R_{et} value determines the lower water vapour transmission of the measuring sample. The effect of fabric weight on water vapour permeability is shown in Figure-40 for both coated and uncoated samples. It is clear that R_{et} values of all samples increase with the increases of fabric weights in both cases. The fabric becomes uncomfortable with increasing the fabric weight and evaporative resistance. Among the four samples, WMF-3 and WMF-4 samples have the lower water vapour permeability due to their higher R_{et} values. The reason is their higher fabric weights and inner knitted fleece structures which cause more air entrapment preventing the diffusion rate of water vapour. As a result, it can be difficult to release sweat from the body in the form of water vapour. On the other hand, WMK-1 and WMK-2 samples show better water vapour permeability due to their lower fabric weights. Again, WMK-1 sample has less densely outer woven structure and less stitch density of inner knitted structure along with lower thickness and lower fabric weight which make it best water vapour permeable among all the samples. The more water vapour transmission of this fabric results in higher fabric breathability. From ANOVA of Table-25, it can be said that there are no significant changes in R_{et} values for all four samples after coating because F-ratios are lower than F-critical values and P-values are more than 0.05. The reason is that applied finish, like, hydrophobic water-repellent coating to a fabric has no great effect on the diffusion process [50]. As a result, no significant change in water vapour permeability is obtained after coating for any sample.

Table 25. ANOVA for evaporative resistance (R_{et}) of coated and uncoated sample fabrics

Compared pairs (coated and uncoated)	Source of Variation	SS	df	MS	F-ratio	P-value	F -critical
WMK-1	Between Groups	0.225	1	0.225	2.885	0.128	5.318
	Within Groups	0.624	8	0.078			
	Total	0.849	9				
WMK-2	Between Groups	0.441	1	0.441	4.20	0.075	5.318
	Within Groups	0.84	8	0.105			
	Total	1.281	9				
WMF-3	Between Groups	0.196	1	0.196	2.904	0.127	5.318
	Within Groups	0.54	8	0.068			
	Total	0.736	9				
WMF-4	Between Groups	0.144	1	0.144	1.882	0.207	5.318
	Within Groups	0.612	8	0.077			
	Total	0.756	9				

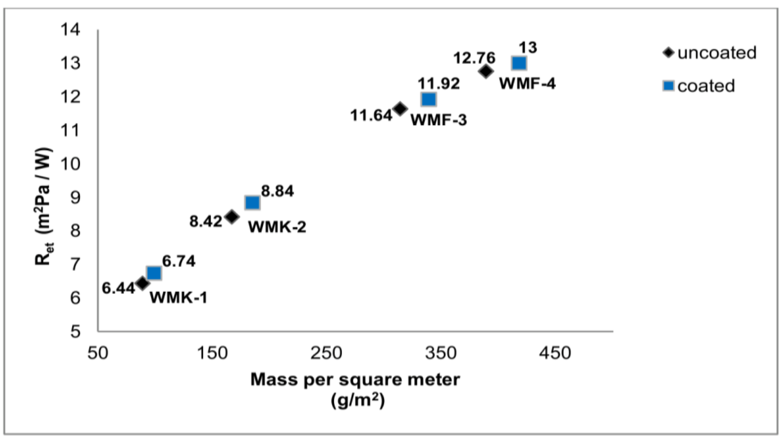

Figure 40. Evaporative resistance (R_{et}) of coated and uncoated samples

5.2.2.7 Comparison of air permeability

In order to determine the changes of air permeability after coating for all samples, analysis of variance of Table-26 and Figure-41 can be discussed. From ANOVA table, F-ratios of all samples are lower than F-critical values and P-values are more than 0.05 which indicates that there are no significant changes in air permeability after coating for all fabric samples. Figure-41 also reveals the same appearance that there are actually on big differences in air permeability between coated and uncoated samples. So, it can be said that the effects of applied water-repellent coating solution on air permeability of different PTFE laminated fabrics are not significant.

Table 26. ANOVA for air permeability of coated and uncoated sample fabrics

Compared pairs (coated and uncoated)	Source of Variation	SS	df	MS	F-ratio	P-value	F -critical
WMK-1	Between Groups	0.005	1	0.005	2.454	0.135	4.414
	Within Groups	0.035	18	0.002			
	Total	0.040	19				
WMK-2	Between Groups	0.008	1	0.008	3.113	0.095	4.414
	Within Groups	0.044	18	0.002			
	Total	0.052	19				
WMF-3	Between Groups	0.019	1	0.019	4.366	0.051	4.414
	Within Groups	0.082	18	0.005			
	Total	0.102	19				
WMF-4	Between Groups	0.019	1	0.019	3.793	0.067	4.414
	Within Groups	0.091	18	0.005			
	Total	0.110	19				

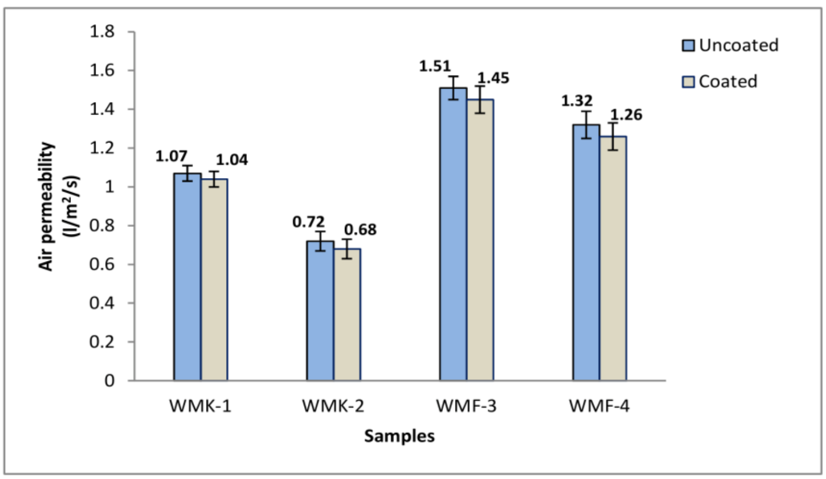

Figure 41. Air permeability of coated and uncoated samples.

6 Evaluation of results and new finding

This study newly designed and prepared microporous PU membrane laminated waterproof breathable fabrics with different layered structures that could be used as outdoor sports fabrics and their different properties, like, hydrostatic resistance, thermo-physiological comfort properties and mechanical behaviors were statistically analyzed. A novel approach of coating was applied in this study on four different types of PTFE membrane laminated different structured waterproof breathable fabrics. The following findings are drawn from the results of the experiment.

Hydrostatic resistance values of prepared two-layered and three-layered PU membrane laminated fabrics are obtained more than 50000 N/m^2 which indicates the fabrics as good quality products for using as outdoor sports clothing. Compactness of outer woven layers with different warp and weft cover factors make the laminated fabrics with different fabric weights and densities which influence on hydrostatic resistance values. From statistical evaluation of test results, it has been found that hydrostatic resistance property is positively influenced by fabric weight and fabric density. Added knitted layers to three-layered samples contribute to increase fabric weight and density. And these three-layered fabrics show better hydrostatic resistance values than two-layered samples. Sample prepared by outer woven layer with more warp cover factor and weft cover factor or more compact structure shows higher hydrostatic resistance property than others.

Obtained R_{et} values of all prepared PU membrane laminated samples are between 6-10 m^2Pa/W. This means that all prepared samples are good breathable fabrics. Water vapour permeability of the prepared sample fabrics are greatly influenced by fabric weight and fabric thickness. Test results with statistical analysis express that water vapour permeability of the samples are negatively influenced by their fabric weight and fabric thickness. This indicates that the sample fabrics become more comfortable when their fabric weight and thickness are lower. Three-layered samples show less water vapour permeability than two-layered samples due to their increasing weight and thickness after adding knitted inner parts.

Air permeability values of the prepared sample fabrics depend on fabric thickness, fabric density, warp and weft cover factors or compactness of outer woven layers as well as inner knitted structures. From statistical analysis, it has been found negative influences of fabric thickness and fabric density on their air permeability values. Prepared sample fabric with lower thickness and lower density is found as more air permeable and sample fabric of more compactness with more warp cover factor and more weft cover factor of outer woven layer is found as less air permeable. Three-layered samples are less air permeable than two-layered samples as knitted inner layer for each three-layered sample causes more air entrapment resulting in less air permeability. However, thermal resistance values of PU membrane laminated fabrics are positively influenced by their thickness property that has been proved statistically. Three-layered samples show more thermal resistance values than two-layered samples due to their more thickness values after adding knitted parts as inner layers. Moreover, due to using the knitted fabrics, there are more air gaps between fibers that cause the decrease of heat transfer with increasing thermal resistance property. So, prepared three-layered fabrics are more comfortable than two-layered fabrics in comparatively cold condition.

It is evident from the result analysis that breaking strength of the sample fabric is positively influenced by fabric weight and fabric density. All three-layered samples show more breaking strength property than all two-layered samples due to their higher fabric weight and density after adding knitted fabrics as inner layers. Prepared laminated fabric with outer woven layer of more warp cover factor and more weft cover factor shows higher breaking strength due to the more compactness of the fabric. Again, bending rigidity of PU membrane laminated fabric is influenced positively by the thickness property of the fabric. Three-layered sample fabric with outer woven layer of highest warp cover factor and weft cover factor shows the highest bending rigidity value among all the samples due to its highest thickness value with maximum compactness.

During application of coating solution on four different types of PTFE membrane laminated three-layered waterproof breathable sample fabrics, the best mixing ratio of 50 g/L C_6-based fluorocarbon water repellent chemical and 15 g/L polysiloxane hydrophobic softening agent was selected and applied according to the best results obtained from coating a particular sample. However, all coated four samples show more regular and smooth surfaces under scanning electron microscope due to evenly deposition of coating materials on the fabric layers. All the four coated sample fabrics show complete non-wetting property during spray test even after washing which indicates the proper water-repellent property of the four samples after coating. Hydrostatic resistance and breaking strength properties of all four samples are significantly increased after coating as P-values are obtained less than 0.05 as well as F-ratios are higher than F-critical values from ANOVA for both cases during comparison of coated and uncoated sample fabrics. Bending rigidity is also increased after coating, but it is not as much higher increase as the increases of hydrostatic resistance and breaking strength due to using of softening agent. No significant increases or no big differences are obtained in water vapour permeability and air permeability after coating in four different samples which indicates no significant changes in breathability after coating.

All the above findings of the experiment should be considered with a great importance during designing and preparing outdoor sports waterproof breathable laminated fabrics for the usefulness of the users.

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8 List of papers published by the author

Published articles in impact factor Journal

1. **Razzaque, A.**, Tesinova, P. and Hes, L. (2019). "Enhancement of hydrostatic resistance and mechanical performance of waterproof breathable laminated fabrics". Autex Research Journal, 19(1), 44-53.

2. **Razzaque, A.**, Tesinova, P., Hes, L. and Arumugam, V. (2018). "Hydrostatic resistance and mechanical behaviours of breathable layered waterproof fabrics". Fibres & Textiles in Eastern Europe, 26(1), 108-112.

3. **Razzaque, A.**, Tesinova, P., Hes, L., Salacova, J. and Abid, H. A. (2017). "Investigation on hydrostatic resistance and thermal performance of layered waterproof breathable fabrics". Fibers and Polymers, 18(10), 1924-1930.

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1. Hasan, Md.Z., Asif, A.K.M.A.H., **Razzaque, A.,** Hasan, Md.R., Sur, S. and Faruque, Md.O. (2021). "An experimental investigation of different washing processes on various properties of stretch denim fabric". Journal of Materials Science and Chemical Engineering, 9, 1-15.

2. Asif, A.K.M.A.H., **Razzaque, A.** and Hasan, Md.Z. (2020). "A brief overview of different analytical techniques for material and chemical analysis". International Journal of Instrumentation Science, 7(1), 1-12.

3. **Razzaque, A.** and Tesinova, P. (2019). “Analysis of water resistance and mechanical performance of microporous polyurethane membrane laminated waterproof breathable fabrics". TechConnect Briefs, 86-89.

4. **Razzaque, A.,** Saha, J, Asif, A.K.M.A.H. and Rahman, M. (2015). “Influence of pin spacer on yarn quality in a ring frame”. International Journal of Current Engineering and Technology, 5(4), 2380-2382.

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Contribution in Conference proceeding

1**. Razzaque, A.** and Tesinova, P. “Analysis of water resistance and mechanical performance of microporous polyurethane membrane laminated waterproof breathable fabrics", in TechConnect World Innovation Conference at Boston, Massachusetts, U.S.A., 2019.

2. **Razzaque, A.** and Tesinova, P. “A study on waterproof and thermal performances of coated multi-layered breathable laminated fabrics", in Central European Conference, 2017.

3**. Razzaque, A.** and Tesinova, P. “Analysis of waterproof and thermal properties for multi-layered breathable fabrics”, in Strutex Conference, 2016.

4**. Razzaque, A.** and Tesinova, P. “Thermal and breathable properties of waterproof laminated fabrics”, in Bila Voda Workshop, 2016.

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Publications in Journal:

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1. **Razzaque, A.**, Tesinova, P. and Hes, L. (2019). “Enhancement of hydrostatic resistance and mechanical performance of waterproof breathable laminated fabrics”. Autex Research Journal, 19(1), 44-53.

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7. **Razzaque, A.,** Siddiquee, M. A. B. and Mamun, M. A. A. (2014). “Effect of false twist at the drafting zone of ring frame”. Journal of Science and Technology, 4(1), 137-142.

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2. **Razzaque, A.** and Tesinova, P. “A study on waterproof and thermal performances of coated multi-layered breathable laminated fabrics", in Central European Conference, 2017.

3**. Razzaque, A.** and Tesinova, P. “Analysis of waterproof and thermal properties for multi-layered breathable fabrics”, in Strutex Conference, 2016.

4**. Razzaque, A.** and Tesinova, P. “Thermal and breathable properties of waterproof laminated fabrics”, in Bila Voda Workshop, 2016.

Brief description of the current expertise, research and scientific activities

Doctoral studies: **S**tudent at the Faculty of Textile Engineering
Department of Textile Evaluation
Specialization: Textile Technics and Materials Engineering

List of Exams Passed:
[1] Mathematical Statistics and Data Analysis
[2] Heat and Mass Transfer in Porous Media
[3] Clothing Comfort
[4] Structural Theory of Fibrous Assemblies
[5] Experimental Technique of the Textile

State Doctoral Exam: Passed

Research Projects:
[1] SGS Project- 21148,
Evaluation of methodology for moisture management at different air conditions.
Project participant, 2016

[2] SGS Project- 21199
Alternative testing of laminated materials with textile component and behavior of humidity in textiles.
Project participant, 2017

Recommendation of the supervisor

Supervisor´s opinion on PhD thesis of Abdur Razzaque

Topic: Evaluation of Hydrostatic Resistance and Comfort Properties of Breathable Laminated Fabrics

I am writing this recommendation letter for Abdur Razzaque regarding his final defence. Mr. Abdur Razzaque has been studying and doing research work under my supervision. He is hard working and concerned to the target. Despite he is Textile Engineer, his previous research topics were oriented to polymer science and spinning technology so he had to amend his knowledge for better orientation in thesis topic for comfort properties and laminated materials compositions.

The main aim of his research work is to study waterproof breathable membrane laminated fabrics from point of view of mechanical, thermos-physiological comfort and usage properties, mainly of resistance to water penetration optimal fabrics which protect wearer in outer weather conditions. Materials for sports apparel are constructed all over the world but primarily based on experience only and changes in manufacturing are done by trial and error method. Journal publications nowadays are oriented on the one/two most important properties. A complex study oriented on relation of all properties together with recommendation for producers is needed.

The first study is oriented on complex evaluation of laminated material composed with microporous PU membrane. Deep description of ANOVA followed all measured properties. Second study was designed to evaluate another view of resistance against water. It was prepared materials coated with C6-based fluorocarbon resin and polysiloxane hydrophobic softening agent in examined mixing ratio. Properties correlations are evaluated to the geometrical parameters too.

Abdur Razzaque improved his skills in data analysis and build two experimental parts to reach valuable results. He consulted a lot with specialists and professors at faculty and worked on the recommendation given him by the state examination committee. His publications were accepted in respected journals. When presenting his work on doctoral seminars, he was always straight to topic description and discuss unbreakable.

By conclusion I can say that this thesis is experimentally oriented on hydrostatic resistance related to the use of multilayer composed fabrics. I recommend him for defence as he has completed all necessary exams and work hard to improve himself as a researcher.

In Liberec, 26.08.2021

Ing. Pavla Těšinová, Ph.D.
Supervisor

Opponent's reviews

Dissertation thesis - opponent's report

Thesis author: Abdur Razzaque, M.Sc.

Thesis: Evaluation of Hydrostatic Resistance and Comfort Properties of Breathable Laminated Fabrics

Thesis Topic

The author investigates the effect of the construction of textile laminates on their performance properties. He prepared the first set of samples with PU membrane himself. He applied the final treatment to the second set of samples with PFTE membrane. He evaluated the samples using conventional methods.

Formal evaluation of the work

The thesis is free of significant errors. The English is at a good level. Compared to the usual PhD theses, the thesis is slightly below average in scope. 71 citations are few. 96 pages of text is not enough. The author's publications are slightly below average but acceptable.

The thesis is unnecessarily long - the same data are usually presented 3 times: in one table and two large graphs (e.g. table 22, figure 40 and figure 41). At the same time it is presented in tables R and R2.

Scientific objectives are not defined and therefore not met. The objectives stated in the paper are experimental only.

The experiment is free of gross errors. The methods are appropriately chosen with respect to the experimental objectives.

The description of the experiments is insufficient in places. It is not clear how many times the samples were measured. The description of the textile samples used is unclear.

The results are generally plausible but not technically useful.

Minor errors:

The abstract in the English language has a number of formal and content inaccuracies, e.g. on page VII: "... an approach using a coating solution prepared with an environmentally optimized hydrophobic plasticizer based on a hydrofluorocarbon hydrophobic chemical..."

Page 27 - Figure 7: The figure description is incomplete, the origin of the figure is not clear.

The list of abbreviations is not complete.

Questions to defend:

Linear regression models were used to approximate the results in the graphs. What is the predictive ability of the model? How to interpret the equation?

Describe in detail the preparation of the laminates used in the PhD thesis.

The measured data have a relatively low standard deviation. How many times were the measurements made? Was all data included in the statistical analysis?

Present the measured data +/- SD in graphs. Please provide statistical interpretation.

Why were textiles with such large differences in area weight between 192 and 925 g/m2 chosen (p. 40)?

In this paper, 2 large experiments were performed with different membranes and fabrics. Can these results be compared with each other?

What is the scientific contribution of the work? How can the results of the work be generalised?

Summary:

In this thesis, two randomly chosen sets of samples are measured by the author. The author is only concerned with visualizing the results and making a simple comparison of the larger - same - smaller. The author only measured the properties of common laminated fabrics by standard methods. The number of measured samples is small.

The thesis is at the level of a bachelor's or master's thesis.

Significance of the thesis for the field: it is very small, the thesis has no technical or scientific contribution. The thesis has no concept. The author does not reflect on the causes of the observed phenomena.

I do not recommend the thesis for defence.

In Liberec on 14. 1. 22

Prof. Ing. Jakub Wiener, PhD.

opponent

Opponent's opinion of the doctoral dissertation

Doctoral student: **Abdur RAZZAQUE, M.Sc.**

Name of dissertation thesis: **Evaluation of hydrostatic resistance and comfort properties of breatheable laminated fabrics**

Opponent: **1 Lt. Ing. Jana Švecová, Ph.D.**

Topicality and significance of the topic

Dissertation thesis addresses an important and very beneficial topic. Problematics of evaluation of hydrostatic resistance and comfort properties of breathable laminated fabrics is very topical for several reasons:

- Hydrostatic resistance with suitable breathability together with other comfort properties demonstrably affect the performance and well-being, concentration of the wearer, which is very important for the application of clothing, whether for sports or professional soldiers.
- Novel approach of coating was applied in this study on four different types of PTFE membrane laminated different structured waterproof breathable fabrics.
- Investigation the influence of different parameters of laminated fabrics leads to findings are important for designing and preparing waterproof breathable laminated fabrics for the entire spectrum of applications.

Therefore, I believe that the chosen topic of the dissertation is beneficial and promising.

The aim of the dissertation

The aim of this study was to newly develop waterproof breathable laminated fabrics and to characterize these fabrics in order to evaluate their hydrostatic resistance and other comfort properties. The submitted dissertation corresponds to a pre-selected goal, which is defined in the first chapter. To meet the main goal, 4 the specific objectives were set:

1. To prepare waterproof breathable fabrics.
2. Analysis of hydrostatic resistance of the prepared samples.
3. Study of thermo-physiological and mechanical behaviors of the prepared samples.

4. Application of a novel approach for coating.

These sub-objectives were gradually developed and presented in Chapters three and four. I consider the output in the form of a study of thermo-physiological and mechanical behaviors of the prepared samples to be crucial. Knowledge of this issue is important for the appropriate choice of materials in the design and preparation phase of outdoor sports waterproof breathable laminated fabrics for the usefulness of the users.

Selected methods and solution procedure

The solution procedure has a logical structure, the appropriate graphic and language level. The work can be divided into theoretical and practical part. In the review of literature is provided, inter alia, by a broad overview of studies and theories that have been produced in the field of research. From the review of literature follows to need for the development of a waterproof, breathable fabric that would allow the transfer of water vapor and perspiration from the inside of the fabric to the outside and simultaneously restricts the passage of water from outside to inside. The main attention of the dissertation is devoted to the analysis and statistical evaluation of the effects of various characteristic parameters of newly produced layered fabric samples on their different properties, like, hydrostatic resistance, thermo-physiological behaviors, i.e., thermal property with air and water vapour permeability as well as mechanical properties, i.e., bending rigidity and breaking strength. The chosen solution methods are appropriate for this area of scientific work.

Evaluation of achieved results

Six samples of waterproof, breathable fabrics laminated with a PU membrane, which are a prerequisite for use in outdoor sports fabrics, were newly designed and prepared by a doctoral student. The mentioned samples were analyzed in terms of the effects of different characteristic parameters of the fabric on their different properties and the results were statistically evaluated. From the results of tests and statistical analyzes, it was found that there are significant effects of various fabric parameters on some properties and these findings are important for the design and preparation of waterproof breathable laminated fabrics for use in sportswear. Furthermore, a new approach was applied for coating four different types of microporous polytetrafluoroethylene (PTFE) membrane laminated three-layered waterproof breathable fabrics. Here, eco-friendly C6-based fluorocarbon water-repellent chemical and silicone based polysiloxane hydrophobic softening agent were used to prepare the coating solution in order to enhance the existing hydrostatic resistance and mechanical performance of the fabrics while keeping their water vapour permeability and air permeability in mind. From different test results and statistical analysis, it has been found that hydrostatic resistance and breaking strength have been significantly increased after coating while there are no significant changes in the results of water vapour permeability and air permeability. Furthermore, all the coated fabrics show good water-repellent property which is important for outdoor sports fabrics.

Significance for the practice or development of a scientific field

The dissertation tried to present knowledge that could be useful in defining future directions and to provide researchers with insider references. All the above findings of research experiments should be considered with great importance in the design and preparation of outdoor sports waterproof breathable laminated fabrics. The work opens up further space for the continuation of the preparation of laminated layered waterproof breathable fabrics using parts of the outer layer with fabrics of different types of fibers and the analysis of their comparative studies. Likewise, for the preparation of laminated waterproof breathable layered fabrics using inner layers with lining materials of different types of fibers and analysis of their properties. Last but not least, the preparation of laminated layered fabrics with the same external and internal layers but different types of membranes, i.e. microporous membrane or hydrophilic membrane with different weights and thicknesses and the study of their properties for use as protective or sportswear. The results of the work are beneficial for the development of the field of science and usable in the development, innovation and introduction of new materials for the production of modern outdoor sportswear. The results can also be used for the patterning and innovation phase of functional clothing components of the armed and safety forces of the Czech Republic.

Publication aktivity

The publishing activity of the doctoral student is adequate and relates to the topic of the submitted dissertation. The doctoral student published 3 articles in impact factor Journal and 7 articles in other professional Journals. There were also 4 contributions in Conference proceeding.

Questions and comments on the dissertation:

The comments are more of a formal nature, resulting from the inconsistencies in the structure of dissertations of various universities in the Czech Republic. ČSN ISO 7144 (010161) Documentation - Formal arrangement of dissertations and similar documents: states that the formal arrangement, style and arrangement of the dissertation bibliography must be in accordance with the special rules of the university at which the dissertation is submitted. According to the excerpt from the Study and Examination Regulations TUL Art. 20, point 3) the stated requirements regarding the content of the work were met. The excerpt also states in Article 20, point 5) that the indicative scope of the dissertation and other comments may be further regulated the relevant Dean's Directive. I did not have this document. However, I would like to make some comments, rather recommendations for a better overview and coherence of the text in the future:

- After each chapter, it would be appropriate to have another subchapter in the form of a Partial Conclusion, which summarizes the most important and key, what happened in the chapter, the most important findings.
- Unification of bullets, sizes and locations of images, tables throughout the work.
- For each figure and table, especially in the theoretical part, to state the source, even in the case of your own source.
- If 4 sub-objectives are specified in Chapter 1.2, it would be clearer and preferable to find their solution and results in the form of individual subchapters, eg in the experimental part. The reader must look for them there. It would be appropriate, at least at the beginning of the experimental part, to explain to the reader that he will find them there.
- How many layers of fabric laminated with a PU membrane would you choose to make military clothing in adverse climatic environments in terms of maintaining soldier comfort, sufficient hydrostatic resistance and clothing weight?
- What other direction will you take in your research?

Final evaluation

The submitted dissertation fulfilled the subject and goals set in the introduction. It meets the requirements on dissertation thesis, including verification of authenticity, publication activities and therefore **I recommends work for defense.**

V Brně dne 15. 1. 2022

1 Lt. Ing. Jana Švecová, Ph.D.
Fakulta vojenského leadershipu,
Katedra logistiky, UNOB