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SCIENTIFIC PAPER

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DEVELOPMENT OF A MULTI-LAYERED, WATERPROOF, BREATHABLE FABRIC FOR FULL-WEATHER APPAREL

Article Highlights

- A multi-layered, waterproof, breathable fabric was designed by assembling five layers
- The five layers were a coated knit, a non-woven fabric, a membrane, a veil, and an open-work knit
- The waterproof and breathable properties of the designed laminate were evaluated
- Mechanical performances of the obtained system were investigated

Abstract

In this research, a laminate was produced by assembling five textile layers. These layers were a coated double-sided knitted structure, a non-woven fabric, a hydrophilic membrane that was thermally assembled to a surface veil, and an open-work knitted fabric. The laminated textile's breathability, windproofness, and waterproofness were evaluated. The multi-layered fabric was windproof, and its water vapor permeability was 347.297 $g{\cdot}m^{-2}{\cdot}s^{-1}$ *(CV= 8.902%). Its resistance to water penetration was equal to 117.68 Schmerber (CV = 7.81%). The assembled fabric's mechanical properties were also evaluated. Young's modulus values were equal to 2 MPa (CV= 8.613%) and 1.6 MPa (CV= 8.349%) for both fabric directions. Its flexural rigidity was 5056.659 mg·cm and its surface total deformation was lower than 450 µm when measured under 20, 40, 60, and 80 mN loads. Based on the results obtained, it was concluded that the developed multi-layered fabric could be used to produce raincoats and jackets to protect the wearer from light rain and drizzle.*

Keywords: multi-layered fabric, waterproof fabric, windproof laminate, breathable textile, tensile resistance, flexural rigidity.

Over the last few years, waterproof, breathable fabrics (WBFs) have been gaining interest [1–3]. They were considered an alternative to waterproof fabrics known for causing discomfort to the wearer because of moisture condensation in their inner sides [4]. Since then, the breathability concept has appeared. It was defined as the ability of a garment to evacuate insensible and sensible perspirations and to assure thermophysiological comfort to the wearer. This capacity was always considered a basic need [5–8]. WBFs that are mostly obtained with coating and laminating processes assure not only the protection of the wearer from wind and rain and their moisture evacuation from the skin to the outer side of the fabric [1,8–11]. They were first used for medical gowns, military and fireman uniforms, and space suits for producing traditional apparel [3,10].

Unfortunately, WBF manufacturing processes are quite complex, and the garments produced are expensive [16]. In our previous study [17], an attempt was made to produce a waterproof, breathable fabric

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by coating a double-sided knitted structure with a mixture of fluorocarbon and acrylic resins. The coating process was optimized to obtain the best performance in terms of waterproofness and breathability. Based on the results obtained, we reported that the coated knitted structure was hydrophobic and breathable; however, its windproofness and resistance to water penetration needed to be ameliorated [17]. Since fabric's breathability and surface hydrophobicity are senseless without windproofness and water resistance, in this study, four other layers were added to the already coated fabric to enhance its performance. The aim of this research was the development of a multi-layer fabric by using a flexible manufacturing process and unsophisticated equipment. The obtained laminate comprises a knitted lining, two non-woven fabrics, a hydrophilic membrane, and a coated double-sided knitted structure. The waterproof, breathable properties and the mechanical performances of the designed textile laminate were finally evaluated and discussed.

MATERIALS AND METHODS

Materials and used chemicals

The laminate outer layer was a double-sided knitted structure coated with an acrylic paste (CHTT GLOSSY FINIH) and a fluorocarbon resin (Fluorotex FO/57W). Both products were kindly supplied from CHIMITEX-Tunisia. The coated laminate outer layer was reproduced based on our previous study [17] and using the screen coating method.

To produce the hydrophilic membrane, an aliphatic polyester polyurethane copolymer dispersion (Appretan® N 5122 liq.) and an acrylic ester copolymer dispersion (Appretan® N 92101 liq.) were used. Archroma, Spain, kindly provided used products for the membrane synthesis. A Werner Mathis laboratory coating machine AG (Oberhasi, Switzerland) with a knife on a roller was used to obtain the hydrophilic non-porous membrane. The obtained membrane thickness was equal to 293 µm ± 3.94%.

The remaining laminate layers, i.e., the polyester non-woven fabrics and the knitted lining, were purchased from the Tunisian textile market.

Laminate development

A five-layer laminate was developed (Fig. 1). The inner layer of the multi-layered fabric (in direct contact with the wearer's skin) is an open-work knitted polyester structure. The second layer is a carded polyester veil thermally assembled with a polymeric membrane (third layer). The hydrophilic membrane was produced with 16 g of polyester polyurethane and 40 g of acrylic ester copolymers. It was dried at 115 °C and reticulated at 165 °C. Drying and reticulation times were equal to 3 minutes each. The fourth laminate layer is a non-woven fabric produced with the carding method. The laminate outer layer is a coated cotton-polyester double-sided knitted fabric in contact with the surrounding environment. The coating applied to the polyester face was prepared with 2.71% fluorocarbon resin and 412 g (m^{-2}) acrylic paste. Coating treatment conditions were already described and optimized by Ghezal *et al.* [17]. The five layers were finally assembled with an overlock stitch on the edges.

Figure 1. A real image of the produced multi-layered fabric and the hydrophilic membrane.

Air permeability and windproofness measurement

The clothing's air permeability influences the wearer's thermophysiological comfort [18]. For this reason, it is important to evaluate this factor when designing waterproof, breathable fabrics. The different textile layers and the laminated fabric air permeabilities were measured with an FX3300 measuring device (TEXTEST Instrument, Zürich, Switzerland). Tests were done according to the ISO 9237 standard [19]. Samples were cut in a circular form with an area equal to 20 cm^2 each and subjected to an airflow with 100 Pa pressure. Each test was repeated three times.

Water vapor permeability measurement

A breathable fabric is a textile that ensures wearing comfort by evacuating insensible and sensible perspirations from the microclimate between the skin and the clothing layer to the surrounding atmosphere [8,20,21]. The water vapor permeability was measured using a gravimetric method. For this purpose, a water vapor permeability tester (type M 261, SDL Atlas, Rock Hill, USA) was used. Water vapor permeabilities for the different layers were determined as specified in the BS 7209 standard [22].

Resistance to water penetration measurement

The resistance to water penetration was measured using the hydrostatic pressure method as specified in the ISO 811: 2018 standard [23]. Measurements were carried out with a TEXTEST

Automatic Hydrostatic Head Tester device type FX 3000 HYDROTESTER III from Textest Instrument, Zürich, Switzerland. Obtained values are the results of three replicates.

Tensile strength measurement

The ultimate tensile strength was evaluated with an LLOYD LS5 machine (AMETEK, Pennsylvania, USA) as specified in the ISO 13934-1 standard [24]. Samples were cut in a rectangular form with length and width equal to 150 and 50 mm, respectively. The applied preload and cross-head speed were equal to 5 kN and 10 mm.min^{-1}, respectively. Measurements were done in both sample directions, and the presented results were the average of five tests each.

Fabric stiffness evaluation

The fabric's bending behavior was tested to evaluate the laminate stiffness with a Cantilever tester (SDL Atlas, Rock Hill, South Carolina, USA) as specified by the ASTM D1388 standard [25]. Sampling was performed according to the laminate warp direction.

Outer surface deformation analysis

To investigate the micro-mechanical deformation of the laminate outer surface, a universal surface tester (UST) was used. A fabric square with a 30 mm edge was placed under the sample stage. A rounded-shaped steel ball tip with a diameter equal to 5 mm was moved along the tested surface. The scanned distance was fixed at 20 mm. The same sample path was scanned three times. Under 20, 40, 60, and 80 mN loads, tests were done. Total, permanent, and elastic deformations were recorded and plotted for each applied load with software connected to the UST device.

RESULTS AND DISCUSSION

Study of the physical properties of the multi-layered fabric

To produce the waterproof, breathable fabric, a five-layer laminate was designed by assembling a coated cotton-polyester double-sided knitted structure, two non-wovens, a hydrophilic membrane, and an open-work knitted fabric. The developed laminate and its different layers and positions are presented in Figure 2.

Due to its surface hydrophobicity, the coated double-sided knitted fabric was used as an outer layer for the developed laminate. The polyester outer face of the knitted structure was coated with a fluorocarbon resin and an acrylic paste. The use of the coated fabric as an outer layer of the laminate would guarantee the protection of the wearer against rain and wind. In previous studies, water repellency and breathability of the outer layer were evaluated [17,26]. The coated double-sided knitted fabric was found to be breathable, and its coated polyester outer surface was hydrophobic; however, its water resistance and windproofness must be ameliorated [17,26].

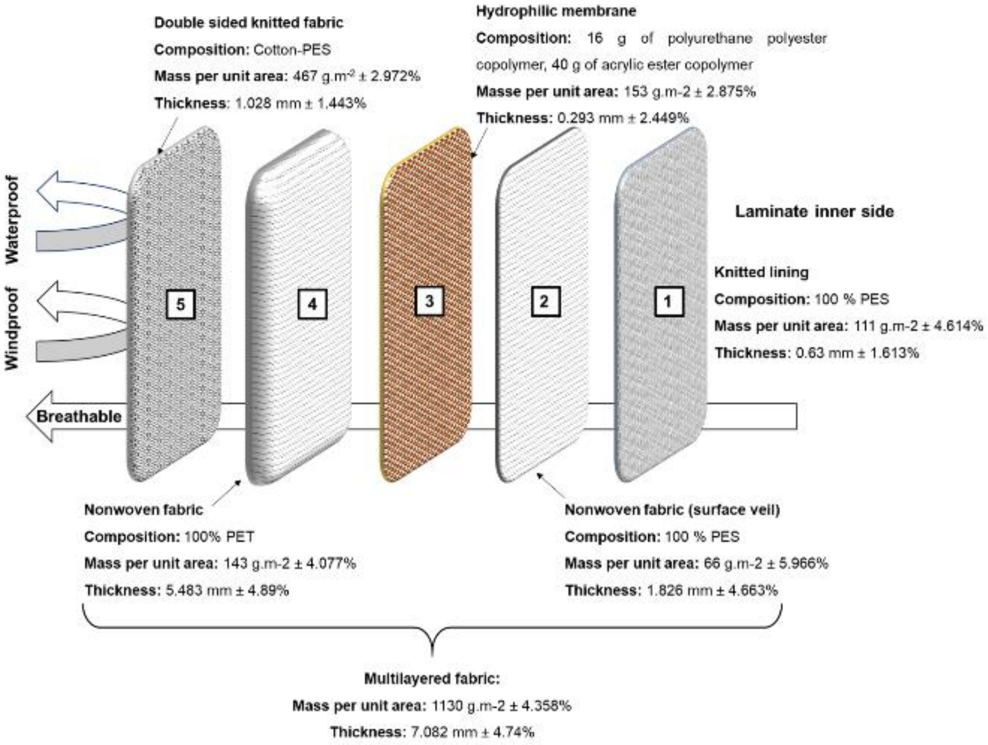

Figure 2. Different laminate layers and characteristics.

The lamination of additional layers was investigated to enhance the performances of the coated fabric in terms of water resistance and windproofness. First, a polyester non-woven fabric was assembled with the coated knitted structure to enhance its resistance to water penetration and windproofness without restricting its breathability. An open-work knitted structure was added as a lining layer to give the assembly a cloth-like feel. It was found that the non-woven structure did not really enhance the assembly resistance to water and wind. For this reason, the idea of adding a non-porous membrane emerged. The hydrophilic membrane would not restrict the other layers' breathability. On the other hand, it would impart resistance to wind and water penetration to the already assembled three layers.

In a previous study [27], a super-absorbent material was joined to the back of a hydrophobic lining. The hydrophobic material was placed in direct contact with the skin to facilitate moisture transport to the super-absorbent material and to ensure the wearer's skin was dry [27].

The fragile, non-porous hydrophilic membrane was thermally assembled to a hydrophobic polyester veil to preserve it and prevent its direct contact with the wearer's skin. The hydrophobic veil would also ensure rapid moisture transport from the skin to the non-porous hydrophilic membrane to prevent sweat accumulation near the wearer's skin. The non-woven hydrophobic veil was inserted at the other side of the hydrophilic membrane to facilitate moisture evacuation and avoid microclimate saturation.

The fabric's physical properties affect a garment's manufacturing process and comfort properties. Thereby, masses per unit area and thicknesses were measured for the different layers and the developed laminate, respectively, according to ISO 3801 [28] and ISO 5084 [29] standards. Obtained results are shown in Table 1. Each value is the average of three measurements.

Table 1. Characteristics of the different used layers and the produced laminate.

Layers	Structure and composition	Mass per unit area (g.m^{-2})	Thickness (mm)
Layer 1 (Laminate inner layer)	Polyester open-work knitted structure.	110.767 ± 4.614%	0.630 ± 1.613%
Layer 2	Polyester surface veil.	66.218 ± 5.966%	1.826 ± 4.663%
Layer 3	Non-porous membrane mainly composed of acrylic ester and polyester polyurethane copolymers.	152.96 ± 2.875%	0.293 ± 2.449%
Layer 4	Polyester non-woven fabric.	143.124 ± 4.077%	5.483 ± 4.890%
Layer 5 (laminate outer layer)	Double-sided knitted structure with a cotton inner face and a polyester outer face.	466.96 ± 2.972%	1.028 ± 1.443%
Laminate	_	1130.329 ± 4.358%	7.028 ± 4.74%

Evaluating the laminate breathability and waterproofness

The air permeability was measured to evaluate the breathability of the different layers used and the produced laminate. Obtained results are shown in Table 2. The air permeability of the knitted polyester lining was equal to 2779 L.m^{-2}.s^{-1} ± 2.771%. The highest air permeabilities were obtained for the non-woven structures. Values were equal to 3188 L.m^{-2}.s^{-1} ± 2.832% and 3603 L.m^{-2}.s^{-1} ± 3.474% for the non-woven fabric and the surface veil, respectively. The hydrophilic membrane is a pore-free medium, so its air permeability was equal to 0 L.m^{-2}.s^{-1}. Based on the previous study of Ghezal *et al.* [17], it was found that the double-sided knitted structure pores were clogged with the applied coating, which explains the low air permeability value of the laminate outer face. The final laminated fabric was also windproof since the hydrophilic membrane was used to produce the five-layer system.

The hydrophilic membrane's water vapor permeability was 504.148 g.m^{-2}.day^{-1} ± 1.283%. Hence, the hydrophilic membrane is impermeable to air but can still evacuate water vapor through its section into the surrounding environment. Based on the obtained results, it is obvious that the outer layer has a higher vapor permeability than the dense membrane. Indeed, the passage of water vapor through a porous medium is easier and faster than through a non-porous one. So, it can be deduced that the water vapor permeability is related to the chemical nature and structure of the tested layer. On the other hand, the hydrophilic membrane indeed restricted the air passage through the five-layer system. However, it was found that the laminated fabric is still breathable. In a previous study, Ghezal *et al.* [17] determined the water vapor permeability index of the coated cotton- polyester double-sided knitted structure. It was equal to 83.852% ± 0.589% [17]. Based on both results, it is obvious that the absence of pores in the tested structures does not restrict water vapor evacuation.

Body thermophysiological comfort is related to the garment's porosity and air permeability [30,31]. Nevertheless, moisture can be evacuated, and breathability can be achieved even with non-porous structures via physico-chemical mechanisms [8,12]. Indeed, for a porous structure, the water vapor evacuation can occur through pores according to Poiseuille, transitional, or Knudsen flows. For non-porous media, water vapor molecule evacuation is assured by the adsorption-diffusion-desorption (solution-diffusion) mechanism [32,33]. The water vapor permeability of the developed multi-layered system was determined to be 347.9 g.m^{-2}.day^{-1} (CV= 8.902%). Based on the obtained result, the multi-layered system was judged breathable.

In the literature, many test methods were used to evaluate fabrics' breathability [34,35]. Mukhopadhyay and Midha [36] reported water vapor transport (WVT) values for some laminates. The WVT for two-layer and three-layer polytetrafluoroethylene laminates were equal to 205 and 174 g.h^{-1}m^{-2}, respectively [36]. A lower value of 119 g.h^{-1}.m^{-2} was reported for a hydrophilic polyurethane laminate [36]. In a previous study [34], the WVT value for Pertextion fabric was measured with the upright cup method and according to the ASTM E 96 B standard. The obtained value was 446.4 g.m^{-2}.day^{-1} [34]. Gugliuzza and Drioli [35] also reported the water vapor transmission rates (WVTR) measured according to the ASTM E96B for Dermizax® (a laminate with a non-porous membrane) and Helly-Tech Extreme® (a laminate with a microporous membrane) to be 700 and 785.2 g.m^{-2}.day^{-1}, respectively [34,35]. Although breathability is a fundamental characteristic when producing a waterproof, breathable fabric, comparing the water vapor permeabilities, water vapor transmission rates, or water vapor resistance values is arduous due to the variety of procedures and standards used to evaluate a fabric's breathability [34,36].

The resistance to water penetration was also investigated with the hydrostatic pressure method. The obtained results are presented in Table 2. The non-porous membrane resistance to water penetration is the lowest one. This value is insufficient for producing a waterproof fabric. The resistance to water penetration of the coated double-sided knitted structure was previously determined [17]. Even though the outer layer of the laminate fabric was coated, its resistance to water penetration is still very low due to the presence of pores in the coated structure and the deformation of the coated knitted fabric under the applied hydrostatic pressure [17]. After assembling the five layers, the resistance to water penetration of the multi-layer system increased and reached 117.68 Schmerber ± 7.81% due to the decrease in the fabric-free volume and the higher resulting thickness obtained after layers assembling.

In general, fabric type, structure, and properties influence its air permeability, water vapor permeability, and resistance to water penetration [37,38]. Knitted structures' high porosity and deformability rate originate from their high air and water vapor permeability, low windproofness, and insufficient water penetration resistance [11]. Based on the obtained results, it can be deduced that the developed multi-layer system is windproof and breathable. However, its resistance to water penetration needs to be ameliorated. To conclude, the developed multi-layer system can produce raincoats and jackets to protect the wearer from drizzle and light rain.

Table 2. Waterproof, breathable characteristics of the coated double-sided fabric, the non-porous membrane, and the multi-layer fabric.

Characteristics	Air permeability (ISO 9237, 1995)	WVP/ WVPI (BS 7209, 1990)	RWP (ISO 811, 2018)
Coated double-sided fabric [17]	147.75 L.m^{-2}.s^{-1} ± 1.156%	80.490% ± 0.589%	78.453 Schmerber ± 1.8%
Non-porous membrane	0 L.m^{-2}.s^{-1}	504.148 g.m^{-2}.day^{-1} ± 1.283%	88.260 Schmerber ± 1.6%
Multi-layered fabric	0 L.m^{-2}.s^{-1}	347,927 g.m^{-2}.day^{-1} ± 8.902%	117.680 Schmerber ± 7.8%

WVP is the water vapor permeability (g.m^{-2}.day^{-1}), WVPI is the water vapor permeability index (%), and RWP (Schmerber) is the resistance to water penetration.

Study of the tensile strength

Tensile strength was evaluated for the different used layers and the resulting laminate. The obtained results are recapitulated in Table 3. The strain was also measured according to warp and weft directions for the knitted lining. It was equal to 0.484 ± 5.843% and 1.332 ± 1.069%, respectively. The loop geometry explained the important deformation mode when the load was applied according to the weft direction.

For the two used non-wovens, the strain according to both tested directions was almost the same. For the non-woven fabric (layer 3), the strain was equal to 0.515 ± 3.088% and 0.720 ± 6.277%, respectively, according to the production direction and transverse one. For the non-woven surface veil, deformation values according to the production direction and the transverse one were equal to 0.479 ± 4.085% and 0.433 ± 4.111%, respectively.

When testing the tensile strength of the hydrophilic membrane, the strain was 3.194 ± 2.940% and 1.951 ± 0.327%, respectively, according to the production and transverse directions. Even though the deformation rate for the hydrophilic membrane was the highest according to the production direction, the highest deformation of the multi-layered system was obtained when tests were done according to direction (2).

To evaluate the tensile strength of the laminate, strain, stress, work at maximum load, and Young's modulus were determined from the stress-strain curves (Fig. 3) and recapitulated in Table 3.

Tests were done according to both laminate directions. The first direction, which was noted as direction (1), is defined by the warp directions of the coated fabric and the knitted lining and the production directions of the two used non-wovens and the hydrophilic membrane. The direction (2) is the transverse one.

The stress at maximum load and Young's modulus values were almost similar for both multi-layer fabric directions. The highest strain value was equal to 1.844 ± 0.289%. It was obtained when tests were done according to direction (2). This direction corresponds to the weft direction of both used knitted structures and the production direction of the other three layers.

Table 3. Tensile strength tests result for the laminate according to both directions.

Tensile mechanical properties	Direction (1)	Direction (2)
Strain (mm/mm)	0.581 ± 3.350%	1.844 ± 0.289%
Stress at maximum load (MPa)	1.438 ± 3.194%	1.864 ± 1.450%
Work at maximum load (J)	11.512 ± 4.440%	33.332 ± 5.575%
Young's modulus (MPa)	2 ± 8.613%	1,6 ± 8.349%

Based on the results obtained, it was found that the deformation aspect of the multi-layered fabric is very similar to the deformation mode of the double-sided knitted structure already investigated by Ghezal et al. [39]. Therefore, it can be deduced that the laminate mechanical behavior is governed by its knitted-coated outer layer.

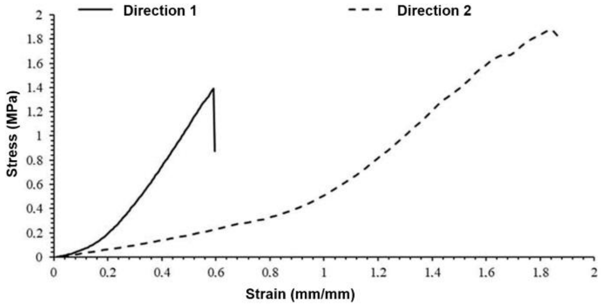

Figure 3. Stress (MPa) versus strain (mm/mm) for the multi-layer fabric in both directions.

Study of the flexural rigidity of the multi-layered fabric

The flexural rigidity of the multi-layer fabric was evaluated with a Cantilever Tester. The bending length was determined according to the laminate warp direction and was equal to 3.55 cm (CV= 1.99%). Using flexural rigidity and mass per unit area of the designed laminate, the flexural rigidity was determined to be 5057 mg.cm as specified by the ASTM D1388 standard. The high obtained flexural rigidity value results from the coating treatment applied to the laminate polyester outer face, the properties of the different layers, and the assembling technologies used for producing the multi-layered system.

Study of the surface profile and deformation of the multi-layered fabric

The polyester face of the laminate outer layer was tested under different loads before and after the coating treatment. Measurements were recorded under 20, 40, 60, and 80 mN loads. The results obtained were almost the same under the different loads used. Thus, only profiles and deformations under 20 mN loads were represented in Fig. 4.

The uncoated laminate outer layer surface profile is presented in Figure 4a. The polyester multifilament pattern was easily perceptible, and the total deformation reached 1200 µm. A smoother surface was obtained after the coating treatment (Fig. 4b). Also, elastic and permanent deformation values decreased significantly. Therefore, it can be deduced that the coating treatment ameliorated the deformation

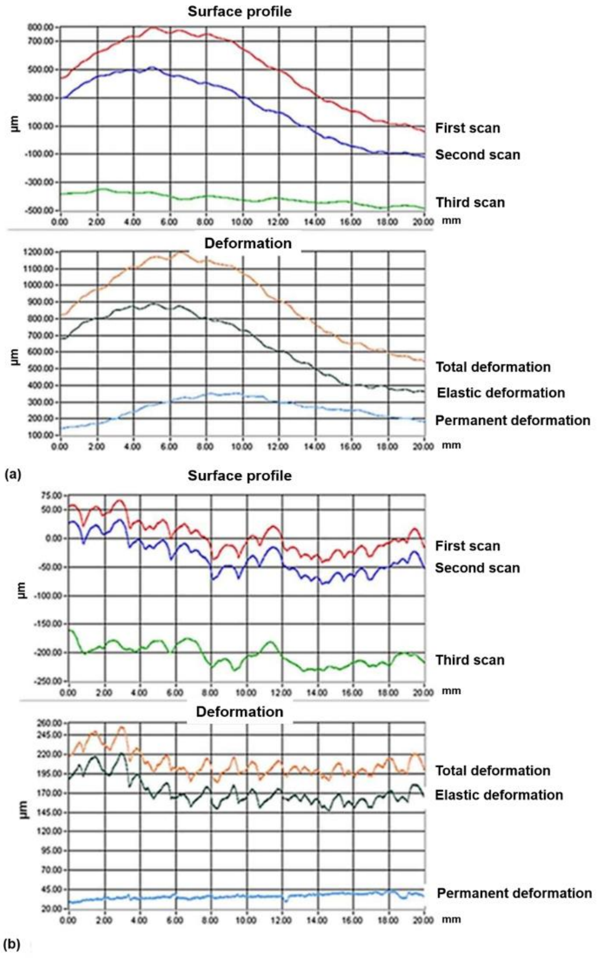

Figure 4. . Surface profiles and deformations of the polyester face of the laminate outer layer under 20 mN applied load. (a): Uncoated layer, (b): Coated layer.

resistance of the laminate outer layer.

To analyze the effect of the applied load on the laminate outer layer, the coated polyester surface was tested under 20, 60, and 80 mN loads. From Fig. 4b, it can be noticed that the highest elastic and total deformations obtained under a 20 mN load were equal to 220 and 260 µm, respectively. When the applied load was increased to 60 and 80 mN, the total deformation increased significantly and reached 400 µm (Figure 5). From Figs. 4b and Figure 5, it can be noticed that the elastic deformation is more important than the permanent one for low solicitations. Thus, the coated surface can return to its initial state after deformation.

CONCLUSION

The aim of this research was to employ simple methods for producing a waterproof, breathable laminate. For this purpose, the final product was assembled into a coated knitted structure, a non-woven fabric, a membrane, a surface veil, and an open-work knitted lining. The multi-layered fabric air permeability, water vapor permeability, and resistance to water penetration were equal to 0 $L.m^{-2}. s^{-1}$, 347.927 $g.m^{-2}.day^{-1}$, and 117.68 Schmerber, respectively. The developed fabric was judged windproof and breathable. However, its resistance to water penetration needed improvement. Considering that the mechanical properties affect the final product handle, manufacturing process, and durability, the tensile strength, flexural rigidity, and surface deformation were also investigated. The strain-stress curves of the tested laminate showed that it has the same tensile behavior as its coated knitted outer layer. The multi-layered fabric tensile strength could be ameliorated by using other assembling techniques. The laminate outer surface deformation was also evaluated. It was found that the laminate outer layer had almost an elastic behavior under low loads. To conclude, the developed multi-layered fabric can produce raincoats and jackets to protect the wearer from light rain and drizzle.

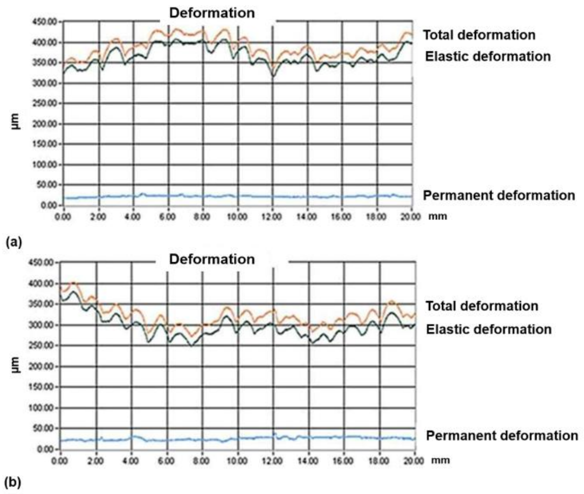

Figure 5. Surface deformations of the coated polyester face of the laminate outer layer under different applied loads. (a): Applied load: 60 mN, (b): Applied load: 80 mN.

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NAUČNI RAD

RAZVOJ VISESLOJNE, VODOOTPORNE, PROZRAČNE TKANINE ZA ODEĆU ZA SVE VREMENSKE USLOVE

U ovom istraživanju laminat je proizveden sklapanjem pet tekstilnih slojeva. Ovi slojevi su bili obložena dvostrano pletena struktura, netkana tkanina, hidrofilna membrana, koja je termički spojena na površinski veo, i pletena tkanina otvorenog tipa. Procenjivane su prozračnost, vetrootpornost i vodootpornost laminiranog tekstila. Višeslojna tkanina je bila otporna na vetar, a propustljivost vodene pare iznosila je 347,3 g m^{-2} s^{-1} *(CV= 8,9%). Njena otpornost na prodiranje vode iznosila je 117,7 Schmerber (CV = 7,8%). Takođe, procenjena su mehanička svojstva sastavljene tkanine. Vrednosti Jangovog modula bile su 2 MPa (CV= 8,6%) i 1,6 MPa (CV= 8,3%) za oba smera tkanine. Njena krutost na savijanje iznosila je 5056,7 mg cm, a ukupna deformacija površine bila je niža od 450 μm kada je merena pod opterećenjem od 20, 40, 60 i 80 mN. Na osnovu dobijenih rezultata, zaključeno je da se razvijena višeslojna tkanina može koristiti za proizvodnju kabanica i jakni za zaštitu korisnika od slabe kiše.*

Ključne reči: višeslojna tkanina, vodootporna tkanina, laminat otporan na vetar, prozračni tekstil, otpornost na zatezanje, krutost na savijanje.