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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 1-2^{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).

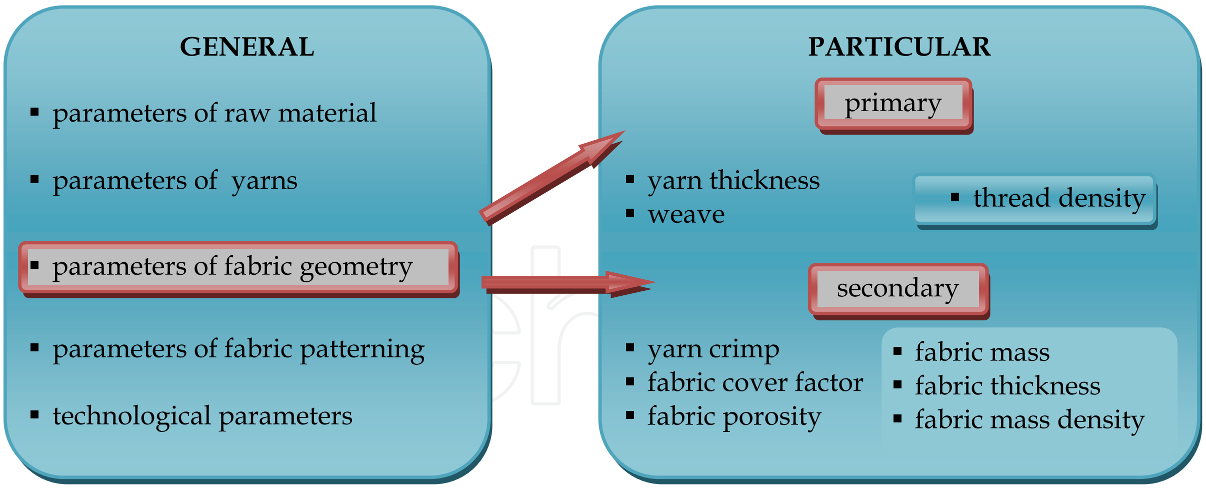


Fig. 2. Classification of woven fabric constructional parameters

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):

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

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 cm³, ρ_f is the fibre bulk density in g per cm³, 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):

$$V_1 = \frac{\sqrt{(v_1^2 + 2v_1v_2)} \cdot R_1}{v_1R_1 + \frac{a_2(2,6 - 0,6z_2)}{f_2}\left(\sqrt{(v_1^2 + 2v_1v_2)} - v_1\right)} \tag{5}$$

$$V_2 = \frac{\sqrt{(v_2^2 + 2v_1v_2)} \cdot R_2}{v_2R_2 + \frac{a_1(2,6 - 0,6z_1)}{f_1}\left(\sqrt{(v_2^2 + 2v_1v_2)} - v_2\right)} \tag{6}$$

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.

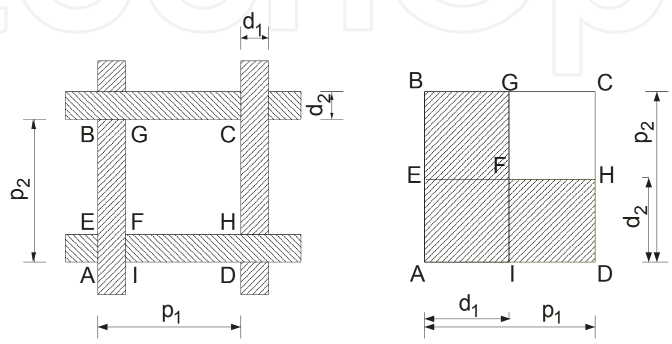


Fig. 3. Woven fabric geometry by fabric cover factor definition

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 cm^2, A_p is the area of macropore's cross section in cm^2, 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 cm^3, V_{fab} is the fabric volume in cm^3, 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 cm^3, and ρ_y is yarn bulk density in g per cm^3. **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.

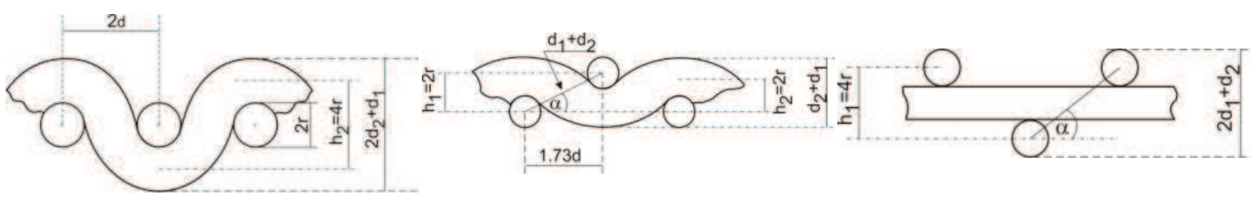


Fig. 4. I., V. and IX. Novik's fabric construction phases

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 m^2, 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 m^2, 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 cm^3. It can be calculated according to Eq. (24):

$$\rho_{fab} = \frac{M}{D \cdot 100} \quad (24)$$

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).

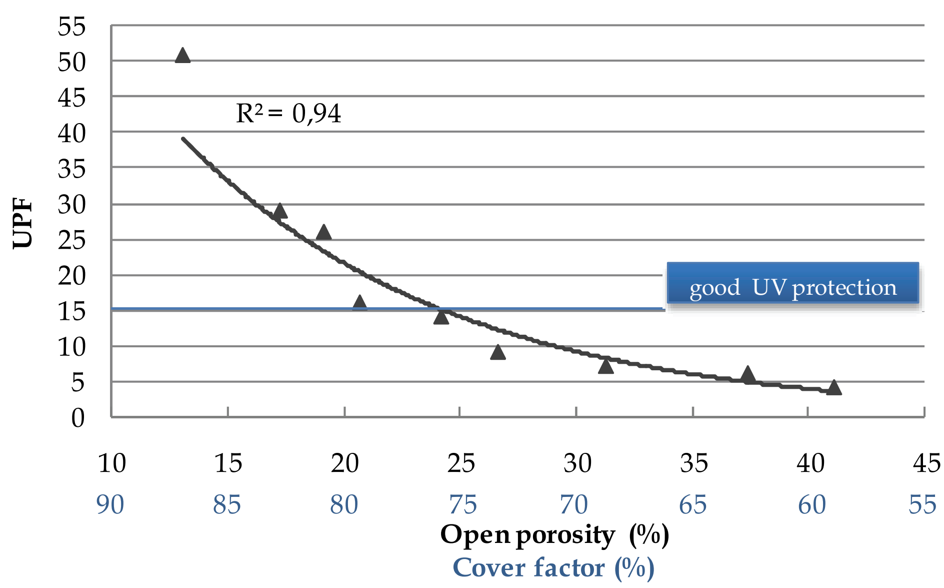
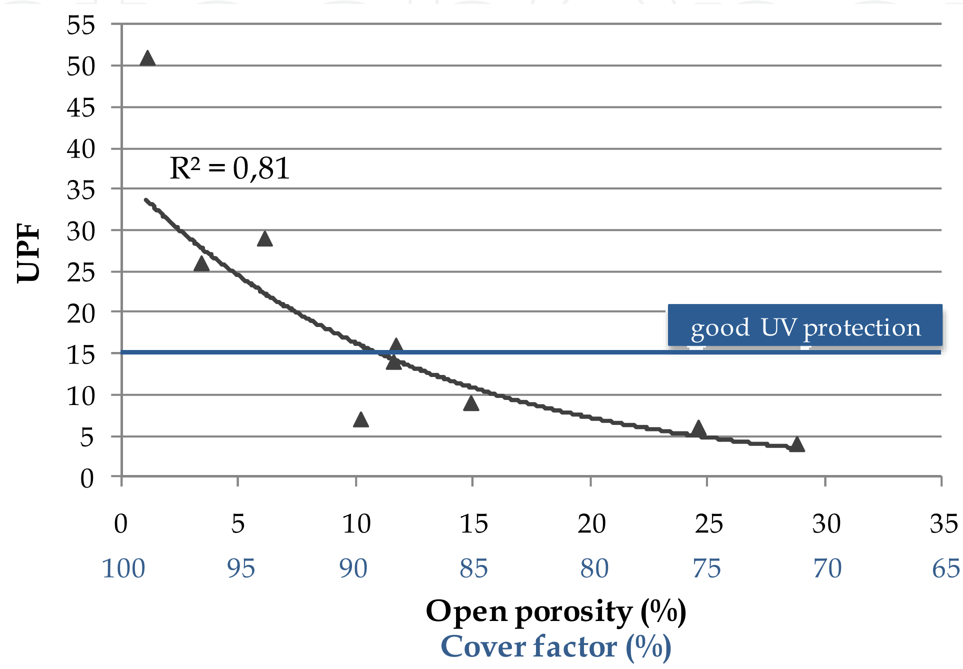
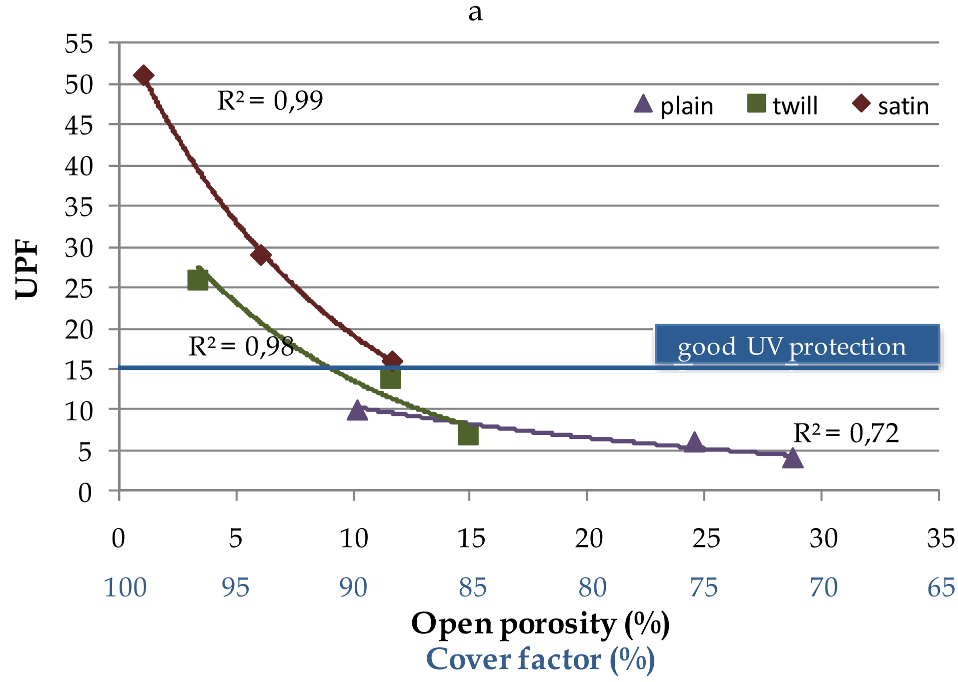


Fig. 5. The influence of theoretical values of open porosity or cover factor on UV protection of cotton fabrics in a grey state

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).

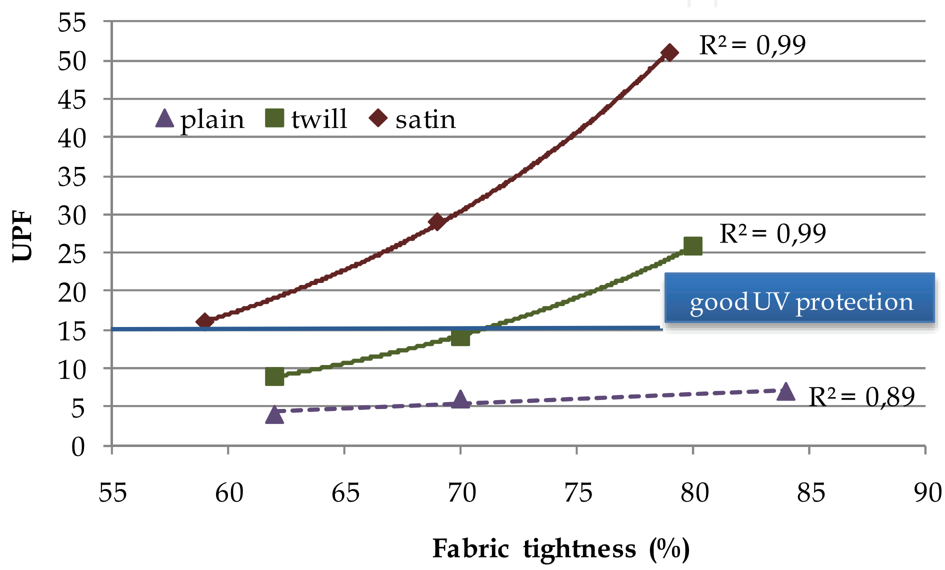


Fig. 7. The influence of fabric tightness on UV protection of cotton fabrics in a grey state

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.

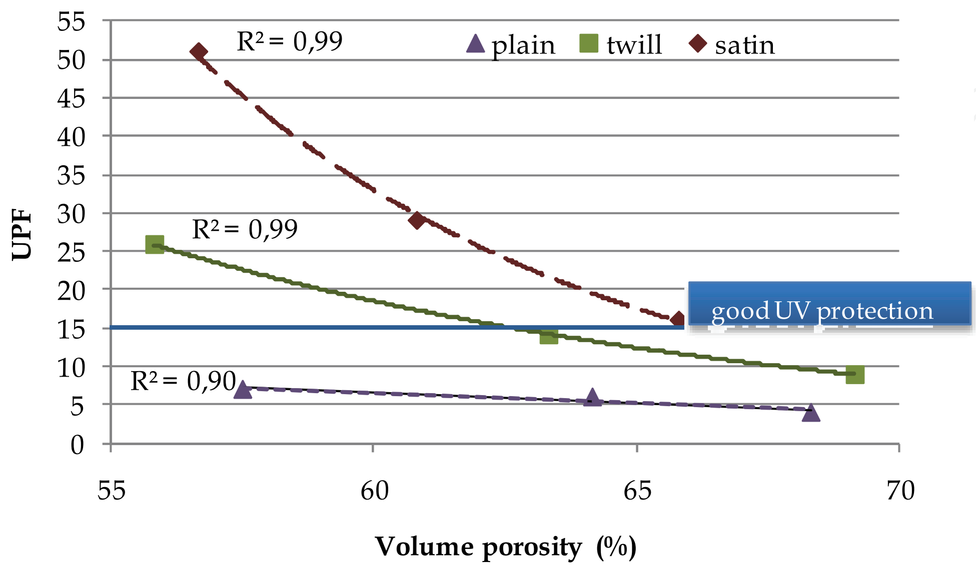


Fig. 8. The influence of fabric volume porosity on UV protection of cotton fabrics in a grey state

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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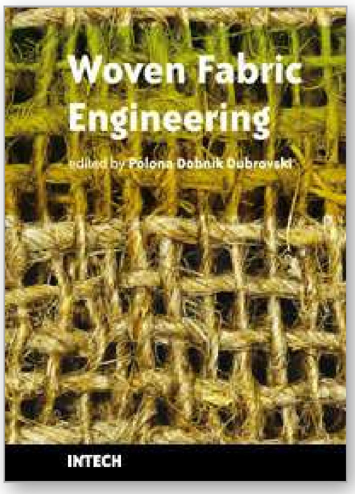

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The main goal in preparing this book was to publish contemporary concepts, new discoveries and innovative ideas in the field of woven fabric engineering, predominantly for the technical applications, as well as in the field of production engineering and to stress some problems connected with the use of woven fabrics in composites. The advantage of the book Woven Fabric Engineering is its open access fully searchable by anyone anywhere, and in this way it provides the forum for dissemination and exchange of the latest scientific information on theoretical as well as applied areas of knowledge in the field of woven fabric engineering. It is strongly recommended for all those who are connected with woven fabrics, for industrial engineers, researchers and graduate students.

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