d. Textile Production Engineering

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Coated Textile Materials

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1. Introduction

Top finishes began to be used already in the 18th century when fabrics were coated with linseed oil to produce oilcloth. This was the first procedure of coating several agents to the textile substrate and can be considered as the predecessor of multi-layered materials. Textile surface materials coated with chemical l structures have been developed continuously for several last decades. The basic substrate of the surface material is mostly textile fabric coated on one or both sides with one or more polymer layers. This kind of products with the basic textile material has many improved properties and multiple advantages over the classic textile material [1 - 3].

Polymer layers can be polyurethane, polyvinylchloride or polyacrylate layers. To improve their properties, appropriate additives are added: softeners, porosity-generating agents, filling materials, binders, fungicides etc. Coated polymers are applied to the textile material directly, and indirectly using paper or coagulation procedure. The constant development of the coating technique resulted in the newest achievements the result of which is the application of nanoporous polymers to the textile substrate. The use of these products is increasing and they are gaining greater importance in the clothing industry. They are especially widespread in the protective clothing where they meet all the market requirements. The design of a multilayered material is based on a target product so that it is very easy to obtain a material with desirable properties. As it is not always possible to satisfy the market with classic textile materials made of textile fibers and yarn, especially the requirements of the protective clothing, after-treatments of textile materials were introduced, either by applying polymers or some other agent or by thermal joining several different laminates. This was the introduction of the so-called composite materials which according to their structure and properties were in line with the requirements for specific purposes. With their especially good properties such as strength, durability, protection against UV radiation, wind, rain and other necessary properties they did not lose comfort, airiness, design and easy care. Multilayered materials, especially in the textile industry, contain at least one layer of the textile material which may be a woven fabric, knitted fabric or nonwoven fabric, whose only function is primarily comfort (comfort is the emotion of pleasant feeling related to tactile sensation, while pleasant is a broader term, a person can be pleasant), elasticity and airiness. Multilayered materials can be produced in different ways:

- by laminating a polymer layer to the textile surface material,
- by direct applying a polymer to the textile material,
- by indirect applying a polymer to the textile material.

The chemical compositions of polymer coatings are constantly developed and new types of polymer additives are increasingly introduced. The influence of industry globalization, the requirements of suppliers and consumers as well as new technologies change the market and expand the use of polymer coated textile materials.

The key factor for the success of polymer coating is its versatility and long durability. This chapter will deal with polyurethane (PU) polymer coats with different nanopores for coating and laminating the textile. Abrasion resistance and strength are by far higher in polyurethane in comparison to other polymers. Polyurethane has the property of good adhesion which can be strengthened by addition of cross-linking agents. Hardness or softness can be achieved by variation of polymer structures without using a plasticizer. It is also possible to reduce fragility by the impact of light [1, 4].

2. Lamination of fabrics with nanopur coating

Laminated fabric with polyurethane coating with nanopores is a multilayered composite material. Textile composite materials are composed of two or more different materials with at least one textile layer (woven fabric, knitted fabric or nonwoven material). All components composing the final product affect the properties of multilayered composites. The portion of individual components can be different which enables obtaining a composite with target properties for the predetermined purpose. Nowadays the material with woven fabric on the front side and polyurethane with nanopores on the back side is mostly used for military or police outerwear as well as for civil uses. For military purposes camouflage fabric in different shades and designs or less frequently single colored is used, while single-colored fabrics in blue shades are used for police purposes. This kind of composites have multiple advantages over the classic fabric since they are more durable and stronger, their body protection against meteorological effects (rain, wind, UV radiation), they did not lose their comfort (they are airy and have good sweat permeability), they are more resistant to abrasion and load, and they have less anisotropic properties in contrast to the classic fabrics.

Properties of composites with the woven fabric as the basis depend to a great extent on weave type, warp and weft density, yarn count and the angle of the straight line under which the load acts in relation to the warp and weft direction. The highest breaking strength is expected in the warp direction and then in the weft direction. According to the previous investigations the stress of the composite material with the woven fabric outside the warp and weft direction considerably reduces fabric breaking force. Through the action of the external force on the composite material the internal cohesion forces resist more strongly to the warp and weft direction in relation to other directions. The relaxation of the internal forces in the state of stress begins earlier if the force acts under a certain angle in relation to the warp and weft direction. This phenomenon defines fabric anisotropy which reflects on the composite material with one or more fabric layers. Load is expressed as the ratio of the internal forces acting on the area unit of the sample [5-7].

Deformations of the materials used for making clothing occur in joint areas such as elbows, knees and sitting trouser part due to multiaxial loading. After longer loading in the places mentioned deformations occur expressed as irreversible elongation and baggy appearance of the garment at this place. Using composite materials reduces this phenomenon in relation to standard fabrics, especially by use of nanopur coating on the back side of the fabric because it increases durability and strength of the composite material, while on the other hand it decreases anisotropy.

To join the fabric with other materials a binder for better adhesion or only thermal joining is used. Figure 1 shows examples of laminating a fabric to a fabric or fabrics with other materials.

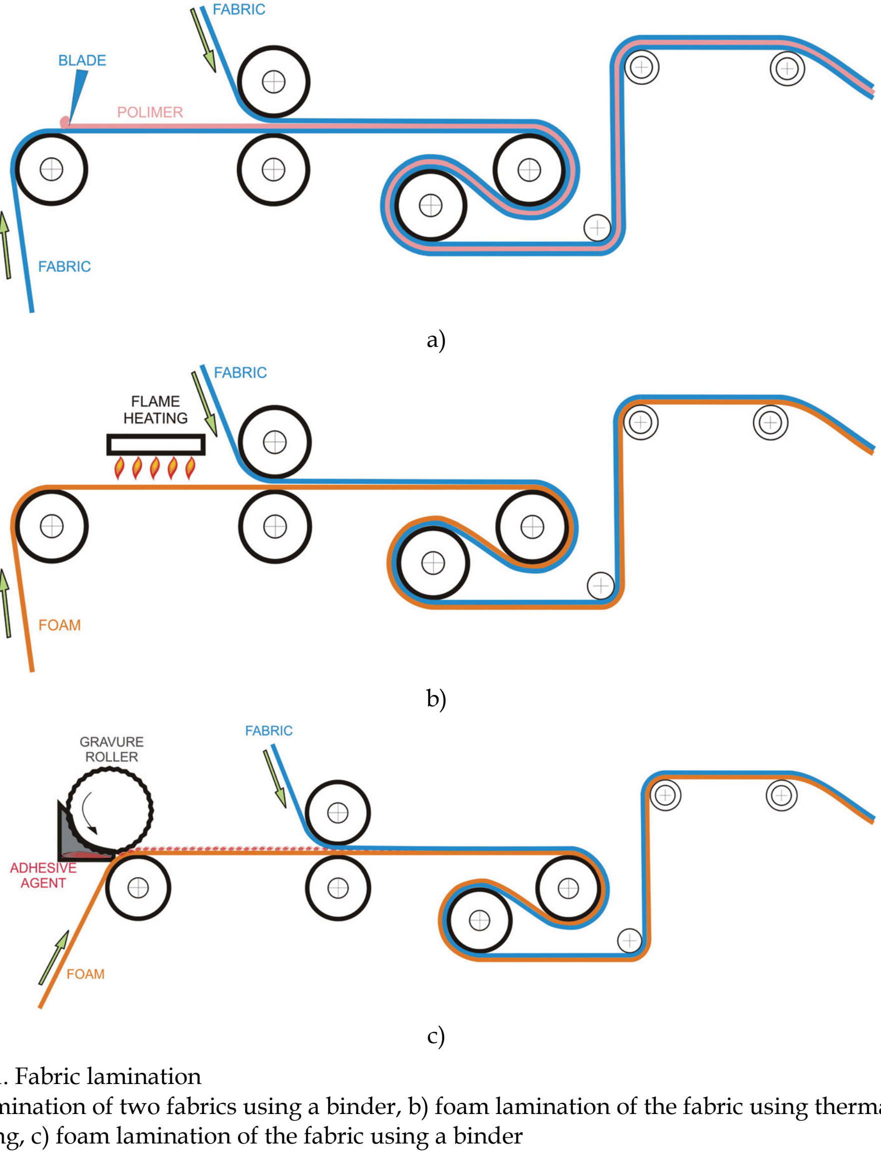


Fig. 1. Fabric lamination
a) lamination of two fabrics using a binder, b) foam lamination of the fabric using thermal joining, c) foam lamination of the fabric using a binder

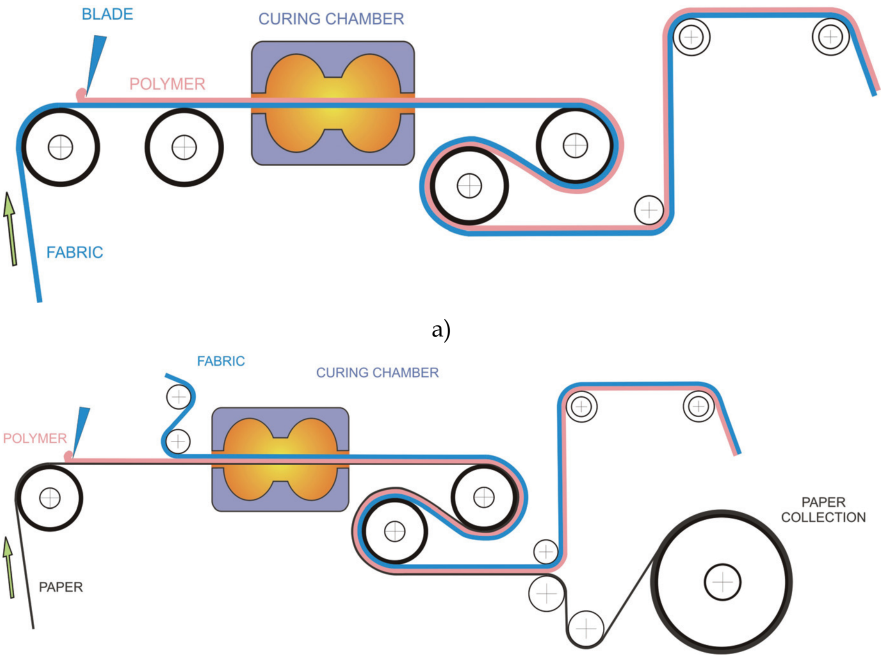
3. Polymer coating on the textile material to produce the so-called artificial leather

Polymer coating on the textile material provides new properties of the fabric. Polymer-coated textile materials have a wide range of application, from the textile industry to technical textiles. The advantage of this kind of textiles in the clothing industry is their water impermeability, while on the other hand they are air and water vapor permeable, resulting in good properties of concurrent protection and comfort. Depending on the use, nonwoven, woven or knitted fabric is used as coating substrate. As far as their properties are concerned, new man-made fibers or materials can be similar to natural or even they can surpass the properties of natural fibers, resulting in an increasing application for coated materials. Nowadays companies are adapting to new challenges, they are trying to expand the domestic and world market; thus, it is understandable that great efforts are being made to develop new products and to improve the properties of the available ones. As the substrate for coated materials synthetic (perhaps better to say artificial than synthetic) materials are frequently used due to their relatively high strength and good abrasion resistance. Artificial materials possessing high elasticity, airiness and appropriate strength are used as the substrate for coated materials. They are mostly used for protective and sports clothing for children and adults.

It is important that the properties of the substrate meet the requirements of the final product. The following substrate parameters are of special importance:

- good mechanical properties such as elasticity, elongation at break, strength, frictional resistance,
- type of yarn: filament and texturized yarn, where spun yarn exhibits good adhesion because of protruding fibers which excellently join with the coat, but when making thin polymer materials these short hairs or cut filaments can penetrate the surface, causing water permeability of the fabric,
- dimensional stability,
- adhesion, absorption – the substrate must have good binding properties so that the coating could penetrate the substrate to a sufficient extent, and binding characteristics could improve by addition of the binding agent either in the pretreatment of the substrate or in the PU coat,
- pretreatment – agents such as softeners and dyes can negatively affect the subsequent production procedure; several treatment types, such as water repellent and antibacterial treatment can improve the properties of the final product,
- thermal stability – PU coating requires high temperatures to form the film, and thus the substrate have to endure high temperatures,
- uniformity of the substrate – uniform substrate thickness is a particularly important feature for subsequent treatments [4, 8, 9].

Polyurethane is mostly used for coating the textile material. The coating procedure can be direct or using siliconized paper. When polyurethane is coated directly, the polymer is coated using special coating blades indirectly to the textile material (Fig. 2a). When coating is indirect, the polyurethane polymer is coated first to the paper, and then is laminated with the substrate and the textile material respectively (Fig. 2b). When it is first coated to the paper, it can be in several layers. After each coating, the polymer is dried and cooled down. Upon completion of the coating procedure, the paper is separated from the finished material. The paper returns to the machine entry and can be used for further coatings, approximately from 8 to 10 times. This method is applied for low density fabrics so that the coated polyurethane remains on the back of the textile material and cannot penetrate to the front side. By adhesion to the fabric and by partial penetration into the fabric structure the PU coat remains permanently bonded and fused into a compact material. The composition of the layers in case of indirect PU coating does not need to be always the same, neither in the composition nor in the coating thickness. Both the material composition and the coating thickness and the number of coating procedures depend on the application of the final product.



b)

Fig. 2. Schematic of the process of polyurethane coating
a) Direct coating with one passage, b) Indirect coating using silicone paper with one coating passage

3.1 Polyurethane (PU) coating

The selection of polymers is very important to obtain desirable properties of the finished product, and the coating composition is determined according to the application of the finished product.

The coating consists of the basic polymer and additives. In the selection of the basic polymer the properties are as follows: thermo plasticity, mechanical properties of polymers, possibility of film formation, stiffness, good adhesion, abrasion resistance, heat, water and air conductivity, resistance to solvents and hydrolysis, resistance to UV radiation, melting point etc.

The basic polymer is mostly polyurethane that may be strong and rigid, soft and elastic. Polyurethanes belong to the group of very durable plastic materials. The main property of polyurethane is its wide application. It can be coated to textiles, leather, in solution, dispersion, with a low solvent content or without it, as granules or powder. Softness or hardness can be obtained by varying polymer structures.

Polyurethane has good washproofness and cleaning resistance, good adhesion to the fabric, good durability at low temperatures, it is possible to use it without softeners, it has good viscosity and abrasion resistance, at the same time it has a pleasant and soft touch, a low specific mass, resistance to oils and fats. Polyurethane can be coated to textile materials in more ways:

- as a two-component polyurethane with isocyanate cross-linking,
- as one-component aromatic or aliphatic polyurethanes with chemical reactions performed in the production, and during the coating and drying process it is linked between evaporation chains and solvents,
- as a one-component product that enables dispersion in water and is environmentally friendly
- as a solid product with possible coating of greater quantities in each coating passage,.

3.2 Additives

Additives improve properties of coating polymers such as:

- softeners imparting better flexibility and softness of the finished multilayered product, and they enable a more uniform distribution of the polyurethane paste (Vithane),
- cross-linking agents and binders that improve the bond between the textile material and the coated polymer (Larithane CL 1, Larithane MA 80, Toulen),
- antimicrobial agents (Sanitized),
- light fastness agents (Tinuvin),
- various pigments for dyeing the polymer coating (pigments).

To achieve a good material quality, it is very important to dose the solvent regularly in the binding coating. Too small a quantity of the solvent in the binding coating causes the swelling of the binder instead of its dissolving, resulting in poor bonding of the material to the substrate. On the other hand, too great a quantity of the solvent in the binding coating causes too rapid dissolving of the binder, resulting in too great penetration of the PU coating into the substrate. The final result is too great material rigidity [5].

4. Properties of coated textile materials

Properties of coated textile materials primarily depend on their application. Nowadays modern technologies, optimization of the conditions of the production process and use of certain agents and recipes enable making a target product which will meet all the requirements. Since it is not possible to use the classic textile for many technical purposes, excellent properties are obtained by combination with other substances which are coated in the form of paste or laminated to the material. By use of the value-added material, nanoproducts and modern technology the use of textile materials has been enhanced several times. For the purposes of this study samples of the woven fabric with nanopur coating on the back side were chosen to test basic properties. They are used for police and military uniforms. The fabrics have the same construction parameters in different colors and different properties of the nanopur coating (Tables 1 and 2).

Likewise, samples of the artificial leather with polyurethane coating on the knitted fabric, namely with different properties of polyurethane in two colors (Table 3), will be considered.

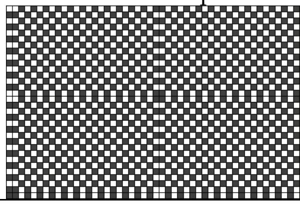
Woven fabric parameters	Yarn/woven fabric			Laminated fabric		
	Green	Blue	Camouflage (printed)	Green	Blue	Camouflage (printed)
Fabric weave	Plain weave + Rep weave 					
Thread density/10 cm warp / weft	360 / 207					
Count of warp/weft (tex)	17x2 / 40					
Raw material composition of warp/weft	(PA 6.6/ cotton 50/50) / (PA 6.6/ cotton 50/50)					
Warp yarn twist single/plied/weft (turns/m)	938/622/673					
Fabric thickness + nanopur coating (mm)	0.39	0.39	0.39	0.41	0.41	0.41
Mass (g/m²)	217	220	211	266	271	259

Table 1. Basic parameters of fabrics and yarns in fabrics

Laminate	Color	Nanopur coating	Properties of laminated fabric
1	Green	Nanopur FR 30 – 30 g/m²	Not made water-repellent
2	Dark blue		Made water-repellent
3	Camouflage		Made water-repellent

Table 2. Properties of the laminated fabrics and polyurethane nanopur coating

4.1 Anisotropy of multilayered materials

Coated textile products either as artificial leather or as laminates assume properties of the materials they are made of. Since they are partially made of the textile that is in its properties mostly anisotropic, coated material as a whole is also anisotropic, meaning that the coated material behaves differently in different direction when stressed.

Two features are differentiated related to material load, namely: determination of the dependence of strength on the direction of force application in relation to the directions of the body structure known as anisotropy and assessment of the strength of anisotropic bodies in the case of complex states of stress [10-14].

Anisotropy of woven and knitted fabric is outstanding. Anisotropy is reduced by addition of a coating agent, but it is not eliminated. Thus, the properties of coated materials do not only depend on the components, but also on the direction of load.

In woven fabrics laminated with nanopur coating outstanding anisotropy is observable in all three samples (Figs. 3 and 4). The differences in the samples are in fabric color and hydrophobicity (Table 2). An exceptionally high anisotropy is present in the fabrics without nanopur coating. The highest anisotropy of breaking forces is visible in the camouflage fabric, and the lowest one in the single-colored, blue fabric. The highest sensitivity of all the fabrics is when they are loaded at an angle of 15°, then at an angle of 75° followed at angles of 30° and 60°. The essential point is that the fabric at an angle of 45° is even more strongly than in the weft direction. This means that the threads in the binding points are strongly bound and they do not allow shearing at an angle of 45°. Since the fabrics were woven in the combination of plain and rep weave with a relatively high density in the warp and weft direction, their compactness is outstandingly high. The thermal joining of the nanopur foil

<table>
<tr><th>Sample</th><th>Color</th><th>Mass (g/m²)</th><th>Thickness (mm)</th><th>1st coating</th><th>2nd coating</th><th>3rd coating</th><th>Knitted fabric</th><th>Property of artificial leather</th></tr>
<tr><td>I</td><td>White</td><td>185</td><td>0.58</td><td rowspan="2">Larithane AB 4228</td><td rowspan="2">Larithane AB 4228</td><td rowspan="2">Ucecoat ID 9229</td><td rowspan="6">Plain jersey, mass: 90 g/m², raw material composition 100% PA 6.6, thickness: 0.45 mm</td><td rowspan="2">Standard recipe</td></tr>
<tr><td>Ia</td><td>Blue</td><td>175</td><td>0,56</td></tr>
<tr><td>II</td><td>White</td><td>188</td><td>0.55</td><td rowspan="2">Larithane AB 4228 + Lomaflam TDCP</td><td rowspan="2">Larithane AB 4228 + Lomaflam TDCP</td><td rowspan="2">Ucecoat ID 9229</td><td rowspan="2">Additional flameproof treatment in the 1st and 2nd coating</td></tr>
<tr><td>IIa</td><td>Blue</td><td>174</td><td>0.55</td></tr>
<tr><td>III</td><td>White</td><td>187</td><td>0.50</td><td rowspan="2">Larithane AB 4228 Larithane AB 4228</td><td rowspan="2">Larithane AB 4228 Larithane AB 4228</td><td rowspan="2">Larithane BTH 146 + Larithane CL 16</td><td rowspan="2">In the 3rd coating polyurethane was used, it has greater water vapor permeability</td></tr>
<tr><td>IIIa</td><td>Blue</td><td>163</td><td>0.48</td></tr>
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Table 3. Basic parameters of polyurethane coating, knitted fabric and artificial leather

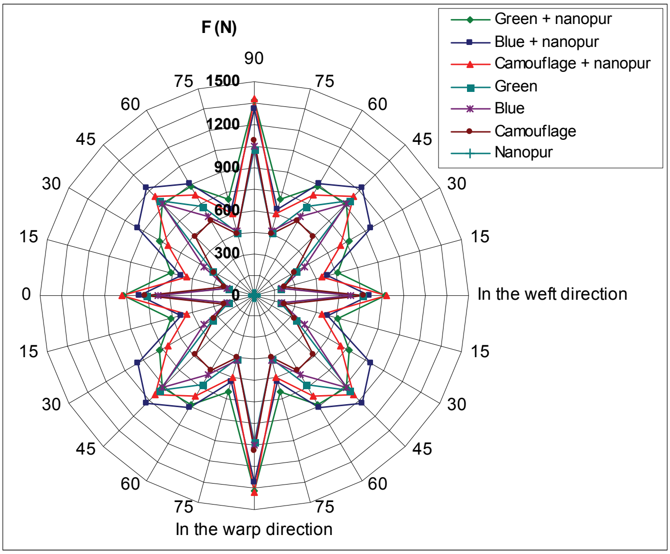


Fig. 3. Breaking force in different directions

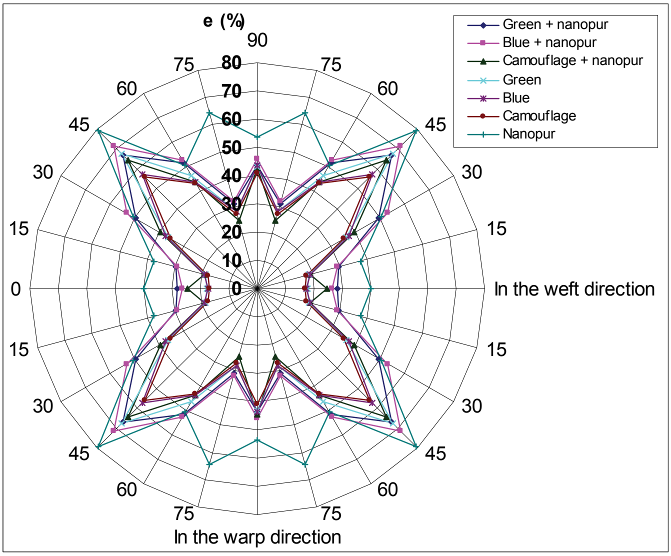


Fig. 4. Elongation at break in different directions of the fabric samples with nanopur coating

to the back side of the fabric increased material strength and reduced fabric anisotropy. However, anisotropy is present and follows the course of fabric anisotropy. The nanopur foil does not have outstanding strength and is almost invisible in the polar diagram. The breaking forces of the samples containing the fabric mostly followed the course of breaking forces, except in the weft direction where elongation at break is the lowest. The nanopur foil has an outstandingly high elongation at break which is in most cases higher than in the samples containing the fabric and its anisotropy is lower. The highest elongation at break occurs in all samples at an angle of 45°, and the lowest in the weft direction.

In the case of artificial leather the material strength is changed by altering the composition of coating (Fig. 5). Anisotropy of all materials in all testing directions is noticeable. Nevertheless, the course of the curve of breaking forces is almost identical in all three samples, and there is no difference among the samples. The greatest sensitivity of all materials is at angles of 15° and 30°. The highest breaking forces are in the warp direction or in the sample length, then at angles of 75° and 60°. In the weft direction or in the sample width breaking forces are similar as in the direction of 45°. The knitted fabric has a little lower breaking force than the artificial leather in all testing directions, meaning that the breaking force did not increase substantially by coating the polyurethane layer to the knitted fabric. Elongation at break is also different according to testing levels, and there is no particular difference among the samples (Fig. 6). The highest elongation at break is observable in the weft direction in all samples, and it is the lowest at angles of 60° and 75° and in the warp direction. The anisotropy of the artificial leather assumed the anisotropy of the knitted fabric, when observing breaking forces and elongation at break. The samples of artificial leather and knitted fabric for testing breaking force and elongation at break were prepared in dimensions 200x50 mm and tested on the Statimat M tensile tester made by Company Textechno in accordance with the standards ISO 13934-1:1999; EN ISO 13934-1:1999.

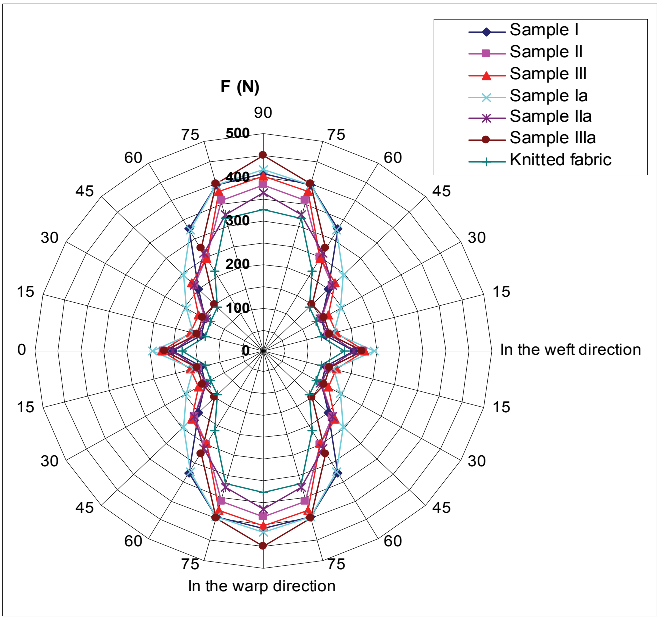


Fig. 5. Breaking force in different directions of the artificial leather (polyurethane coating + knitted fabric) and the knitted fabric before PU coating sample I, II, III - white samples defined according to Table 3; Ia, IIa, IIIa - blue samples defined according to Table 3

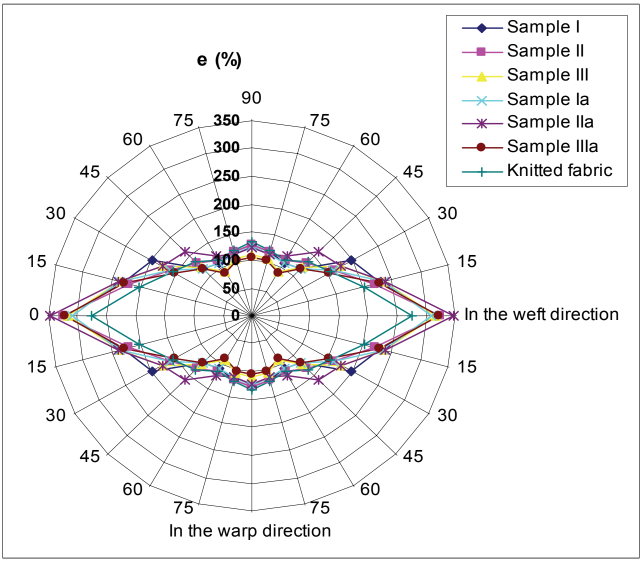
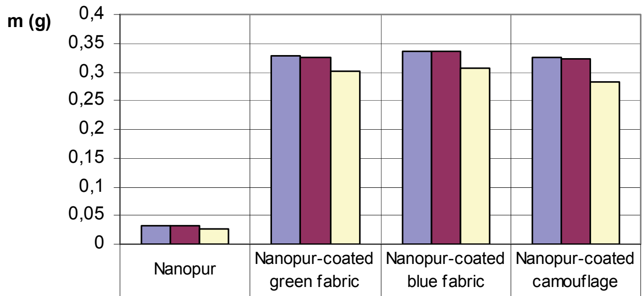


Fig. 6. Elongation at break in different directions of the artificial leather (polyurethane coating + knitted fabric) and the knitted fabric before PU coating sample I, II, III - white samples defined according to Table 3; Ia, IIa, IIIa - blue samples defined according to Table 3

4.2 Abrasion resistance

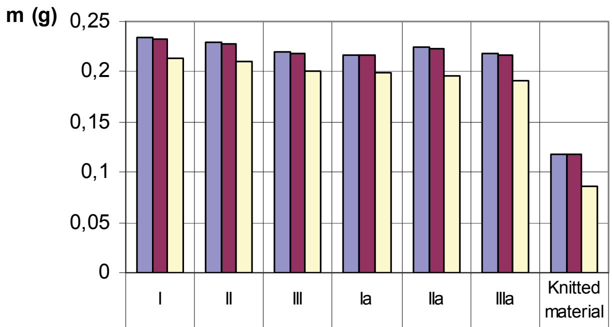
To test the abrasion resistance of laminated fabrics with nanopur coating, the determination of mass loss by the Martindale method after 5,000 and 10,000 cycles according to the standard ISO 12947-3:1998+Cor 1:2002; EN ISO 12947-3:1998+AC 2006 was used. According to the results obtained, a certain difference between the samples of the laminated fabrics and the artificial leather is noticeable. The lowest loss of mass records the blue sample followed by the green sample, while the printed or camouflage sample records the highest difference (Fig. 7).

In the artificial leather with knitted fabric on the back the loss of mass is also different (Fig. 8). The first white sample records a slightly lower loss of mass than the blue sample, while the other two samples in blue color record a noticeably higher loss of mass. This means that the pigments applied in the artificial leather affect the coating in such a way that they reduce abrasion resistance. The white coating has a lower loss of mass than the coating dyed with blue pigments.



	Nanopur	Nanopur-coated green fabric	Nanopur-coated blue fabric	Nanopur-coated camouflage
Mass before abrasion	0,0332	0,327	0,337	0,325
Mass after 5,000 cycles	0,032	0,326	0,336	0,323
Mass after 10,000 cycles	0,028	0,301	0,306	0,282

Fig. 7. Mass loss of the nanopur-coated laminated fabrics



	I	II	III	Ia	IIa	IIIa	Knitted material
Mass before abrasion	0,2335	0,23	0,219	0,21655	0,22385	0,2174	0,11825
Mass after 5,000 cycles	0,23325	0,22845	0,2186	0,216	0,22315	0,2164	0,1171
Mass after 10,000 cycles	0,213	0,21	0,201	0,1983	0,1955	0,191	0,0855

Fig. 8. Mass loss of the coated textile materials

4.3 Bursting strength

The determination of bursting strength with a steel ball was carried out in accordance with the standard AN 12332 1:1998, ASTM 3787 using a strength tester made by Apparecchi Branca S.A., Italy. On the basis of the results obtained there is a difference in bursting strength and elongation at break among the tested fabric samples. The nanopur-coated blue fabric has the highest bursting strength, while the camouflage fabric has the lowest values (Fig. 9). The nanopur-coated blue fabric having the highest bursting strength has the lowest anisotropy (Fig. 10).

Differences in bursting strengths are also visible in the artificial leather (Fig. 10). Samples III and IIIa have the highest bursting strength, while samples I and Ia have the lowest values. It is essential to emphasize that white samples (I, II and III) have higher bursting strength and elongation at break than the blue ones (Ia, IIa, IIIa), which is not the case in testing bursting strength using strip test method (Fig. 5).

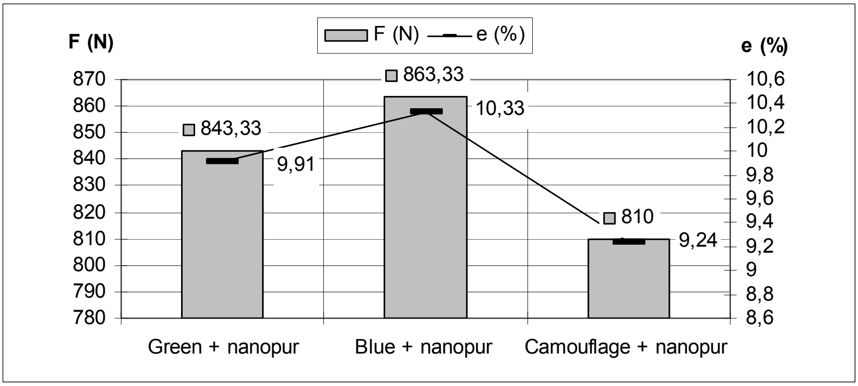


Fig. 9. Bursting strength of the artificial leather

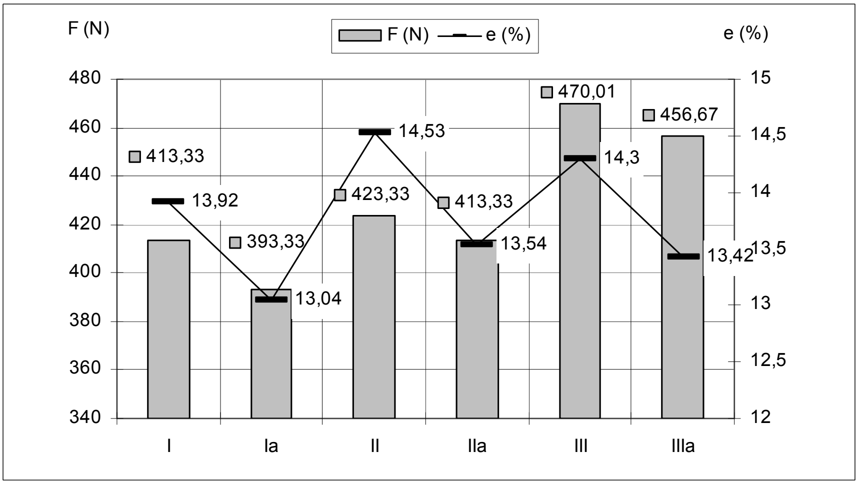


Fig. 10. Bursting strength of the nanopur-coated laminated fabrics

4.4 Thermal resistance

The determination of thermal resistance was performed in accordance to the standard ISO 11092 on the Sweating Guarded Hotplate made by MTNW, USA. According to the results obtained for the laminated fabric samples there is a certain difference (Tab. 4). The white fabric exhibited the highest thermal resistance before and after lamination, while the camouflage fabric exhibited the lowest thermal resistance. In the case of the artificial leather there is also a certain difference in thermal resistance among the samples. Flameproof samples (III white and IIIa blue) have the highest thermal resistance, while the samples with higher water-vapor resistance have the lowest thermal resistance.

No.	Sample designation	Measured value Rct (R_{ct} - m^2KW^{-1})	
		$\overline{X}$	CV (%)
1	Knitted fabric	0,0053	6,71
2	Green	0,0111	5,43
3	Blue	0,0127	7,36
4	Camouflage	0,0115	6,88
5	Green + nanopur	0,0101	4,31
6	Blue + nanopur	0,0113	4.06
7	Camouflage + nanopur	0,0103	5,62
8	Nanopur	0.0091	3,55
9	I	0,0134	4,71
10	Ia	0,0200	3,20
11	II	0,0143	3,70
12	IIa	0,0220	3,75
13	III	0,0105	4,88
14	IIIa	0,0113	3,80

Table 4. Thermal resistance using the sweating guarded hotplate

5. Conclusion

On the basis of the performed theoretical considerations, design of the coated textile products and corresponding properties, it is possible to make a target product which will meet all requirements. In the case of the observed multi-layered textile composites, it is necessary to define material anisotropy in the weakest directions, which are also the most responsible for deformation. In these places deformations in form of changes in material dimensions per unit of length are created and the so-called baggy shape results.

By use of woven fabrics as the basic layer of textile structured multi-layered composites in laminating a relatively high anisotropy occurs which can be reduced by polymer coating. However, due to an exceptionally good strength in the warp and weft direction and its abrasion resistance, breaking and good physiological properties its presence will be relatively widespread in relation to knitted and nonwoven fabrics. The use of the fabric on the composite front side provides great design possibilities such as printed fabric for camouflage military clothing etc.

By coating polyurethane paste to textile materials, materials known as artificial leather is obtained. They occupy an important place on the market. Artificial leather is unthinkable without the textile substrate. In most cases these are woven or knitted fabrics which transfer their properties to the final properties of artificial leather. Since they are materials mostly used as outerwear or upholstery fabrics, their physiological properties are essential. Air,

water and water vapor permeability, their strength and durability depend on the properties of individual properties of coated materials and final products. Since structured multilayered materials consist of different materials and various binders, besides material comfort it is important to pay great attention to their compatibility in different conditions. The target product to meet market requirements can be produced by appropriate selection of recipes for polymer coating, and by determination of construction parameters of the textile fabric as well as raw materials and production conditions.
Subsequent investigations should include multiaxial testing of a series of models with different woven and knitted fabrics in order to reduce anisotropy, especially of the materials being less strong and having higher elongation. A change in polymer coatings and their properties related to textile materials affect final properties of multilayered materials. Likewise, adding a target polyurethane coating and after treatment, even the selection of color can provide a target product with appropriate properties.

6. References

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Porosity of the Flat Textiles

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1. Introduction

Flat textiles play an important role in clothing and as component of composites. Besides of that, it would be difficult to imagine the processes of filtration without the flat textiles. They can be divided into three main groups: woven fabrics, knitted fabrics and non-woven textiles if their design is disregarded. The quality of the flat textiles can be defined by many parameters. In this chapter, we will focus on one of them - the porosity.

What is porosity? How could we define it? Way and where is it important? Usually we have more questions than answers. The porosity in flat textiles is defined as a void part of the textile's full volume. The full textile's volume is usually occupied by a mixture of three components: fibres, air and water. The part of the volume that is occupied by fibres is constant. On the contrary the portion of the volume that is occupied by water may vary considerably. For instance, there is no water in the absolutely dry flat textile, and in the absolutely wet condition, air is replaced by water. The water content in the textiles plays very important role in the clothing insulation due its effect on the clothes' thermal resistance. The coefficient of the thermal resistance of air is much larger than the coefficient of the fibres or water. Hence, it is extremely important to keep the clothing dry in a cold weather.

The coefficient of the thermal conductivity scales in the inverse manner with the coefficient of the thermal resistance and both are frequently used in the literature. The coefficient of the thermal conductivity is not solely influenced by the porosity in terms of its water content in the still weather, but also by the moving air - windy weather - that can penetrate the pores in the flat textiles.

The porosity can be defined by several parameters. The pore distribution is an important parameter and it is seldom well known. Even the average pore size is difficult to estimate. Yet, our aim was to describe the pore distribution by it attributes: average pore diameter, number of pores and distribution of pore diameters in a histogram form. The method that is capable of providing us with all these data is described in this chapter. The surface of the flat textile open to the flow of the fluid is of the interest as well. Additionally, the velocity of the fluid flow through the flat textile, driven by the pressure difference between textiles surfaces, is important when analysing the process of filtration or the properties of clothing. In the latter case the fluid is air.

Clothing has certainly a specific role in our life. It protects us against cold, wind, rain and sun radiation. Clothing must be suitable in the dry and wet, cold and hot weather and in the windy weather. Only one set of clothing can't be enough for all these situations – we do not have the universal clothing. Instead, we use clothing composed in layers. Problem may arise as energy or heat is produced by our metabolism. Heat production depends on the intensity and sort of the activity. Sweating is the body response on its own temperature rise and it is wetting the clothes. The thermal resistance coefficient of the wet clothing is smaller that the dry one. The similar effect can be observed when wind velocity increases. The influence of the temperature, water and wind velocity on the thermal coefficient is show in equation (1) for a flat surface (Jakšić, 2004).

$$R_s = \frac{d_c}{\lambda_0(1 + k_T \Delta T_c + k_w \Delta G_c) + bc_a \gamma_c V_a d_c} + \frac{0.0429}{0.4 + 2.0\sqrt{v}} \tag{1}$$

where R_s stands for the clothing's coefficient of thermal resistance, d_c for the thickness of the clothing, λ_0 for the coefficient of thermal conductivity of clothing in the standard environment, k_T for the coefficient of direction curve temperature - the thermal resistance of the clothing, ΔT_c for the difference of the clothing temperature regarding the temperature in the standard environment, k_w for the coefficient of direction curve for the content of water in clothing - the thermal resistance of the clothing, ΔG_c for the change of the water content in the clothing, b for the coefficient, which describes the tightness of the clothing (if the value is 1, the air flows through the surface of clothing layers and not through the holes in the clothing, c_a for the specific heat of the air, γ_c for the specific mass of the air, V_a for the volume of the air which penetrate through the clothing due to the velocity v of the air flow.

The use the flat textile in the composites and as the geo textiles, the diameters of pores are also very important. For example, in a composite structure the diameters of pores must allow resin a good connection between the layers of the flat textile. The pores must simply be large enough to allow resin penetration. On the other hand, the diameters of pores in woven fabrics used as geo textiles must be small enough to effectively filtrate earth particles. Pores in the woven fabrics are voids between threads of the warp and weft and the light can go directly through. This sort of material is not suitable for use in the masks destined for protection against viruses. Viruses are extremely small and we can't get pores in textiles to be smaller. Hence, non-woven fabrics are used for the masks design in spite of the fact that the pores are many times larger than the viruses. The walls of pores are defined by fibres, and not by treads, in the non-woven fabrics. Pores change direction many times from one surface of the non-woven fabrics to another. The probability for the aerosol flowing through such a pore to deposit fine solid or liquid particles including bacteria and viruses on the fibres is extremely high, even 100% for some limited time. The micro fibres, which diameter is about 1 to 2 micrometers, must be used for this purpose. The porosity of the non-woven fabrics is high enough to enable us to breathe normally. The protection against microbes and viruses are tested in the special laboratories. However, if we could measure the composition and the porosity of masks, the number of those tests would be reduced. It would be enough to estimate porosity only, but it is not so strait forward without a suitable method.

We have developed a method for the assessment of the parameters of the porosity in all flat textiles. The method is relatively simple and efficient at the same time. The apparatus for measuring the airflow through a flat textile sample due to the pressure difference is needed. The application software has been developed on a basis of the method's algorithm.

2. Methods for estimating the porosity of the flat textiles

There are several different methods available for the assessment of the parameters of porosity, such as: geometrical methods (Matteson & Orr, 1987), (Piekaar & Clarenburg, 1967) and (Dubrovski & Brezocnik, 2002), liquid intrusion methods (Dosmar et al., 1993), (Rucinski et al., 1986) and (Rebenfeld & Miller, 1995), liquid extrusion methods (Miller & Tyomkin, 1986a), (Miller & Tyomkin, 1986b) and (Rushton & Green, 1968), liquid through methods (Hssenboehler, 1984), etc. Some of them can only give truly very approximate values, which may not be accurate enough. On the other hand some of them are not capable of estimating all the relevant porosity parameters.

A lot of work has been done over the years to overcome the mentioned shortcomings. We have developed a method for estimation of the parameters defining the textile's porosity. The method is suitable for all types of flat textiles: woven fabrics, knitted fabrics and non-woven fabrics (Jakšić, 2007). We have named it J-method after the first letter of authors' surname.

Main feature that set J-method apart of the other methods is that J-method is also suitable for the non-woven fabrics.

3. Theoretical bases for J-method

A flat textile product gets wet and the fluid pushes the air out of the product - especially from voids, if the product is immersed into a fluid. These voids are formed out of pores between fibres in the non-woven fabrics, as well as out of pores between threads in the woven and knitted fabrics. The pores between the threads of the warp and weft in the woven fabrics, figure 10a, are the most interest from the practical point of view. The pores between the threads of the warp and weft are well defined in textile fabrics made of monofilament and of some multifilament yarns. The pores can be counted on a defined area in such cases. This is not the case with the fabrics made of wool yarn where some fibres jut out of the yarn and thus cover the pores. A pore is thus divided into several smaller pores. It is thus impossible to ascertain the exact number of pores in the non-woven fabrics.

The porosity parameters that are needed in most of the cases are: the pore size distribution, the average hydraulic pore diameter, the open area for fluid flow and the air volume velocity as a function of the air pressure. The method under consideration is able to provide mentioned parameters with sufficient accuracy.

The method is based on selectively squeezing the fluid in the pores out of the wet fabrics by air pressure and on the presumption that a pore is approximated with a cylinder. The selectivity is assured by the fact that the fluid is squeezed out of the pores with a certain hydraulic diameter providing that the precise value of the air pressure is applied. The air pressure is inversely proportional to the hydraulic diameter of the pores (see equation (3)). Latter is important, while the process of squeezing out the fluid contained in the pores of the wet fabrics is under examination. There is always a small amount of the fluid that remains at the edges of pores if such edges exist.

The pore cross-section is approximated by a circle of the diameter d. The parameter d is the hydraulic diameter of the pore. It is defined by equation (2) where f denotes the surface of the cross-section of the pore, o the circumference of the cross-section of the pore w, the width of the pore cross-section and l denotes the length of the pore cross-section.

$$d = \frac{4f}{o} = \frac{2wl}{w+l} \tag{2}$$

The pressure difference p_i between the opposite surfaces of the flat textile, equation (3) and (4), results in squeezing the fluid out of the pores, which diameter is equal or larger than d_i. The fluid is characterised by the surface stress α.

$$d_i \geq \frac{4\alpha}{p_i} \tag{3}$$

$$p_i = \rho g h_i \ ; d_i \geq \frac{4\alpha}{\rho g h_i} \tag{4}$$

The fluid is first squeezed out from pores, which have the largest hydraulic diameter. The flow of air will establish itself through these pores that are now empty. The volume flow rate of air through the flat textile can be described by equation (5)

$$V_i = Ap_i^b = Pap_i^b = Pv_i \tag{5}$$

where V_i stands for the air volume flow rate through the sample at the air pressure p_i, A for a regression coefficient when fitting equation (5) to the measured dry data, P for the open surface, v_i for the linear air flow velocity, a for the coefficient and b for the exponent. The parameters a and P are unknown and they have to be estimated as well. The solution of the problem is enabled by equation (6) by putting the velocity v_i in the relationship with the air pressure p_i. The value for the exponent b is bounded between 0.5 and 1.0. The air volume flow rate depends on the degree of porosity of the flat textile fabrics and the air pressure difference between the two surfaces of the fabrics. Larger porosity means larger air volume flow rate through the fabrics at the constant pressure. The last part of equation (6) holds in the ideal circumstances, when all of the energy dissipation mechanisms are neglected.

$$v_i = a_0 p_i^b = 1.28 p_i^{0.5} \tag{6}$$

Suppose that the fluid is squeezed out from the largest n_1 pores with hydraulic diameter of d_1 at the pressure difference p_1. The volume flow rate of V_1 is thus established through empty pores, equation (7).

$$V_1 = \frac{\pi d_1^2}{4} n_1 v_1 = \frac{\pi}{4} a p_1^b n_1 d_1^2 \tag{7}$$

Additional n_2 pores will open at p_2, $p_2 > p_1$, and the volume flow will rise to value V_2, equation (8).

$$V_2 = \frac{\pi}{4} a p_2^b (n_1 d_1^2 + n_2 d_2^2) \tag{8}$$

The pressure value can be increased incrementally till all pores are opened. Hence at the i^{th} incremental step the volume flow rate is V_i, equation (9).

$$V_i = \frac{\pi}{4} a p_i^b \sum_{j=1}^{i} n_j d_j^2 \tag{9}$$

The selective squeezing out the fluid from pores as described in equations from (3) to (9) enables us to compute the number of pores at each interval defined by the incremental pressure growth. The number of pores of the first interval n_1 can be estimated as

$$n_1 = \frac{4V_1}{\pi a p_1^b d_1^2}, \tag{10}$$

for the second interval as

$$n_2 = \frac{4}{\pi d_2^2}\left[\frac{V_2}{a p_2^b} - \frac{\pi d_1^2}{4} n_1\right], \tag{11}$$

and for the i^{th} interval as

$$n_i = \frac{4}{\pi d_i^2}\left[\frac{V_i}{a p_i^b} - \frac{\pi}{4}\sum_{j=1}^{i-1} d_j^2 n_j\right]. \tag{12}$$

It is clear from the equation (9) that

$$\frac{\pi}{4}\sum_{j=1}^{i-1} d_j^2 n_j = \frac{V_{i-1}}{a p_{i-1}^b} \tag{13}$$

and hence, equation (12), which defines the number of pores in the i^{th} interval, can be rewritten as

$$n_i = \frac{4}{\pi a d_i^2}\left[\frac{V_i}{p_i^b} - \frac{V_{i-1}}{p_{i-1}^b}\right] \tag{14}$$

and by taking into account equation (3), the final form of the equation for the number of pores in the i^{th} interval can be derived as

$$n_i = \frac{p_i^2}{4\pi a \alpha^2}\left[\frac{V_i}{p_i^b} - \frac{V_{i-1}}{p_{i-1}^b}\right] \tag{15}$$

The air volume velocity through the wet sample depends on the air pressure and on the open surface of the sample. As the pressure increases, the open surface increases as well due to the squeezing the fluid out of pores with smaller hydraulic diameter. Hence, the rise of the air volume flow rate is consequence of the open surface and the pressure growth. As a consequence the sequential pore opening of the wet sample is achieved by increasing the air pressure gradually when testing. When the pressure is increased then the open surface and the linear velocity of the airflow is also increased. This enables us to calculate the portion of air volume flowing through the empty pores and to calculate the number of pores in i^{th} pore's diameter interval by starting from the first interval with the pores with the largest hydraulic diameter, equation (7), where p_1 and V_1 stand for the air pressure and the volume flow rate respectively when the first air bubble is spotted during the testing of the wet sample.

The presumption of the equal regime of the airflow through the wet sample's open area and the dry one at the same pressure is taken into account. Small values of the Reynolds number,

Re < 50, in the extreme causes (maximal hydraulic diameter of pore), support that presumption. The airflow is either laminar through open pores in the wet sample and through all pores in the dry sample, or the type of the airflow is the same. This is the criterion for using the exponent b, which is estimated when equation (5) is fitted to the measured dry data, in the process of determining the pore distribution from the measured wet data.
The method's algorithm can be presented in step-by-step scheme:

1. The measurements of the air volume velocity flowing through a dry sample as a function of the air pressure at several distinct air pressures produce the "dry data".
2. The measurements of the air volume velocity flowing through a wet sample as a function of the air pressure at several distinct air pressures produce the "wet data".
3. The weighted power approximation is fitted to the dry data, and thus the exponent b is estimated, see equation (5).
4. The approximating cubic splines are fitted to the wet data thus smoothing it.
5. The porosity parameters are computed with the help of b, estimated in the step 3, and with the help of smoothed wet data together with equations (2) – (4) and (6) – (15).
6. The procedure is repeated at step 3 on the portion of measurements (at the pressure interval) where pores were identified in the first algorithm sweep.

When the dry and wet data are measured (steps 1 and 2) the numerical data processing can start. A computer application was built for that purpose to enable one to interactively carry out the porosity parameters numerical computation. A user interaction with the application is needed at steps 3 and 4 when choosing weights to the approximations used to fit the dry and wet data and at the step 5 where a user chooses between two procedures for computing porosity parameters and defines the length of the base interval of the pore diameter distribution (histogram). At step 6 the algorithm is repeated from the step 3 on. The exponent b is computed on the portion of the dry data measurements (pressure interval) where pores were identified in the first algorithm sweep. The upper limit is the pressure, which squeezes the fluid from the smallest hydraulic pore detected by the first algorithm sweep.
Two different procedures are foreseen depending on the type of the flat textile under consideration. The first procedure is suitable for the flat textiles where the number of pores between threads of the warp and weft is known e.g. very thick monofilament woven fabric (sample d). The second procedure is used in other cases e.g. cotton fabric woven out of cotton yarn (sample a).
The corresponding coefficient a_j are also determined by equation (16)

$$a_j = 1.28\frac{n_{cj}}{n_t} = \frac{1.28}{a^*}\ ;\ a^* = \frac{n_t}{n_{cj}} \tag{16}$$

where n_t stands for the true number of pores, n_{cj} for the computed number of pores and a_j for the corrected a in equation (11). The values of theoretical limits, for exponent b (b_0 = 0.5) and coefficient a (a_0 = 1.28), that are used in the second procedure are shown in the last part of equation (6).
The first procedure is totally valid for the monofilament woven fabrics, which have the same or similar density of the warp and weft and have threads of the yarn of the similar size (yarn count) and quality. It can be used for monofilament and multifilament fabrics, which have similar density of the warp and weft and if the coefficient a_0, equation (6), is smaller then 1.28 (theoretical maximum). A single pore between threads of the warp and the weft can be

counted for several hydraulic pores if pores are of rectangular shape (sample b) due to the differences in the densities of the threads of the warp and the weft or due to differences in fineness of the yarn and possibly due to the binding. The value of the coefficient a_0 is greater than theoretical maximum and the computation of the porosity, is continued by using the second procedure.
As a rule, the second procedure should be used if the number of pores is unknown or a_0 is larger than 1.28 or the type of fabrics unsuitable for the first procedure is used. The number of pores in intervals are computed first by using equations (10) and (15) and using maximal value of the coefficient a (a_1 = 1.28). The computed number of pores is minimal and so is the corresponding estimated open surface. If the computed coefficient a_0 is larger than 1.28 then the true value of the coefficient a, is computed as quotient between a_1^* and a_0'. Whole procedure is repeated with newly computed a. For example $a_1' = 1.28$; $a_0' = 8$; $a_0'/1.28 = 6.25$; $a_1/6.25 = 0.2048 = a$; $a_1^*/a_0' = 0.2048 = a$; $a_0 = 1.28$.

4. Experiment

Four different samples were used for the method's testing, which practically encompasses all the fabric types that the method is suitable for. The basic design parameters of the woven fabrics are presented in table 1. They are made of monofilament, multifilament and cotton yarn. The measured average pore's hydraulic diameters of the textiles are in the interval of 18 up to 200 micrometers. The wide assortment of textiles is thus covered.

Sample	Description	Interval of measurement [μm]	Numbers of pores per cm^2	Warp/weft, threads per cm
(a)	Cotton woven fabric	160 – 20	452	22/21
(b)	Thick monofilament fabric	80 – 10	2200	55/40
(c)	Multifilament woven fabric	270 – 140	960	32/30
(d)	Very thick monofilament woven fabric	24 – 12	32400	180/180

Table 1. Samples used in the testing of J-method

The results of the textile's porosity tests are presented in table 2 and in figures 1 – 8. The first procedure is used for all four samples. The second procedure was used for porosity parameters estimation of samples (a) and (b) due to large value of the parameter a_0.
We worked under two presumptions:

- The regime of the airflow through the dry and the wet sample is the same at same pressure difference regardless of the size of the open area of the wet sample.
- The number of the hydraulic pores is not the same as number of pores between threads of the warp and weft if the ratio of the rectangular sides, which represents real pore's cross-section, is at least 3:1.

The first presumption applies that the airflow regime through all pore's should be the same regardless of their diameter. This is certainly true for sample (d) due to the fact that the 90% of all pores are in the interval between 18 and 20 micrometers. If the regression parameters of the air flow through dry samples are obtained on the measurement's interval of pressures where pores actually exist then the values of the pore's average diameter obtained by the microscope and the scanning-electron microscope are in good agreement with those obtained with the method presented here indicates justification of the presumption of the same regime of the air flow through dry and wet sample at the same pressure difference. This holds for all tested samples due to low Reynolds number. Reynolds numbers have values 12 and 39 for flow through sample (d) and sample (c) respectively, if we take into account the average hydraulic diameters of 18.78 μm for sample (d) and 199 μm for sample (c). Hence, the flow through all samples is laminar and the exponent b, which is estimated by equation (5), can be used in equations (7) – (11).

The nomenclature in table 2 – b stands for the exponent in equation (5), h [μm] for the width of the interval of the pore distribution, m for the number of the distribution intervals, n_t for the true number of pores between the threads of the warp and the weft per cm^2, n for the computed number of hydraulic pores between the threads of the warp and the weft per cm^2, when the true number of pores (or number of hydraulic pores) is unknown (second procedure), d for the average hydraulic diameter of pores, d_t for the optically measured average hydraulic pore diameter – for samples (b), (c) and (d); the pores are ill-defined in sample (a), P [%] for the average open hydraulic flow area, P_t [%] for the average open flow hydraulic area computed on the bases of the optical experiment, a_0 for the coefficient a, equation (5), at presumption that exponent b has minimal value (b = 0.5).

Porosity test procedure	Parameter	Samples			
		(a)	(b)	(c)	(d)
Porosity parameters when the number of pores is known (first procedure)	b	0.5794	0.6647	0.8329	0.7174
	h [μm]	14	10	13	2
	m	10	7	10	7
	n_t	452*	2200	960	32400
	d [μm]	45.04	31.37	200.45	18.84
	d_t [μm]	53	30	199	18.78
	P [%]	0.98	2.07	31.32	9.06
	P_t [%]	1.00**	3.43	29.84	8.98
	a_0	9.4074	2.3872	0.28	0.8791
Porosity parameters when the number of pores is unknown (second procedure)	d [μm]	45.00	31.35		
	P [%]	6.96	3.87		
	n	3314	4115		
	a_0	1.28	1.28		

Table 2. Parameters of porosity estimated with J-method for all four samples. * – the number corresponds to the product of the warp and weft. ** – corresponds to the 452 measured pores – between the threads of warp and weft only one typical pore was measured in each void between the threads of warp and weft.

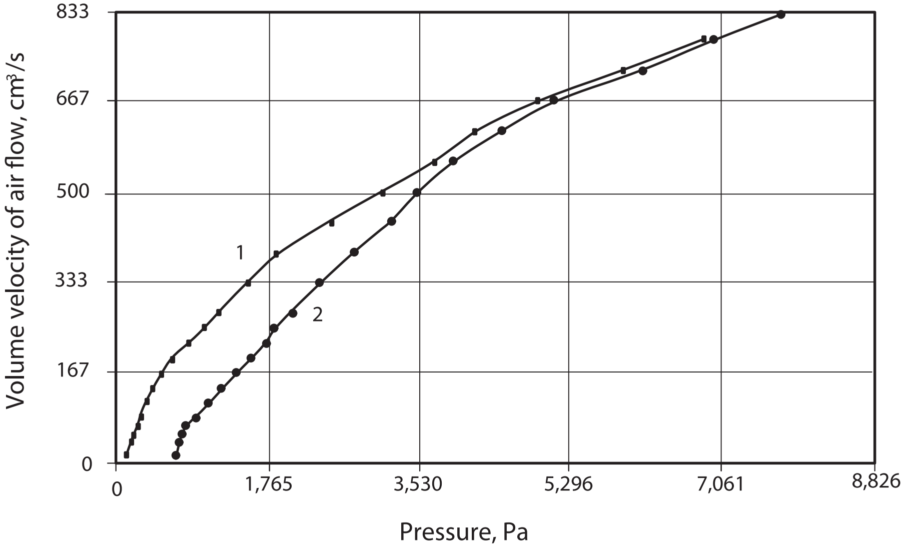


Fig. 1. Diagram of the volume velocity flow through open area of the sample (a) as a function of the pressure difference; 1 - velocity of the air through the dry sample; 2 - velocity of the air flow through the wet sample

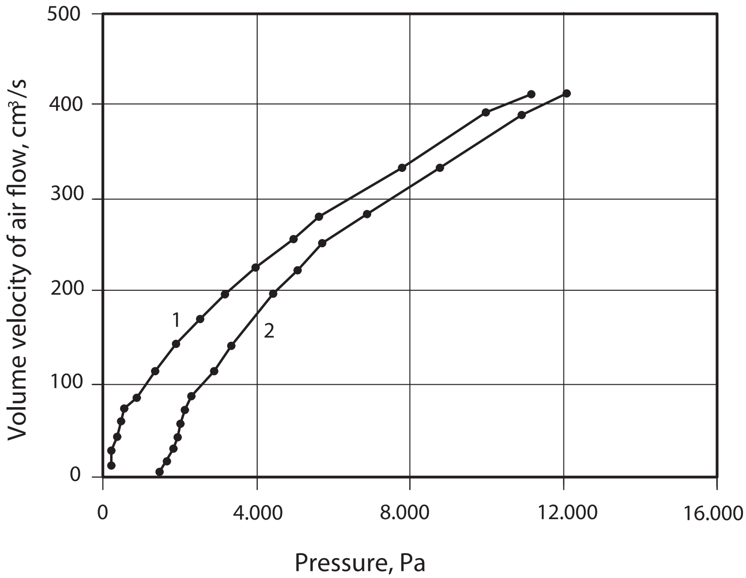


Fig. 2. Diagram of the volume velocity flow through open area of the sample (b) as a function of the pressure difference; 1 - velocity of flow air through the dry sample; 2 - velocity of the air flow through the wet sample

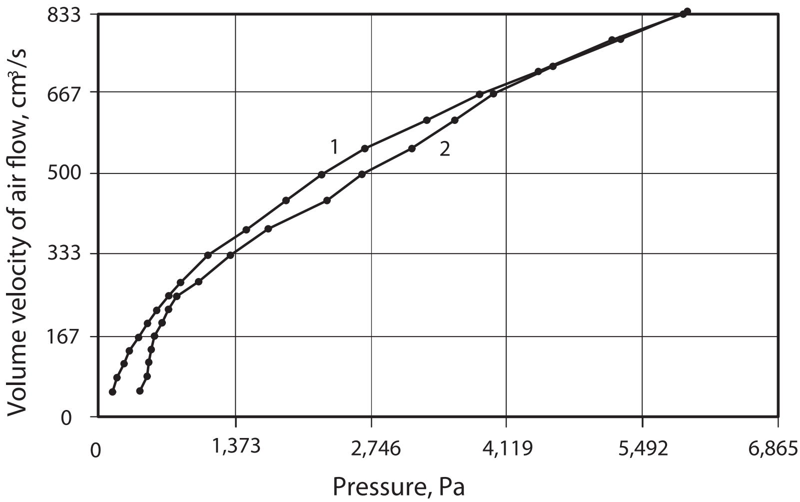


Fig. 3. Diagram of the volume velocity flow through open area of the sample (c) as a function of the pressure difference; 1 - velocity of the air flow through the dry sample; 2 - velocity of the air flow through the wet sample

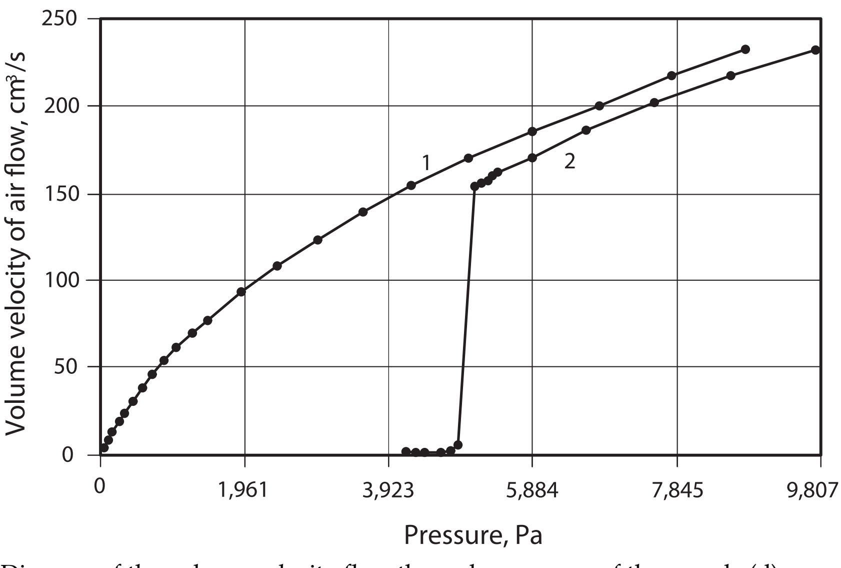


Fig. 4. Diagram of the volume velocity flow through open area of the sample (d) as a function of the pressure difference; 1 - velocity of the air flow through the dry sample; 2 - velocity of the air flow through the wet sample

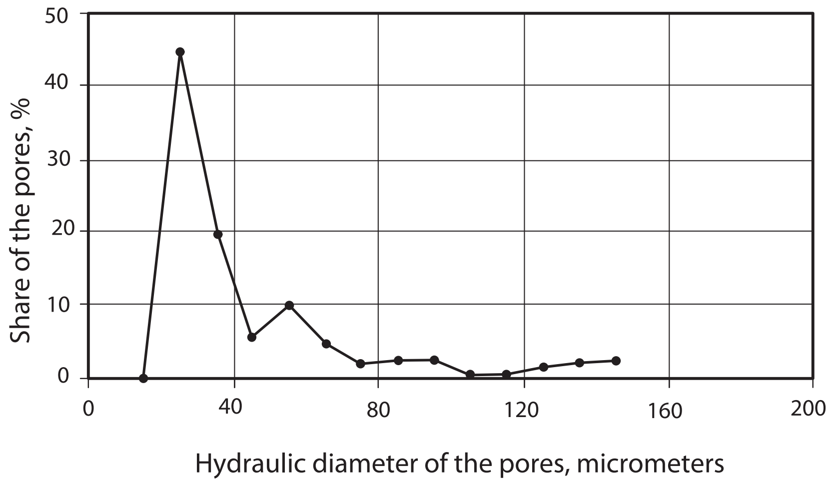


Fig. 5. Diagram of pore's distribution in sample (a)

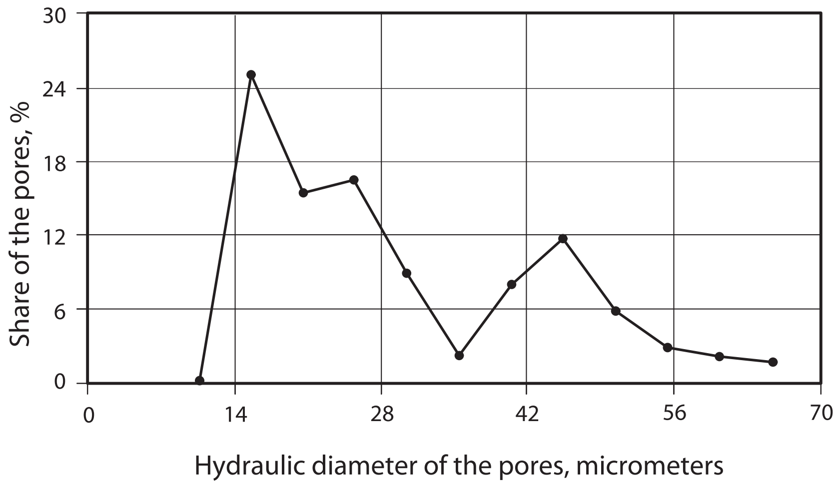


Fig. 6. Diagram of pore's distribution in sample (b)

Statistic parameters	w [µm]	l [µm]	d_t [µm]	$P_{real} = w*l$ [µm^2]	P_{hydr} [µm^2]	l/d_t
Mean	20.13	66.06	30.00	1364.67	786.29	2.50
Standard deviation	7.77	13.75	10.19	664.13	461.38	1.19
Minimum	4.76	23.81	8.82	287.12	61.07	1.04
Maximum	34.92	87.3	46.91	2519.68	1727.43	6.86
Total				68233.43	39314.56	

Table 3. Results of the scanning-electron microscope pore's shape and open area measured on 50 pores of the sample (b)

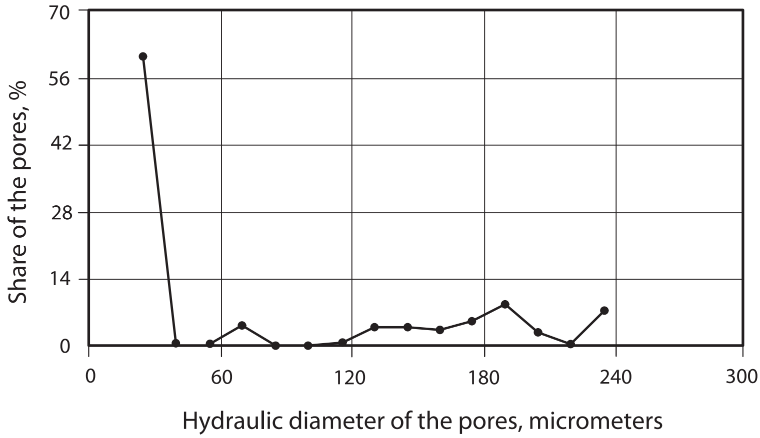


Fig. 7. Diagram of pore's distribution in sample (c)

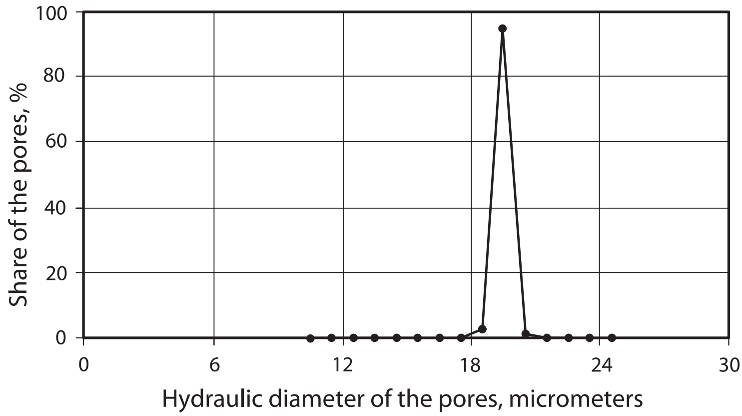
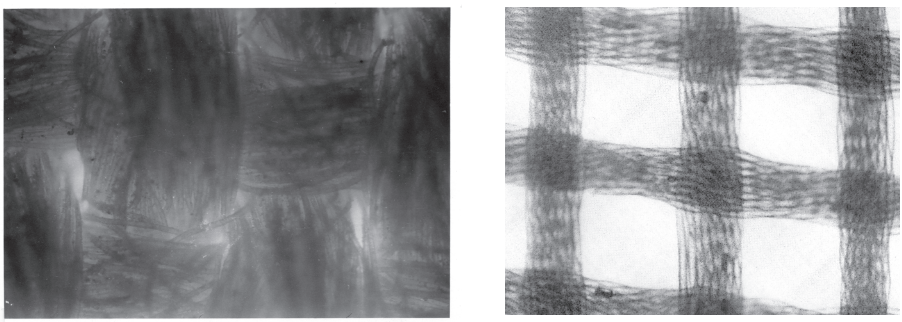


Fig. 8. Diagram of pore's distribution in sample (d)



Sample (a) Sample (c)

Fig. 9. The photos of tested samples (a) and (c)

When dealing with the sample (b), the average ratio l/w, equation (2), in table 3 is 66.06/20.13 = 3.23, see also figures 9 – 11. Hence, the criterion of having more than one hydraulic pore in a pore between threads of the warp and weft, figure 12, is thus met. The maximum value of the ratio between the value of the longer rectangular side l and the hydraulic diameter belonging the same pore is 6.84.

This results in almost doubling in number of hydraulic pores – from the 50 pores measured by the scanning-electron microscope with magnification of 630, a detail can be seen in figure 11b, to estimated 99 hydraulic pores. The real number of hydraulic pores is thus 4356, if the results in table 3 are extrapolated to the test area of 1 cm^2, which is in good agreement, with 4112 hydraulic pores estimated by the J-method by using the second procedure, see table 2, sample (b). The difference in number of hydraulic pores is only 4.5 %. The true open area of pores extrapolated from results in table 3 to the test area of 1 cm^2 is 3.01 % and the true hydraulic open area 3.34 %. The estimated open area obtained by the method is 3.87 %, table 2, or 12.83 % more than true hydraulic open area, and 28.57 % more than true open area.

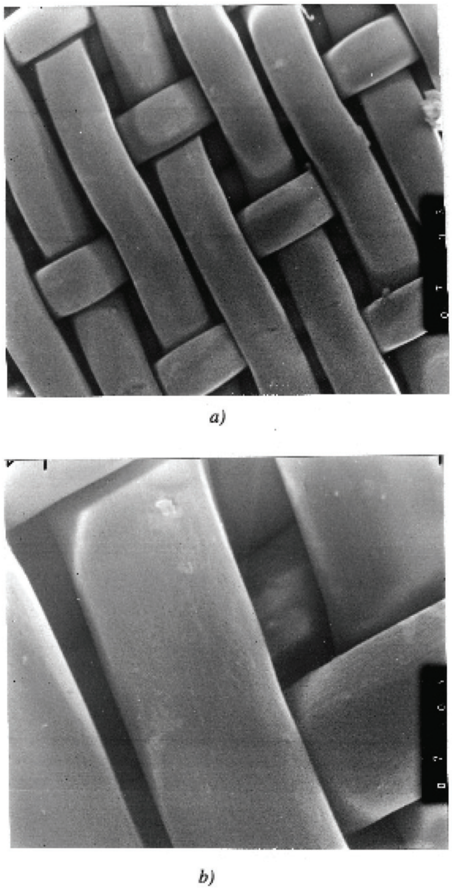
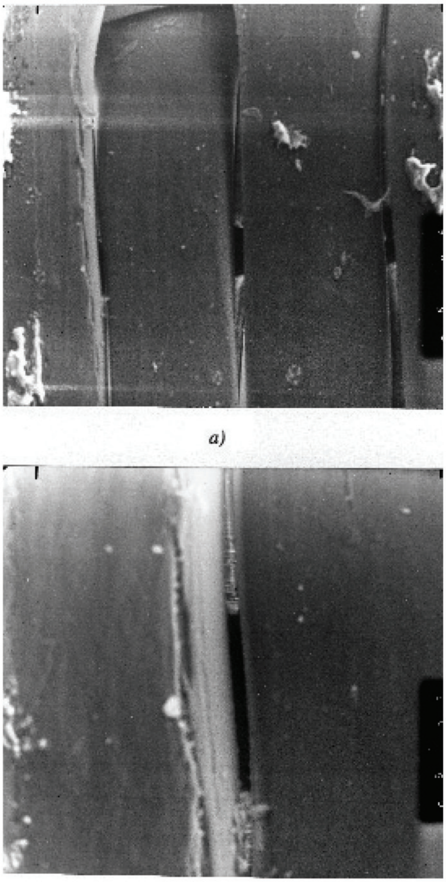


Fig. 10. Sample (b): a) magnification 63x, b) magnification 190x



a)

b)

Fig. 11. Sample (b): a) magnification 190x, b) magnification 630x

The fibres that jut out of the yarn enmesh the pores between the threads of the warp and weft and thus dividing them into smaller pores with no regular geometrical shape if the textile is made of spinning yarn e.g. cotton woven fabric such as sample (a). The values of the porosity parameters of the cotton fabric obtained by the first procedure are shown in table 2. The most distinctive pore in voids between the threads of the warp and weft is taken into account when inspecting the fabric with a microscope and thus obtaining the number of pores of 452 and the average pore's hydraulic diameter of 53 micrometers. The lower value of the pore's hydraulic diameters set to 20 micrometers when computing the porosity parameters in this case. The value of a_0, is high as well as the value of a_1 (a_1 = 1.7416), see equation (6). Both values are higher than theoretical maximum at b = 0.5. The number of pores is inversely proportional to the value of the coefficient a, equation (5), and the maximal value of the coefficient a, is 1.28. Hence, the porosity parameters of the samples (a) and also (b) are computed with the second procedure.

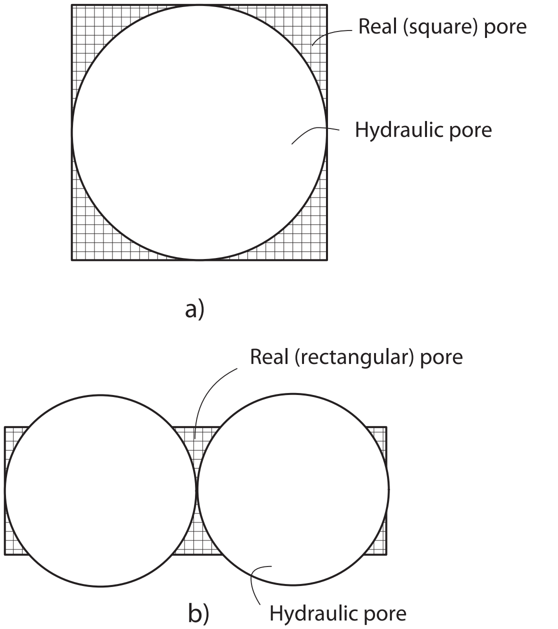


Fig. 12. Influence of the form of pores on the number of hydraulic pores in one pore between threads of the weft and warp in the woven fabric: a) square real pore, b) rectangular real pore

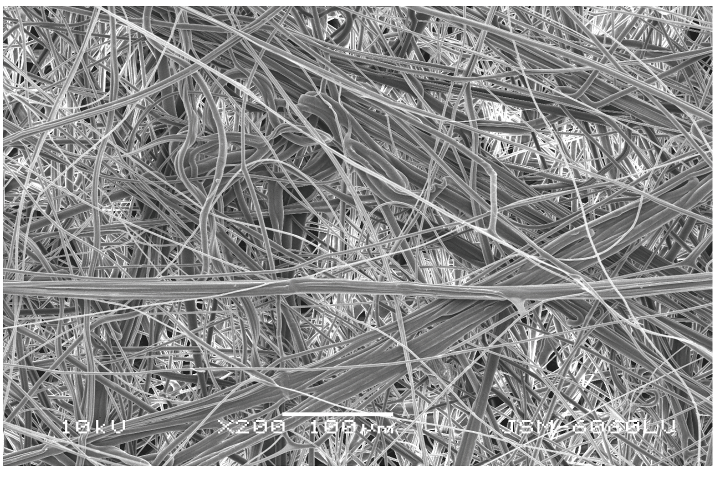


Fig. 13. The inner non-woven layer in the medical mask

The non-woven flat fabrics are extremely difficult to characterise in terms of porosity due to their irregular structure. The structure makes them better, more effective filtration media in comparison to the woven fabrics. Hence, the challenge is to estimate their porosity parameters. The experimental results presented in table 1, especially sample (b), proved that the porosity of the non-woven flat textiles can be estimated by J-method.

We have applied J-method in order to characterise the porosity of a medical mask. The mask fabric, figure 13, is composed of three layers. The data of layers is presented in table 4. The outer layer and the layer suite on the face of subject are composed from fibres which diameter is 18 µm. The inner layer is composed from microfibers which diameter is 2 µm. In this layer the fibres are arranged in 37 layers.
The walls of pores are defining by fibres. In contrast to a woven fabric, where pores are straight from one surface to the opposite one and where the length of pores is equal to thickness of the fabric, the pores in the non-woven fabric changes its direction and are thus much longer than the fabric's thickness. It is this property that makes them an excellent filtration media and at the same time, very difficult to characterise. Even though the viruses are much smaller than the hydraulic diameter of pores, the configuration of pores allows for 100% filtration efficiency.
The schematic airflow through the medical mask is shown in figure 14. The air flows through pores in a complex pattern. It is fairly difficult to developing a real theory of filtration due to that fact.
The number of the pores on 1 cm^2 is estimated as 63970, the maximal diameter of pores is 30.19 µm and the open area (free for air flow) is 8.42%.
The results for porosity parameters estimated by J-method are presented in table 5 and the pore distribution in table 6. The coefficient a (regression equation (5)) - flow air through dry sample is 0.0890 and the exponent b (regression equation (5) - flow air through dry sample) is 0.7521. The mean hydraulic diameter of pores is estimated to the value of 12.46 µm, table 5. The nomenclature of table 5 is as following: d_{max} stands for the average pore diameter of the first interval (the largest pores), d_{min} stands for the average pore diameter of the last interval (the smallest pores), d_p stands for the average pore diameter of the sample and P stands for the average open hydraulic flow area.

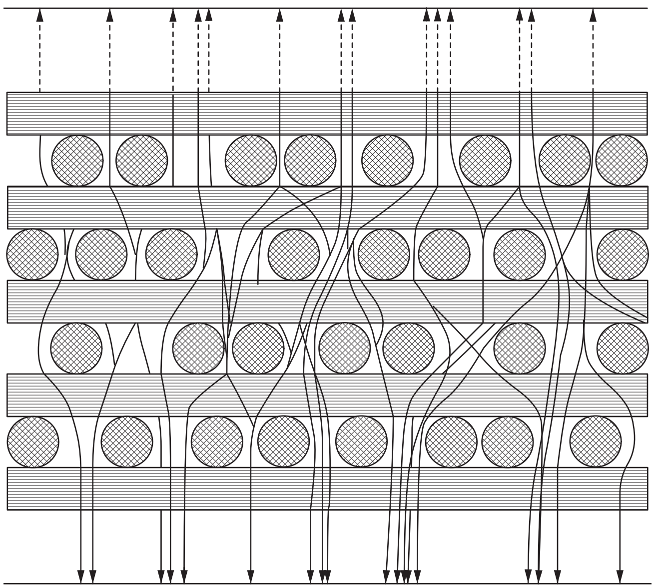


Fig. 14. Stream of air through the non-woven mask due to the respiration

Non-woven layer	Mass [g/m²]	Thickness [µm]	Numbers of the fibres layers	Thickness of the fibres [µm]	Active surface (not blocked whit resin) [%]	All surface of non-woven [cm²]
Outer	17.6	92	5	18	87	160
Inner	20.4	74	37	2	100	160
Outer on the subject face	19.1	120	7	18	75	160

Table 4. Comparison of chosen physical parameters of the fibres from different layers, that the mask is made of.

Parameters of porosity	Outer non - woven layer	Inner non - woven layer	Outer on the subject face	Mask (all three non-woven layers)
The biggest pore [µm]	305	38	211	30
dmax [µm]	275	28	195	28
dmin [µm]	15	8	15	8
dp [µm]	83.2	12.46	76.3	12.61
b	0.6183	0.7313	0.6143	0.7521
a	0.249	0.0889	0.2925	0.089
P [%]	27.71	8.43	25.32	8.42
Width of the classes [µm]	13	2	18	2
Number of the classes	13	10	10	10
Number of pores/cm²	3745	64016	4506	63970

Table 5. Parameters of porosity for all three non-woven layers of mask; the surface of samples: 1 cm2; liquid in the pores: n-butanol

Meas. num.	Limits of the gradual classes [µm]	Hydraulic diameter of pores [µm]	Pressure [kPa]	Volumes flow [cm³/s]	Number of pores	Portion of pores [%]
1	26-28	27	0.360	0.924	136	0.36
2	24-26	25	0.389	2.115	184	0.19
3	22-24	23	0.423	4.412	388	0.57
4	20-22	21	0.463	9.833	1029	1.61
5	18-20	19	0.512	21.504	2488	3.97
6	16-18	17	0.572	41.916	4859	7.75
7	14-16	15	0.649	74.346	8770	13.82
8	12-14	13	0.748	113.669	11324	17.70
9	10-12	11	0.884	157.730	10611	16.59
10	8-10	9	1.081	219.088	24281	37.96

Table 6. Parameters of porosity for mask (for all three non-woven layers)

5. Conclusions

J-method of porosity assessment of the flat textiles is presented here. It enables us to compute maximal and average hydraulic diameter of pores and relative distribution of pore's diameters regardless of the type of the flat textile by using both procedures. It is also possible to compute distribution of pore's diameters and true value of the hydraulic open surface if the number of pores is known and first procedure is used. If the number of pores is unknown the second procedure should be used. In that case the distribution of pore diameters and true value of the hydraulic open surface are determined approximately but well enough to meet most requirements.
The results are in good agreement with those obtained by the microscope and scanning electron microscope. Considering the results obtained when testing woven fabric we have concluded that the method could be used to determine the porosity parameters of knitted fabrics and thinner non-woven fabrics.
Method is suitable for assessment parameters of porosity in textiles filters, if the average hydraulic diameters are in interval 5 to 200 µm (Jakšić, 2007).

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15

Woven Fabrics and Ultraviolet Protection

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1. Introduction

The increasing awareness of negative effects of ultraviolet radiation and regular, effective protection are actual themes in general public in many countries. In professional journals, daily papers and internet sides a lot of different subscriptions can be noticed, where dermatologists, meteorologist, biologist and other professionals warn us about UV radiation, ozone depletion and give us some recommendations for effective protection. The problem of UV radiation is interdisciplinary – it is also the subject of textile scientists. Behaviour outdoors can significantly affect exposure to solar UVR and use of items of personal protection can provide a substantial reduction in the UVR dose received. Clothing made from woven fabrics can provide convenient personal protection however not all fabrics offer sufficient UV protection. This chapter gives the short overview of the role of UV radiation on human health, protection against UV radiation with the emphasis on woven fabric construction and other factors influencing the UV protection properties of woven fabrics.

2. Ultraviolet radiation

Ultraviolet radiation (UVR) is electromagnetic radiation, which we can not see or feel, and it is emitted by the natural or artificial sources. The natural source of UV radiation is the Sun, which emits different types of electromagnetic radiation with different wavelengths and energies. UV radiation has wavelengths shorter than that of visible region, but longer than that of soft X-rays, in the range of 10 nm to 400 nm, and energies from 3 eV to 124 eV. The UVR spectrum can be subdivided into near UV (400 - 300 nm), middle UV (300 – 200 nm) and vacuum UV regions (200 – 10 nm) by physicists, or into UVA (400 – 315 nm), UVB (315 – 280), UVC (280 – 100 nm) and UVD (100 - 10 nm) regions by biologists (Williams & Williams, 2002).
The artificial sources of UV radiation are different types of lamps for phototherapy, solariums, industrial/work place lightening, industrial arc welding, hardening plastics, resins and inks, sterilisations, authentication of banknotes and documents, advertising, medical care, etc. UV lasers are also manufactured to emit light in the ultraviolet range for different applications in industry (laser engraving), medicine (dermatology, keratectomy) and computing (optical storage). Lamps and lasers emit UVA radiation, but some of them can be modified to produce also a UVB radiation.

2.1 Effects of UV radiation on human health

There are big differences between the UVA, UVB and UVC (or UVD) radiation regarding their effects on human health. UVA radiation is also known as glass transmission region while ordinary glass blocks over 90% of the radiation below 300 nm and passes the radiation abut 350 nm. UVA radiation is thought to contribute to premature ageing and wrinkling of the skin while it damages collagen fibres and destroys vitamin A in the skin. It penetrates deeply under the skin but does not cause sunburn, only sun tanning. Sun tan is a defence mechanism of the skin. Brown pigment melanin namely absorbs UVA radiation and dissipates the energy as harmless heat, blocking the UV from damaging skin tissue. Today it is also known that UVA radiation can generate highly reactive chemical intermediates which indirectly damage the DNA and in this way induces the skin cancer. UVA is the main cause of immune-suppression against a variety of infectious diseases (tuberculosis, leprosy, malaria, measles, chicken pot, herpes and fungal disease) rather than UVB, but the effects are also positive (type 1 diabetes, multiple sclerosis, rheumatoid arthritis). UVB radiation is known as sunburn region and has been implicated as the major cause of skin cancers, sun burning and cataracts (Yalambie, 2003). It damages the fundamental building element – DNA directly at molecular level as well as collagen fibres and vitamin A in the skin.

UVA radiation	UVB radiation	UVC radiation
λ = 400-315	λ = 315-280	λ = 280-100
Energy: 3.10-3.94 eV	Energy: 3.94-4.43 eV	Energy: 4.43-12.4 eV
Mean energy: 340 kJ/mol	Mean energy: 400 kJ/mol	Mean energy: 810 kJ/mol
Intensity: 27 W/m^2	Intensity: 5 W/m^2	Intensity: -
It has 1.7 times bigger mean energy than visible radiation[1].	It has 2 times bigger mean energy than visible radiation[1].	It has 4.1 times bigger mean energy than visible radiation[1].
Its intensity represents the 7,9% of solar radiation[2].	Its intensity represents the 1,5% of solar radiation[2].	-
Damages collagen fibres and accelerates skin ageing.	Damages collagen fibres and accelerates skin ageing.	Damages collagen fibres and accelerates skin ageing.
Destroys vitamin A.	Destroys vitamin A. Initiates vitamin D-production.	Destroys vitamin A.
Responsible for tan.	Responsible for deeper tan of longer duration. Responsible for sunburn.	Responsible for sunburn.
Indirectly destroys DNA and contribute to skin cancer.	Directly destroy DNA and causes skin cancer.	Directly destroy DNA and causes skin cancer.
Suppresses immune system protection by some diseases or have positive effect by others.	Has negative or positive effect on immune system.	-
Penetrates under the skin.	Dangerous to the eyes.	Dangerous to the eyes.

[1] mean energy of visible radiation: 200 kJ/mol, [2] average solar radiation: 342 W/m^2 (Ron, 2005)

Table 1. Main differences between UVA , UVB and UVC radiation

UVB radiation increases the melanin production as a means of protection which leads to a long lasting tan with 2-day lag phase after irradiation. It is known that, biologically, sunburn corresponds to a real damage to the genome in the skin cells and that although the effects may be reversed by repair processes permanent genomic damage can occur (Cesarini, 2001). The cornea, the lens and the retina can be damaged if we are too much exposed to

UVB radiation. UVB radiation is also the component that initiates vitamin D production in the skin (Johnston, 2005). In this way it has a good effect on human health while the vitamin D is vital for normal functioning of the nervous system, bone growth, etc. UVC radiation is known as bacterial region and it is extremely dangerous while it has the highest energy. It destroys DNA directly. Table 1 shows the main differences between the UVA, UVB and UVC radiation (Zabetakis, 2002).

2.2 UVR transmission and ozone depletion

99% of the UV radiation that reaches the Earth's surface is UVA radiation and it is not absorbed by ozone. UVA radiation is most intense in early morning and afternoon and can pass through the window glass. UVB radiation is mostly absorbed by ozone, although some reaches the Earth. The amount of UVB radiation received by a location is strongly dependent on: latitude and elevation of the location (average UVB exposure at the poles is over a thousand times lower than at the equator), cloud cover (the reduction in UVB exposure depends on cover's thickness), and proximity to an industrial area (protection offered by photochemical smog, which absorbs UVB) (Sparling, 2001). UVB radiation does not penetrate through the window glass and is most pronounced midday. UVC radiation is completely absorbed by the atmosphere's ozone layer and normal oxygen before it reaches the ground. However, this is valid for the situation where there is no ozone depletion.

Ozone layer is a concentration of ozone, e.g. a naturally-occurring gas formed by three atoms of oxygen, in the stratosphere, which extends about 10-50 km above the Earth's surface (EPA, 2010). It filters the sun's ultraviolet radiation and protects plant, animal and human life on the planet. This natural shield has been gradually depleted by man-made chemicals like chlorofluorocarbons (CFCs), hydro fluorocarbons (HCFCs) and other ozone-depleting substances (ODS), which are used widely in refrigerators, food containers, plastic foam, home insulation etc. Ozone is degraded also by the absorption of UVB radiation (Cesarini, 2001). Global depletion of stratospheric ozone is nowadays one of the serious environmental and living problems. The reduction of stratospheric ozone has, as a direct consequence, increased the intensity of UVB radiation received at ground level. An increase in exposure to UV for the populations of New Zealand, Australia, Europe and North America has been recently reported. The 1% reduction in ozone will lead to 2% increase in solar UVB radiation at the Earth's surface (Sparling, 2001) and may eventually lead to a 2.3% increase in skin cancer (Roy et al., 1995). The potential biological consequences of this are modifications (of the genome) in the skin and the cornea – two interfaces between the environment and human body. Basal and squamous cell carcinoma (nonmelanoma skin cancers – NMSC) is the most common of all cancers associated with the increased exposure to UV radiation. Risk factors for NMSC include exposure to sun or radiation, fair skin, advancing age, and male sex. The most serious of all cancers e.g. malignant melanoma (MM) is increasing faster than any cancer except lung cancer. Melanoma risk is increased in men, fair-skinned individuals, those with the family history, those with multiple pigmented nevi, the immuno-suppressed and is more than double in those with one or more severe sunburns in childhood (Ferrini et al., 1998). We should be aware of that prolonged and repeated exposure to UV radiation in early childhood increases the risk of malignant tumours in adulthood.

2.3 Protection against solar UV radiation

It is obviously that protection against harmful UV radiation which includes recommendations on behaviour, environment, legislation and personal protection changes, is needed (Edlich et al., 2004; Gies et al., 1998; Turnbull & Parisi, 2005). Protection against solar UV radiation can reduce and individual's solar UV radiation exposure to between 1 and 10% of that without any protection (Gies et al., 1998). Sun avoidance and use of use of protective clothing have been associated with reduced risk of both melanoma and nonmelanoma skin cancers in multiple cohort, animal and case control studies; however, not all studies find effect (Ferrini et. al, 1998).

Behaviour. Avoiding the sun between the 10 and 14 hour is nowadays a well known recommendation on behaviour changes which can play a very important role in the reduction of individual's total UVR exposure. The intensity of solar UVR namely depends on the height of the sun in the sky, which varies according to the latitude, the hour of the day and the seasons (Cesarini, 2001). It is also worth to mention that reflections in the environment (snow cover, surface layer of the sea) increase the dose of UV received directly from the sky. For people dealing with outdoor activities who are not able to avoid the sun between 10 and 14 hour, the provision of shade and subsequent reduction in solar UVR exposure should be a high priority.

Environment and legislation changes. Creation and popularisation of a global UV index by the World Health Organisation was a step forward to reduce the amount of UV dose that people received. UV index represents the maximum effective radiance received on the skin surface, taking into account the cloud cover and all other variables of the environment (Table 2). It is obtained by multiplication of the effective radiance of the solar radiation by 40 and it takes values on a scale from 1 (low) to 11+ (extremely high) (Cesarini, 2001). Knowing the UV index, people can change the environment by provision of shade and other UV radiation protective structures or by adopting personal protection. People who are employed in the building trades, foresters, farmers, those who work on beaches and ski-slopes and other certain professions are much more exposed, by a factor of some 4-5 times, than those who live and work in towns, and in spite of the phenomenon of adaptation, are at higher risk from their exposure.

Personal protection. Sometimes it is even not possible to choose shaded position or to schedule the time spent outdoors. In this case the personal protection e.g. the protection of eye and skin is only option. Significant amounts of UVR personal protection is provided by application of sunscreen to all exposed areas of the skin as well as by wearing good quality sunglasses, a hat and clothing appropriate to the thermal conditions of the environment and the level of activity (Table 2). Sunscreen absorbs, diffuses or reflects incidental UVR thus reducing the fraction of solar UVR reaching the basal layer of the epidermis and dermis. Table 2 shows the recommendations for using the stated protection factors of sunscreens according to the UV index for people with sensitive and normal skin. Sunscreens should be used in conjunction with clothing to protect areas of the body not covered by clothing and should be reapply every two hours. However sunscreens may be associated with adverse effect. They allow users to increase time spent in the sun and to avoid sunburn, but users exposing themselves to harmful UVR, which may be carcinogenic or decrease immune function. Besides that some of the compounds in sunscreens are carcinogenic and are associated with reduced synthesis of vitamin D (Ferini et al., 1998). Sunglasses are equipped with lenses that filter both UV rays and visible light which arrive directly or indirectly through reflection. Eye protection is increased by wearing a hat or visor which extends the natural anatomical projection of the face, which include the nasal edge, eye-lashes, eyebrows and eyelids. A hat with 7 cm peak protects not only face but also the nape and sides of the neck. The best way to avoid the effects of UVR is to cover the skin as much as possible with clothing. Clothing is made by different types of fabrics, which provide a simple and convenient protection against UVR, however not all fabrics offer sufficient UVR protection. In general, personal protection items have been defined with different protection factor (PF) ratings in an attempt to quantify the UVR protection that such products can provide. The PF gives indication of the amount of UVR that is blocked by the protection items. Depending on the personal protection item there are different rating scales. For fabric UPF (Ultraviolet Protection Factor), for sunscreen SPF (Sun Protection Factor) and for sunglasses EPF (Eye Protection Factor) is used.

UV index 1-2	UV index 3-4	UV index 5-6	UV index 7-8	UV index 9 and above
duration of exposure to the sun without protection for sensitive skin / **for normal skin**				
weak sun continuous exposure of $1\text{-}2^{h}$/3^{h} +	moderate sun continuous exposure of 40^{min}/$1^{h}\ 30^{min}$	strong sun continuous exposure of 25^{min}/50^{min}	very strong sun continuous exposure of 20^{min}/40^{min}	extremely strong sun continuous exposure of 15^{min} / 30^{min}
recommendations for UVR personal and environmental protection for sensitive skin / **for normal skin**				
sun glasses	sun glasses + sunscreen with SPF 15 / sun glasses	sun glasses + hat + T-shirt + sunscreen with SPF 25 + sunshade / sun glasses + hat + sunscreen with SPF 15	sun glasses + hat + T-shirt + sunscreen with SPF 40 + sunshade / sun glasses + hat + sunscreen with SPF 30	exposure strongly discouraged / sun glasses + hat + sunscreen with SPF 40 + sunshade

Table 2. Correspondence between solar rays and the universal UV index and recommendations for UVR protection (Cesarini, 2001)

3. Protection factor of fabrics

The ability of fabrics to protect against UV radiation can be tested by two major methods: in vitro method (or instrumental / spectrophotometric method) and in vivo method (or laboratory / human skin method). Both methods assess the amount/degree of sunburn protection provided by the fabrics with so called term UPF by in vitro method and SPF by in vivo method. Theoretically, the UPF and SPF value for any fabrics should be the same. However, some studies indicated that the results of UPF and SPF values are not statistically identical; never the less both values are in a good correlation (Hatch & Osterwalder, 2006).

3.1 Ultraviolet protection factor of fabrics – UPF and measurement techniques

To assign the degree of UVR protection of fabrics, the **u**ltraviolet **p**rotection **f**actor (UPF) is defined as the ratio of average effective UV radiation irradiance transmitted and calculated through the air (effective dose - ED) to the average effective UV radiation irradiance transmitted and calculated through the fabric (effective dose - ED_f) (EN 13758-1, 2002; Scott, 2005):

$$UPF = \frac{ED}{ED_f} = \frac{\sum_{\lambda=290}^{\lambda=400} E(\lambda)S(\lambda)\Delta\lambda}{\sum_{\lambda=290}^{\lambda=400} E(\lambda)T(\lambda)S(\lambda)\Delta\lambda} \quad (1)$$

where E(λ) is the relative erythemal spectral effectiveness, S(λ) is the solar spectral irradiance in $Wm^{-2}nm^{-1}$, Δλ is measured wavelength interval in nm, T(λ) is average spectral transmittance of the fabric specimen, and λ is the wavelength in nm. UPF indicates how much longer a person can stay in the sun when fabric covers the skin as compared with the length of time in the sun without fabric covering to obtain the same erythemal response. The higher the UPF of a fabric, the better is its ability to protect the skin it covers. To assign the degree of UVR protection of fabrics also the term penetration or erythema weighted transmittance - EWT is in use, which is the inverse value of UPF (Eq. (2)). The values of EWT lie between 0 and 1 (or 0% and 100%). The lower the percent of EWT is, the greater is the sunburn protection provided by fabric.

$$EWT = \frac{1}{UPF} \quad (2)$$

There are two in vitro quantitative measurement techniques to test UVR transmission through fabrics: radiometry, where the total transmission of UVR through a fabric is measured using a real or simulated solar spectrum, and spectrophotometry, where the transmission of UVR through a fabric is measured as a function of wavelength. Both methods include ultraviolet radiation source that emits both UVA and UVB radiation. The spectrophotometric technique relies on the collection of transmitted and scattered radiation with the aid of an integrating sphere positioned behind the fabric specimen. Suitable UV sources are Xenon arc lamps, Deuterium lamps and solar simulators. The procedure has two major steps: transmittance testing and calculations based on the transmittance data collected. The principle of this method is to direct a beam of monochromatic radiation in the UV light and of known quantity perpendicular to the surface of the fabric specimen and to measure the amount of radiation transmitted through and scattered by the fabric. The sending the beams of radiation continues until all wavelengths in the UV range (or wavelengths at 2 or 5 nm intervals) have been directed to the fabric face and transmittance data collected. It is also possible to direct a beam of polychromatic incident radiation. In that case the transmitted radiation is collected monochromatically. Then the transmittance data are used to calculate UVA and UVB percent transmittance values and a total percent transmittance value. The calculation of total UV percent transmittance for a fabric specimen is the ratio of the amount of radiation transmitted to the amount of radiation directed perpendicular to the fabric specimen surface. The calculation of a UPF is accomplished by combining the transmittance data with data collected that established the relative power of UV wavelengths to cause the skin to redden. These later data, data collected using human subjects, are given in the erythemal action spectra. In this way we may say that in vitro method also has an in vivo component to it. It is also worth to mention that percent transmittance data do not take into account that certain wavelengths in the UV range are more responsible for skin damage than others. On the other hand, the erythemal action spectra data in UPF calculation take into consideration that fabrics that allow a greater portion of the most harmful skin reddening rays to be transmitted will receive a numerical value lower than a fabric that allows less of the powerful skin reddening rays through, even when both fabrics transmit the same amount of radiation (Hatch et al., 2006).

The radiometric technique uses a broad band UV light source filtered for UVB or combined UVA and UVB bands to illuminate a fabric specimen. The total UV transmittance through a fabric is measured by a radiometer. The protection factor is determined by taking the ratio of the measured power in the absence of the fabric to the measured power in the presence of the fabric. Such measurements do not yield a definitive value for the protection factor of a fabric. This technique is more useful when a relative variation in UPF is needed, such as the variation in protection factor from site to site within a fabric or the effect of stretching the textile on the protection factor (Scott, 2005).

3.2 Sun protection factor of fabrics – SPF and measurement technique

SPF is defined as a ratio of radiation dose to produce minimal sunburn under fabric covered skin to the radiation dose to produce the same sunburn of uncovered skin:

$$SPF = \frac{MED_{ps}}{MED_{us}} \quad (3)$$

where MED_{ps} is minimum erythemal dose of protected skin in J, and MED_{us} is minimum erythemal dose of unprotected skin in J. The higher the SPF value, the better the fabric's protection ability against sunburn. MED is defined as the minimum quantity of radiant energy (using incremental UVB doses) required to produce first detectable reddening of the skin, 22 ± 2 hours after exposure. The measurement technique to estimate SPF of fabric is known as in vivo method. The procedure is to attach rectangular pieces of fabric to the back of human subject and determine the minimum erythemal dose of unprotected and protected skin.

3.3 Standards, classification and marking of UV protective fabrics/clothing

Several standards for measuring, classification and marking of fabrics' UV protection properties are in use. All of standards employ the Eq. (1) for measuring UPF of fabrics and differentiate regarding the scanning intervals, positioning of the fabrics in the instrument, the erythemal action spectrum designated, classification and marking.

European standard EN 13758-1:2002 specifies a method to asses UPF of fabrics, without those which offer protection at a distance (umbrellas, shade structures) or artificial UV radiation sources. The instrument records the transmittance between 290 nm and 400 nm by wavelength interval of at least 5 nm. The sample UPF is average UPF of sample minus standard error. When sample UPF is less than the lowest positive UPF measured for a particular sample, then the UPF of that specimen is reported. When the UPF of fabrics is greater than 50 only UPF>50 needs to be reported. By fabrics with areas of various shades and/or construction the lowest positive UPF value measured is reported as the sample UPF.

EN 13758-2:2003 specifies general clothing design requirements, marking and labelling. The clothing design which offers UV protection to the upper and/or lower body shall at least cover the upper and/or lower body completely. This standard classifies UV protective clothing only in one category for which the lowest UPF value is larger than 40 and the average UVA transmission is smaller than 5%. According to this standard UV protective clothing is marked with pictogram (Fig. 1), which includes the number of this standard and UPF 40+, and the wording: "Sun exposure causes skin damage" / "Only covered areas are protected" / "The protection offered by this item may be reduced with use or if it stretched or wet", or can be marked with the wording: "Provides UVA+UVB protection from the sun".

Fig. 1. Pictogram for UV protective clothing according to the EN standard 13758-2

Australian/New Zealand Standard AS/NZS 4399:1996 specifies requirements for determining UPF of sun protective (un-stretched and dry) textiles, garments and other items of personal apparel (hats) which are worn in close proximity to the skin, and appropriate detailed labelling. Standard is not valid for sunscreen products, fabrics for architectural or horticultural use (shadecloth) and items which offer protection at a distance from the skin. Also, it does not cover protection form UV radiation sources other than the sun. The rated UPF value is the mean UPF value of four testing samples reduced for the standard error in the mean UPF, calculated for the 99% confidence level, and finally rounded down to the nearest multiple of five. If the rated UPF is less than the lowest individual UPF sample measurement, the rated UPF is the lowest value of measured UPF rounded to the nearest multiple of five. According to this standard sun protective clothing is categorized to its rated UPF as given in Table 3.

UPF range	UVR protection category	Effective UVR transmission, %	UPF ratings
15 to 24	Good protection	6,7 to 4,2	15, 20
25 to 39	Very good protection	4,1 to 2,6	25, 30, 35
40 to 50, 50+	Excellent protection	< or = 2,5	40, 45, 50, 50+

Table 3. UPF classification system according to AS/NZS and ASTM standards

According to this standard UV protective clothing is accompanied by the following information: the manufacturer's name, trade name and mark; UPF rating; protection category; the wording: "This UPF rating is for the fabric and does not address the amount of protection which is afforded by the design of the article. The manipulations involved in garment manufacture such as stretching and sewing may lower the UPF of the material". For headwear following wording is used: "This item doses not provide protection against reflected or scattered solar UVR".

In the **United States** several standards or methods refer to the UV protective clothing. AATCC Test Method 183-2004 determines UPF and provides the procedure for measuring UPF for fabrics either in dry or wet states. The method prescribes a minimum of two specimens of tested fabric, which should be prior prepared according to the ASTM D 6544. Fabric samples should be exposed to the laundering (40 times), simulated sunlight and in the case of swimwear fabrics to the chlorinated pool water prior the UV transmission testing. ASTM D 6603-07 provides a uniform system of labelling on UV-protective textile products. The UPF value which is placed on a garment needs to be the lowest protection value expected during consumer use over a two-year period. The calculation of fabric UPF value and the protection classification (Table 3) are similar as described in AS/NZS standard. The fabric is not labelled as sun or UV-protective if the calculated UPF value is less than 15. If it is greater than 50, only 50+ is placed on the label. Label shall contain following elements: a UPF value; a classification category; a statement that the UV-protective textile product has been labelled according to the ASTM D 6603 standard guide and some other elements which are not obligatory as previous mentioned elements.

4. Woven fabric constructional parameters

Woven fabric is a flat product which consists of several interlaced thread systems oriented in different direction. Regarding the orientation of threads following woven fabrics are known: bi-axial, tri-axial and tetra-axial. Biaxial woven fabric has at least two orthogonal thread systems: lengthways – warp thread system (warp), and transversal – weft thread system (weft). In addition to the woven fabric classification by technology and type of weave, this chapter is focused on biaxial fabrics with a one warp and one weft thread system. In the phase of a new product development, woven fabrics are engineered to fit desired end-use properties with minimum production costs not only by real but also by trial production. End-use properties strongly depend on several woven fabric constructional parameters, which can be defined in general and particular manner (Dubrovski & Šujica, 1995). In general, woven fabric constructional parameters refer to: the **parameters of raw material** (type of fibre, *dimensional and physical properties* - length, specific density, cross-section shape, fineness, fibre crimp, etc., *mechanical properties* – stress/strain, elastic recovery, module, resilience, stiffness, flexibility, abrasion resistance, etc., *sorptive properties* – absorption of liquid water, vaporous water absorption, oil absorption, oil release, heat of wetting, etc., *thermal properties* - thermal conductivity, heat resistance, thermoplasticity, decomposition, combustibility, etc., *chemical properties* – chemical reactivity, chemical resistance, *miscellaneous properties* – electrical resistivity, resistance to UV radiation, resistance to biological organisms, etc.), the **parameters of yarns** (type of yarn, fibre composition, yarn linear density, number of strands, number of filaments, degree of twist, direction of twist, yarn flexibility, yarn packing factor, etc.), **parameters of woven fabric geometry**, **parameters of woven fabric patterning** (warp pattern, weft pattern, symmetry, colour composition, colour harmony, colour contrasts, etc.) and **technological parameters** of weaving and finishing processes (availability of dobby/jacquard, limitations regarding the fabric width, possibility for weft colour exchange, type of finishing processes, temperature, relative humidity, etc.). In particular, fabric constructional parameters relate to the geometrical structure of the fabric and are classified into **primary and secondary parameters** of fabric geometry. Primary parameters of fabric geometry are: yarn thickness, weave and thread density. Yarn thickness as a constructional parameter belongs first of all to the parameters of yarns, but because of its significant influence on fabric geometry it is classified as primary fabric constructional parameters. Yarn thickness and weave are independent variables, while the thread density is dependent variable. Via the defined selection of primary fabric constructional parameters, all other fabric structure parameters may be seen as constant and dependent on primary parameters. For this reason they are logically classified into the separate category, called secondary woven fabric constructional parameters (Fig. 2).

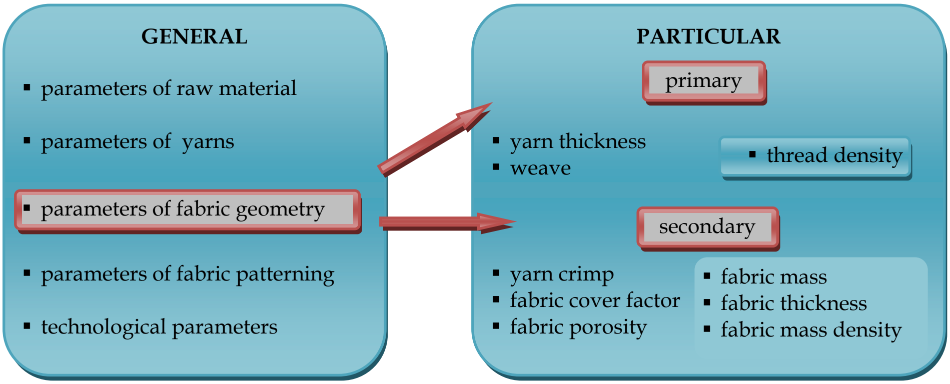


Fig. 2. Classification of woven fabric constructional parameters

4.1 Primary woven fabric constructional parameters

By dealing with woven fabric geometry we assume that yarn is cylinder with circular cross-section. The **yarn diameter or thickness** is then calculated on the basis of yarn linear density according to Eq. (4):

$$d = 3{,}568 \cdot 10^{-2} \cdot \sqrt{\frac{T}{\rho_y}} = 3{,}568 \cdot 10^{-2} \cdot \sqrt{\frac{T}{\rho_f \cdot i}} = 3{,}568 \cdot 10^{-2} \cdot v \qquad (4)$$

where d is the yarn thickness in mm, T is the yarn linear density in tex, ρ_y is the yarn bulk density in g per cm^3, ρ_f is the fibre bulk density in g per cm^3, i is the yarn packing factor, and v is the yarn volume coefficient.

Weave is the pattern of interlacing of warp and weft in a woven fabric (Denton & Daniels, 2002). Several end-use properties of woven fabrics are influenced by the weave, which can be numerically expressed with **weave factor** in warp and weft direction (Kienbaum, 1990a):

$$V_1 = \frac{\sqrt{(v_1^2 + 2v_1 v_2)} \cdot R_1}{v_1 R_1 + \frac{a_2(2{,}6 - 0{,}6z_2)}{f_2}\left(\sqrt{(v_1^2 + 2v_1 v_2)} - v_1\right)} \qquad (5)$$

$$V_2 = \frac{\sqrt{(v_2^2 + 2v_1 v_2)} \cdot R_2}{v_2 R_2 + \frac{a_1(2{,}6 - 0{,}6z_1)}{f_1}\left(\sqrt{(v_2^2 + 2v_1 v_2)} - v_2\right)} \qquad (6)$$

where V is the weave factor, v is the yarn volume coefficient, R is the number of threads in weave repeat, a is the number of passages of yarn in weave repeat from face to back and vice versa, z is the smallest weave shift and f is yarn flexibility. Subscripts 1 and 2 denote warp and weft yarn, respectively.

Thread density is primary constructional parameter which is altered by weave and yarn thickness. It is usually defined as the number of threads per centimetre and expressed for warp (ends) and weft (picks) threads. While the fabric goes thought different technological phases, also thread densities are different and defined for particular production stage. Following densities are known: 1. thread density in finished woven fabric, 2. thread density in raw woven fabric, and 3. thread density by weaving (sett of warp in the reed and sett of weft by weaving). By developing a new fabric construction there is a need to know which densities can be reached by particular woven fabric geometry or yarn thickness and type of weave. The term **limit thread density** was introduced to calculate thread density by limit geometry. Limit geometry refers to the situation where the threads are not deformed and lie in one plane close to each other or there is a minimal space for thread passage. On the basis of limit thread density, woven fabric constructor can decide which **actual thread density** will be set for finished fabric. **Relative thread density** (or **thread tightness**) is the ratio between the actual and limit thread densities, expressed as per cent (Kienbaum, 1990a):

$$t_1 = \frac{G_1}{G_{\lim_1}} \cdot 100\% \qquad t_2 = \frac{G_2}{G_{\lim_2}} \cdot 100\% \tag{7}$$

where t is the thread tightness in per cent, G is the actual thread density in thread per cm, and $G_{\lim}$ it the limit thread density calculated according to the Kienbaum's setting theory. Subscripts 1 and 2 denote warp and weft yarn, respectively. **Woven fabric tightness – t** is then defined as the geometrical average of warp and weft tightness according to Eq. (8).

$$t = \sqrt{t_1 \cdot t_2} \tag{8}$$

According to the Kienbaum's setting theory (Kienbaum, 1990a, 1990b) there are four expressions for limit thread density calculation depending on the yarn construction and yarn fineness: 1. limit thread density calculation for the warp and weft systems with the same yarn construction and fineness (Eq. (9)), 2. limit thread density calculation for the

$$G_{\lim_{1,2}} = 5{,}117 \cdot \sqrt{\rho_{fib_{1,2}} \cdot i_{1,2} \cdot V_{1,2}} \cdot \sqrt{\frac{1000}{T_{1,2}}} \tag{9}$$

$$\begin{aligned} G_{\lim_1} &= 8{,}8622 \cdot \sqrt{\frac{\rho_{fib_1} \cdot i_1}{1 + \frac{2v_2}{v_1}}} \cdot V_1 \cdot \sqrt{\frac{1000}{T_1}} \\ G_{\lim_2} &= 8{,}8622 \cdot \sqrt{\frac{\rho_{fib_2} \cdot i_2}{1 + \frac{2v_1}{v_2}}} \cdot V_2 \cdot \sqrt{\frac{1000}{T_2}} \end{aligned} \tag{10}$$

warp and weft systems with the same yarn construction and different yarn fineness (Eq. (10)), 3. limit thread density calculation for the warp and weft systems with different yarn

$$G_{\lim_1} = \frac{280{,}25}{\sqrt{v_1^2 + 2v_1 v_2}} \cdot V_1 \qquad G_{\lim_2} = \frac{280{,}25}{\sqrt{v_2^2 + 2v_1 v_2}} \cdot V_2 \tag{11}$$

construction and different yarn fineness (Eq. (11)), and 4. limit thread density calculation for the warp and weft pattern with different yarn construction and fineness (Eq. (11)). In the later case the average volume coefficient in warp/weft pattern is first calculated and then put into the Eq. (11). Yarn construction includes following constructional parameters: fibre bulk density, yarn packing factor, and yarn flexibility factor, with the exception of yarn fineness which is stated separately. In the Eq. (9) to Eq. (11), G_{lim} is the limit thread density in threads per cm, ρ_f is the fibre bulk density in g per cm^3, i is the yarn packing factor, v is the yarn volume coefficient, V is the weave factor, and T is the yarn fineness in tex. Subscripts 1 and 2 denote warp and weft yarn, respectively.

4.2 Secondary woven fabric constructional parameters

Yarn crimp is the consequence of yarn interlacing in woven fabrics. It is numerically expressed as percentage crimp, which is 100 divided by the fabric length and multiply by the difference between the yarn length and the fabric length (Denton & Daniels, 2002). Theoretically it can be calculated on the basis of fabric geometry with Eq. (12-14) (Kienbaum, 1990a):

$$\varepsilon_1 = \left[1 - \frac{p_2 R_2}{\left\{ m_1 \cdot \sqrt{(\frac{d_1 + d_2}{2})^2 + p_2^2} \right\} + (R_2 - m_1) \cdot p_2} \right] \cdot 100\% \qquad (12)$$

$$\varepsilon_2 = \left[1 - \frac{p_1 R_1}{\left\{ m_2 \cdot \sqrt{(\frac{d_1 + d_2}{2})^2 + p_1^2} \right\} + (R_1 - m_2) \cdot p_1} \right] \cdot 100\% \qquad (13)$$

$$p_1 = \frac{10}{G_1} \qquad p_2 = \frac{10}{G_2} \qquad (14)$$

where ε is the yarn crimp in percentage, p is the distance between neighbourhood yarns in mm, R is the number of threads in weave repeat, m is the number of thread passages in weave repeat, d is the yarn thickness in mm, and G is the actual thread density in raw fabric in threads per cm. Subscripts 1 and 2 denote warp and weft yarn, respectively.

Fabric cover factor indicates the extent to which the area of a woven fabric is covered by one set of threads according to Eq. (15) (Fig. 3). It is calculated on the basis of warp/weft cover factor which indicates the ratio between the yarn thickness and the distance between neighbourhood yarns or the ratio between the actual thread density and maximal thread density. It is worth to mention that maximal thread density indicates the situation where threads lie close together without any distance among them. Of course, such situation does not occur in the real fabric, while there is always some space for thread passages. A lot of researches define fabric cover factor as a basic parameter which represents the woven fabric structure. However, the faultiness of fabric cover factor is the absence of weave influence.

$$K = \frac{ABGI + AEHD - AEFI}{ABCD} = K_1 + K_2 - K_1 K_2 \qquad (15)$$

$$K_1 = \frac{d_1}{p_1} = \frac{G_1}{G_{\max_1}} = \frac{G_1 \cdot d_1}{10}$$
$$K_2 = \frac{d_2}{p_2} = \frac{G_2}{G_{\max_2}} = \frac{G_2 \cdot d_2}{10} \quad (16)$$

In Eq. (15) and Eq. (6), K is the fabric cover factor, K_1 is the warp cover factor, K_2 is the weft cover factor, d is the yarn thickness in mm, p is the distance between neighbourhood yarns in mm, and G_{max} is the maximal thread density in threads per cm. Subscripts 1 and 2 denote warp and weft yarn, respectively.

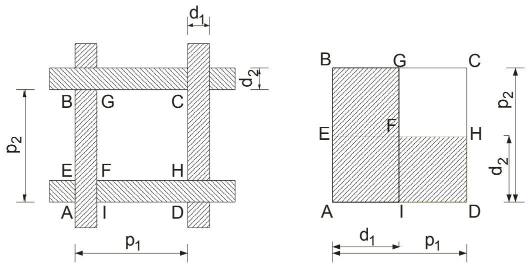


Fig. 3. Woven fabric geometry by fabric cover factor definition

Fabric porosity indicates the portion of pores in woven fabrics. While the woven fabric could be treated as two or three dimensional form, the terms open porosity and volume porosity are distinguished. **Open porosity** indicates the percentage of macropore's area in the fabric area unit. It is calculated on the basis of fabric cover factor or on the basis of the number of macropores and the area of macropore's cross section according to Eq. (17) and Eq. (18), respectively (Dubrovski & Brezocnik, 2005):

$$P_0 = (100 - K) \cdot 100\% \quad (17)$$

$$P_0 = N_p \cdot A_p \cdot 100\%$$
$$P_0 = G_1 G_2 (p_1 - d_1)(p_2 - d_2) \cdot 100\% \quad (18)$$
$$P_0 = (10 - d_1 G_1)(10 - d_2 G_2) \cdot 100\%$$

where P_o is the open porosity in percentage, K is the fabric cover factor in percentage, N_p is the number of pores in pores per cm², A_p is the area of macropore's cross section in cm², and G is the actual thread density in threads per cm. **Volume porosity** indicates the percentage of pore volume in the volume unit of woven fabric (Eq. (19)) with different types of pores (macro, mezzo, micro). It is calculated on the basis of fabric volume fraction which expresses the percentage part of yarn volume with regard to the fabric volume (Eq. (20)). While the fabric mass is actually the mass of yarns used ($m_{fab}=m_y$), the fabric volume fraction represents the ratio between the fabric mass density and yarn bulk density.

$$P_V = (100 - VF) \cdot 100\% \quad (19)$$

$$VF = \frac{V_y}{V_{fab}} \cdot 100\% = \frac{m_y \cdot \rho_{fab}}{\rho_y \cdot m_{fab}} \cdot 100\% = \frac{\rho_{fab}}{\rho_y} \cdot 100\% \quad (20)$$

In Eq. (19) and Eq. (20), P_V is the volume porosity in percentage, VF is the fabric volume fraction in percentage, V_y is the yarn volume in cm³, V_{fab} is the fabric volume in cm³, m_y is the yarn mass in g, m_{fab} is the fabric mass in g, ρ_{fab} is fabric mass density in g per cm³, and ρ_y is yarn bulk density in g per cm³. **Fabric thickness** is distance between the fabric face and back. Theoretically, it represents the sum of height of warp and weft arc according to Eq. (21) (Sokolovič, 1981):

$$h_1 = \frac{d_1 + d_2}{8}(F-1) \qquad h_2 = \frac{d_1 + d_2}{8}(9-F) \tag{21}$$

where *h* is the height of thread arc in mm, *d* is the yarn diameter in mm, and *F* is the number of Novik's fabric construction phase. While by a new fabric development there is no information in which Novik's fabric construction phase the woven fabric will appear, only minimal and maximal value of fabric thickness can be predicted. Minimal value of fabric thickness refers to V. Novik's phase, where warp and weft threads have equal yarn crimp. In this case the fabric thickness is the sum of warp and weft diameter (Fig. 4). Maximal value of fabric thickness refers to I. and IX. Novik's phases. In I. Novik's phase, where warp threads don't have any yarn crimp but weft threads maximal, fabric thickness is the sum of warp diameter and weft diameter multiple by two. In IX. Novik's phase, where warp threads have maximal yarn crimp and weft none, fabric thickness is the sum of warp diameter multiply by two and weft diameter.

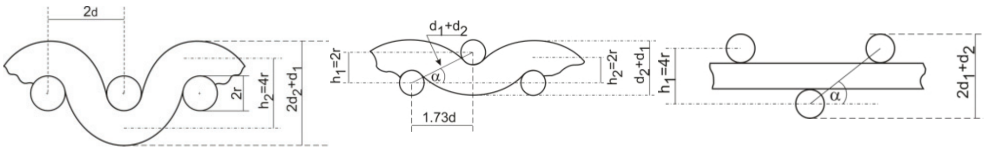


Fig. 4. I., V. and IX. Novik's fabric construction phases

Fabric mass can be expressed as mass per one meter or as mass per square meter. Later is more useful by comparing different types of woven fabrics. Theoretically it can be calculated according to Eq. (22) and Eq. (23) which refers to the unfinished and finished fabric state, respectively:

$$M_g = \frac{G_1 T_1}{100 - \varepsilon_1} + \frac{G_2 T_2}{100 - \varepsilon_2} \tag{22}$$

$$M_f = \frac{M_r (1 - \frac{\Delta M}{100})}{(1 - \frac{\varepsilon_{fin_1}}{100}) \cdot (1 - \frac{\varepsilon_{fin_2}}{100})} \tag{23}$$

where M_g is the raw fabric mass in g per m², *G* is the actual thread density in threads per cm, *T* is the yarn fineness in tex, ε is the yarn crimp in percentage, M_f is the fabric mass in finished state in g per m², ε_{fin} is the yarn shrinkage by finishing in percentage, and ΔM is mass change of raw fabric by finishing in pecentage. **Fabric mass density** expresses the mass of volume unit of woven fabric in grams per cm³. It can be calculated according to Eq. (24):

$$\rho_{fab} = \frac{M}{D \cdot 100} \tag{24}$$

where, ρ_{fab} is the fabric mass density in g per cm^3, M is the fabric mass in g per m^2 and D is the fabric thickness in mm. By fabric engineering it is possible only to predict minimal and maximal value of fabric mass density according to the minimal and maximal value of fabric thickness.

5. Effects of woven fabric construction, maintenance and usage on UV protection

5.1 Effects of yarn structure on UV protection

Woven fabrics are made from different types of yarns. Raw material of yarn or fibre composition is the initial yarn parameter which has an effect on UVR protection. Fibres have different ability to absorb UV radiation and to block most of the incident radiant energy and those prevent it from reaching the skin. There is a lack of studies dealing with the effect of fibre composition only. The reason is that yarn colour, additives and coatings have much more significant impact on UV transmission properties rather than fibre composition itself. Never less, Crews et al. (Hatch & Osterwalder, 2006) conducted a comparison of undyed woven fabrics and determined how fibre composition ranked relative in regard to UV absorbance. They established three distinct groups regarding the decreasing ability of fibre UVR absorbance: 1.group includes polyester, 2. group includes wool, silk and nylon and 3. group includes cotton and rayon fibres. Natural fibres have lower UV blocking properties regarding the synthetic ones, but from the thermo-physiology point of view there are more suitable in hot wearing conditions. Hustvedt et al. (2005) found that naturally-pigmented cotton fabrics have excellent sun protective properties, which are far superior to conventional, bleached or unbleached cotton fabrics. Stankovic et al. (2009) conducted a study of yarn twist effect on UPF of cotton knitted fabric and found that yarn twist to a great extent influenced the UV protection properties through the influence on yarn compactness and surface properties, which in turn influenced the open porosity of the fabric.

5.2 Effects of fabric geometry on UV protection

UV light passes direct through the macropores or fabric open area (direct UV transmittance) and also through the yarns, where changes the direction before leaving the fabric (scattered UV transmittance). Numerous studies focused on different fabric constructional parameters which represent the fabric structure the best and have direct and significant effect on UV protection. Such role has been given to fabric cover factor, fabric open porosity, fabric mass, fabric thickness etc. (Gies et al., 1998; Dimitrovski et al., 2009; Gabrijelčič et al., 2009; Hatch & Osterwalder, 2006).

5.2.1 Effect of cover factor or open porosity

To evaluate only the influence of fabric cover factor (or its complementary relationship – open porosity) on UPF and eliminate other significant factors such as colour and additives, the set of fabrics should be precisely prepared. Our experiment (Dubrovski & Golob, 2009) was focused on 100% cotton woven fabrics in a grey state with the same yarn fineness (14 tex) and different thread densities to achieve fabric cover factor between 59% and 87%. This was possible by introducing different types of weave (plain, twill, satin), while it is known that by plain weave lower densities are achieved due to the high number of thread passages regarding to the twill and satin weaves. Fabric cover factor and open porosity were calculated according to Eq. (15) to Eq. (18). While also cotton yarns absorb some of the incident UVR we could not focuse only on the UVR that goes through the macropores. To eliminate the influence of raw material, yarns with 100% absorption of UV light that strikes them should be used but this is not usually the case. From the Fig. 5 it can be seen that higher cover factor (or lower open porosity) means better UV protection and that cover factor should be at least 80% (or open porosity lower than 20%) to achieve good UV protection according to AS/NZ standard. This is possible only by higher thread densities and definitely not by plain weaves in our case. Even if the plain fabric would have the highest cover factor it would not reach the UPF 15. The results of mentioned study refer to the theoretical values of open porosity and cover factor. In real fabric open porosity is much lower, especially in the case of fabrics made from the staple-fibre yarns, where the phenomenon of latticed pores, the phenomenon of changing the position of warp threads according to the longitudinal axis and the phenomenon of thread spacing irregularity occur. In this case the correlation between the measured open porosity/cover factor (image analysis) and UPF is not so good and should be treated regarding the type of weave (Fig. 6).

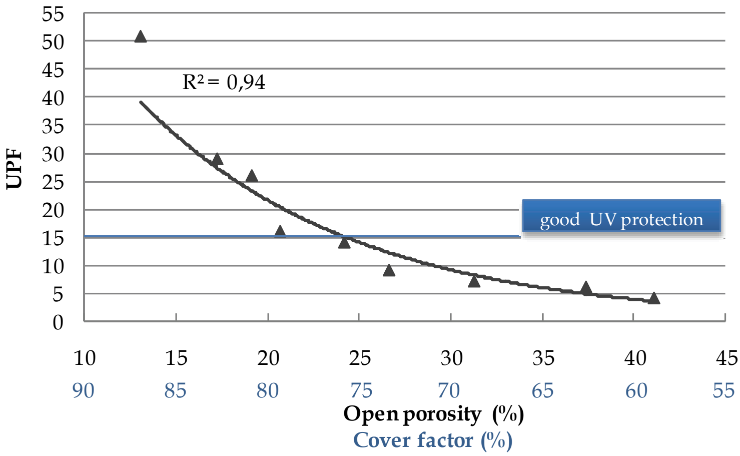
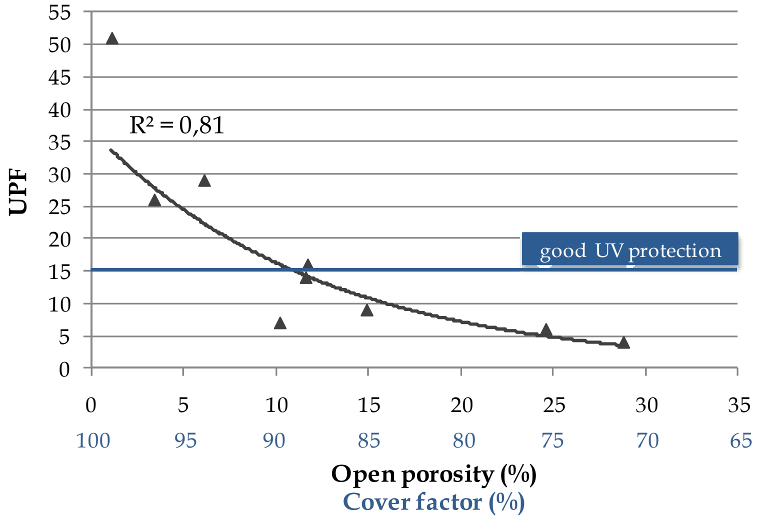
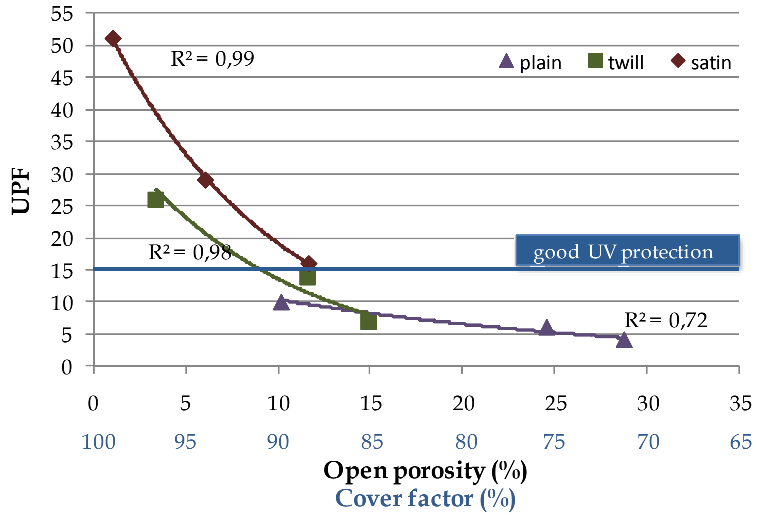


Fig. 5. The influence of theoretical values of open porosity or cover factor on UV protection of cotton fabrics in a grey state

The plain-weave fabric includes the maximum percentage of weave passages (67%) and it is reasonable to assume that all the threads are more or less equidistant and that the effect of fully latticed pores is reduced to its minimum, whereas by satin weave the effect of fully latticed pores is very high those reducing open area for UV transmission. If we observe measured values of open porosity, the limit values to reach good UV protection of fabrics is 12% or lower without taking into account the type of weave. Further observation regarding the type of weave shows that by plain and twill weave it is not possible to reach UPF 15 neither by 12% of open porosity, while by satin weaves this is possible. The results clearly indicate that theoretically defined open porosity/cover factor is not satisfactory parameter to asses its influence on UPF because of the absence of weave influence. In real fabrics, especially in fabrics with staple-fibre yarns, different types of pores regarding the type of weave and other phenomenon are involved, which all reduce the fabric open area in comparison with theoretically calculated values of open porosity. On the other hand, open porosity/cover factor could be a good parameter showing the influence on UPF if the set of fabrics with the same type of weave, raw material and yarn fineness is observed. In our previous research (Dubrovski & Brezocnik, 2002) we also proposed the predictive model of open porosity which is in better correlation with measured values than theoretical ones.



a



b

Fig. 6. The influence of measured values of open porosity and cover factor on UV protection of cotton fabrics in a grey state (a – without weave influence, b – with the weave influence)

5.2.2 Effect of fabric tightness

Fabric tightness or relative fabric density is another parameter which represents the fabric structure or how tight the fabric is woven, similar as cover factor. Advantage of fabric tightness is the consideration of weave by its calculation (Eq. (8) to Eq. (11)). It is known that by satin weave it is possible to achieve higher warp/weft density than with twill or plain weaves, so the limit density as well as actual density will be higher. Consequently, the macropores will be smaller and UV radiation will have less free space to pass through than in twill or plain weaves. The fabric tightness is relative term and according to previous mentioned experiment (Dubrovski & Golob, 2009), the following decreasing rate of UPF values could be seen within the same fabric tightness: satin – twill – plain (Fig. 7).

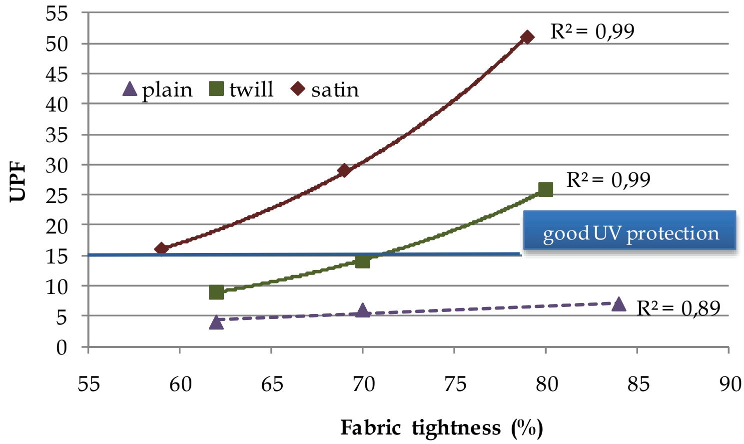


Fig. 7. The influence of fabric tightness on UV protection of cotton fabrics in a grey state

The macropores in plain fabrics have very stable and uniform form as a consequence of more thread passages. On the other hand, the pores in satin fabrics are not as stable due to few thread passages, and tend to group together which further reduces the free space area. By fabrics made from staple-fibre yarns macropores are further reduced because of the phenomenon of latticed pores. Nerveless higher actual warp/weft density by each weave means higher fabric tightness and consequently higher UV protection. Results for fabrics in a grey state show that none of the plain fabrics offered minimum UV protection, even if they were tightly woven. Twill fabrics had good UV protection if they were woven with tightness above 70%, while satin fabrics offered good UV protection already by 60% tightness.

5.2.3 Effect of volume porosity

Thicker and heavier fabrics minimize UVR transmission (Scott, 2005). While some of the researchers focused on fabric mass and thickness, we decided to include volume porosity as a parameter influencing UPF, while it includes fabric mass and thickness through the fabric volume fraction according to the Eq. (19), Eq. (20) and Eq. (25). Results for grey fabrics (Fig. 8) show that there is no direct correlation between volume porosity and UPF. Moreover, results indicate that volume porosity depends on the type of weave and affects UPF as well. This is in accordance with previous mentioned discussion about the macropores. The macropores as three-dimensional forms are bigger, more stable and uniform in plain fabrics compared with macropores in twill or satin fabrics at the same volume porosity. Lower volume porosity means higher UPF. Plain fabrics did not offer any UV protection, while twill and satin fabrics offered good UV protection when volume porosity was less than 64% and 66%, respectively.

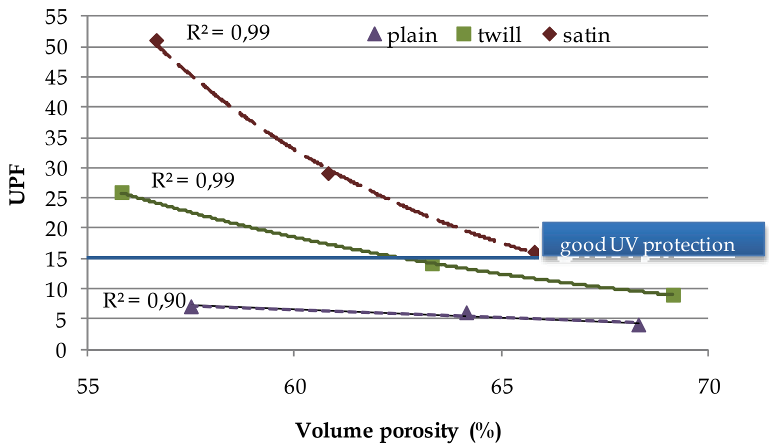


Fig. 8. The influence of fabric volume porosity on UV protection of cotton fabrics in a grey state

5.3 Effects of colour on UV protection

Undyed or bleached fabrics offer much lower protection against UV radiation if any in comparison with dyed fabrics. Dyes react like additives; they improve UV protection abilities, because they absorb UV radiation in the visible and UV radiation band. By bleaching process the naturally occurring pigments and lignin which act as UV absorbers are removed those affect UV absorber ability of cotton fabrics. Hypothesis that the hue of dye is responsible for UV protection of fabric is a matter to discuss.

Gatewood (Scott, 2005) noted that transmission/absorption characteristics of dyes in the UV band were a better predictor of UV protection than the colour of the dyestuff itself.

Srinivasaen et al. (Hatch & Osterwalder, 2006) who studied the effect of fourteen direct dyes on the UPF of cotton fabrics, concluded that colour (hue) is not related to UPF, while fabrics dyed with the dyestuff with the same hue (red 28, red 24, red 80) and identical concentration had different UPF values. Also the black fabric in this study did not have the highest UPF despite the common fact that darker colours (such as black, navy blue, dark green, red) of the same fabric type absorb UVR more strongly than light pastel shades (Yallambie, 2003; Wilson et al., 2008b). Neverless, the results of mentioned study indicate that higher dye concentration means higher UPF. Wilson et al. (2008a) concluded that black fabrics generally transmitted 20% less UVR than their matched white equivalent.

In another study Wilson et al. (2008b) examined the relationship between UV transmittance and colour and found that depth of colour, rather than colour per se is the principal aspect of colour affecting UV transmittance. The best description of the relationship between colour and UVR transmission was provided by the L*, and L* and b* components of the LAB system. He suggested that by developing fabrics for UV protection, selection of dyes that generate colours with CIE Y or L* values of less than approximately 28 or 38, respectively is recommended.

Our study (Dubrovski & Brezocnik, 2009) focused on the effect of woven construction and colour of cotton woven fabrics dyed with the same concentration (1%) of reactive dyestuffs Cibacron LS (red, blue marine and black), bleached fabrics (white) and naturally pigmented fabrics (dirty white). The comparison of UPF of fabrics with the same construction but different colour was made for fabrics in plain, twill and satin weave and by three different levels of fabric tightness (55-65%, 65%-75%, 75%-85%). By satin and twill fabrics at third level of fabric tightness, where higher densities can be achieved and those the influence of open porosity is set to its minimum, the results show that all dyed fabrics posses excellent UV protection (UPF=1000), while naturally pigmented twill and satin fabric had UPF 25 and 50, respectively. UPF of bleached twill and satin fabric was 10 and 15, respectively. The L* component of fabric colour was around 93, 86, 44, 31 and 17 for white, dirty white, red, blue marine and black fabric, respectively. The previous mentioned recommendation that L* value of the dyed fabrics should be less than 38 to develop fabric with good UV protection, could not be generalized, while in our case also white satin fabric with L* of 93 showed good UV protection at third level of fabric tightness. Our results show that there were no big differences between red, blue and black coloured fabrics UPF at higher thread densities by twill and satin fabrics, but there was a huge difference between uncoloured and bleached fabrics UPF on one side and coloured fabrics UPF on another. The general conclusion of mentioned research was that UPF of cotton fabrics dyed with direct dyestuffs is influenced by the colour components (L*, a*, b*), fabric tightness and type of weave so we proposed a prediction model of UPF based on CIELAB colour components, weave factor, and warp/weft density.

Riva et al. (2009) analyzed the influence of the shade and colour intensity of the dyeing as well as their interaction with the initial UPF of the uncoloured cotton fabrics. They proposed UPF prediction model for cotton fabrics dyed with direct dyestuffs (yellow 98, blue 77, red 89) on the basis of the initial UPF of fabrics before dyeing, standard depth of colour, the corrected standard depth of colour and two categorical qualitative variables that define colour hue of dyestuffs.

5.4 Effects of additives on UV protection

During the fibre/yarn/fabric processes there is a possibility to include additives like a dye, pigment, delusterant, optical brighteners and UV absorbers, which have the ability to absorb UV radiation and those improve UV protection properties of fabrics with little UV protection like cotton, rayon, silk, wool, nylon and undyed fabrics. Besides dying, other techniques are known to incorporate additives in fabric structure: 1. addition of additives during fibre/yarn manufacturing, 2. addition of additives during fabric surface treatments or special treatments.

Pigments found in naturally-pigmented cotton are naturally UV absorbers and produce shades ranging from tan to green and brown. According to the study of Hustvedt & Crew (2005), fabrics from naturally pigmented cotton have excellent sun protection properties, which are far superior to conventional, bleached and unbleached cotton fabrics (green UPF=30-50+, tan UPF=20-45, brown UPF=40-50+, bleached conventional UPF=4, unbleached conventional UPF=8). Their UV protection properties remain high enough even after 80 AFUs light exposure.

TiO_2 or ZnO is delusterant pigment which is incorporated during fibre manufacturing and its effect is permanent. Optical brighteners convert a portion of incident UV radiation near 360 nm to the visible blue wavelengths about 430 nm and reflect it. UV absorbers are colourless additives having chromophore system that absorbs very effectively in the UV band. Optical brightness and UV absorbers are recently added to commercial laundry detergents (Yallambie, 2003).

Varga et al. (2009) introduced a nanoparticle coating on yarns. They applied nano ZnO finish on undyed and reactive dyed cotton yarns with the aim of studying the effect of the knitting operation on the durability of the coated nanoparticles and found that such yarns withstand the knitting process. They also performed sol-gel finishing of cotton fabrics, coated with TiO_2 nanoparticles and found that such fabrics are durable to domestic washing, and even there was a reduction in the load of nanoparticles on the fabric surface after washing, the UPF values were not affected.

Abidi et al. (2009) reported that titania or titania-silicia nonosol treatment in the form of thin film at cotton fabric surface offer excellent UV protection. Gorensek et al. (2007) treated cotton fabrics with nanosilver, which was in the form of nano powder added in the dyebath at two concentration (5 mg/L and 20 mg/L) and found that a noticeable increase of UPF was recorded by the 5% mock dyed sample with 20 mg/L nanosilver as well as by pale dyed fabrics in comparison with bleached and dyed cotton fabrics, respectively.

Grancaric et al. (2009) treated PET fabrics for summer clothing with ultrasound (US), ethylene-diamine (EDA), fluorescent whitening agents Uvitex ERN based on benzoxazole derivate (FWAs) and Tinofast PES UV absorbers based on triazine derivate and compared their UPF values. Untreated PET fabrics did not have any UV protection (UPF=5), while all other treatments lead to very good UV protection. EDA treated fabric resulted in better UV protection than US treated fabrics.

5.5 Effects of maintenance and usage on UV protection

When the fabrics for clothing are in use, their initial UPF of fabric is modified by laundering as well as by wearing conditions connected with the tension produced in contact with the body (fabric stretch) and with an exposure to the UV radiation in wet state (swimsuit). Stretching is more common in knitted rather than woven fabrics, with exception of elasticised woven fabrics. Most fabrics shrink when they are laundered which lead to significant improvement in the UPF of fabrics because of the open area reduction (Hatch & Osterwalder, 2006). Another reason of UPF improvement by laundering is optical whiteners which are added to laundry detergent.

Due to the effect of wetness and the effect of opening of the fabrics caused by the tension on tightened and/or elasticized garments, the initial UPF of unstretched and dry fabric does not have proper meaning. European standard EN 13758-1 in annex C considers measurements under stretched and wet conditions informatively, while ASTM D 6544 refers to the preparation of textiles prior to ultraviolet transmission testing which includes exposure conditions (laundering, simulated sunlight and chlorinated pool water).

Algaba et al. (2007) conducted a study on undyed woven fabrics made with three different cellulose fibres (cotton, modal and modal sun fibres that contain UV absorber in the spinning bath) which were exposed to the simulation of the wearing conditions of the clothing. Samples were stretched with a tension of 2, 4, and 6 N and the measurements were carried out after maintaining the samples (unstretched or stretched) in water until saturation. The UPF of fabrics decreased significantly when tension increased. The sign of the influence of the wetness on UPF depended on the fibre type. The UPF of wet cotton and modal fabrics was lower, while modal sun fabrics had higher UPF regarding the dry fabrics. Osterwalder et al. (Scott, 2005) concluded that UV absorbance is independent from environment and therefore treating cotton with UV absorber will afford complete protection when the fabric is wet. Wilson et al. (2008a) reported that by 10 x 20% extension UPF of cotton woven and knitted fabrics were decreased by -30% to -75%.

6. Conclusion

Woven fabrics can provide simple and convenient protection against harmful effects of UV radiation if the necessary attention is paid to their engineering in the phase of a new product development. There are several factors influencing UV protection properties of woven fabrics like yarn construction (fibre type, twist, yarn packing factor), fabric construction with its primary (type of weave, yarn fineness, warp/weft density, relative fabric density or fabric tightness) and secondary (cover factor, open porosity, mass, thickness, volume porosity) parameters of fabric geometry, additives (dye, pigment, delusterant, optical brighteners, UV absorbers), laundering and wearing conditions (stretch, wetness). The proper combination of mention factors allows production of passive woven fabrics with high UV protection properties, which may reduce risk associated with UV overexposure. For subject wearing garment made from UV protected fabrics the information about how long he/she could be exposed to the harmful UV rays before the serious skin damage occur, will be more useful, instead of knowing UPF value of garment. UV exposure time is affected by several factors like subject skin type, geographic position of subject, daily time or the sun position, the presence of clouds, altitude, portion of skin covered by fabric, etc. However, nowadays, there is a trend to develop smart textiles or active intelligent fabrics which, for example, could change their own colour in dependence on external stimulus like UV light (Vikova, 2004). Soon such smart textiles will be developed which will warn the subject how long he/she could be on the sun, what is the average UV index in a particular position, what is the UPF of wearing fabric in a particular moment, when subject should use the shadow, etc.

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