IR and UV Protective Function of Woven Fabrics

Polona Dobnik Dubrovski

Institute of Engineering Materials and Design, Faculty of Mechanical Engineering, Department of Textile Materials and Design, Maribor, Slovenia

*Corresponding Author, e-mail: polona.dubrovski@um.si

Abstract

Nowadays, it is well known that exposure to ultraviolet radiation can have harmful effects. These effects include mainly sunburn (erythema) and tanning (pigment darkening), as well as premature aging of the skin, suppression of the immune system, damage to the eyes, and skin cancer. Currently, between 2 and 3 million cases of non-melanoma skin cancer and 132 000 cases of melanoma skin cancer occur globally each year. Fabric is the most basic and one of the best means of sun protection, however not all fabrics offer sufficient UV protection. In hot weather conditions, the use of UV-resistant materials is not enough. At the same time, a thermophysiological wear comfort is also desired, so clothing should be made from fabrics that protect the body against penetration and absorption of infra-red radiation. The proposed paper describes the influence of fabric constructional parameters on IR and UV radiation transmittance.

Keywords: IR, Sportswear, UV Protective, Woven, Fabric

INTRODUCTION

Fabrics are produced in order to fulfill different performance properties, which are essential for their end-usage application. In general, they should have enough durability, comfort, aesthetic appeal, easy maintenance, and they should support our health and protect us against potentially hazardous substances [1]. During the last several decades, people have become more aware of the negative effects that too much exposure to ultraviolet radiation has on human health. These effects include mainly sunburn (erythema) and tanning (pigment darkening), as well as premature aging of the skin, suppression of the immune system, damage to the eyes, and skin cancer [2-5]. Skin cancer, including melanoma and non-melanoma skin cancer, represents the most common type of malignancy in the white population. Cumulative epidemiologic data from Europe, Canada and the United States indicate a continuous and dramatic increase in incidence during the last decades. The highest incidence rates have been reported in New Zealand with 50 cases per 100,000 persons and Australia with 48 cases per 100,000 persons (59 for males and 39 for females in 2011), followed by the US (21.6 new cases per year per 100,000 in 2012) and Europe (13.2 and 13.1 new cases per year, per 100,000 for men and women, respectively) [6]. Currently, between 2 and 3 million cases of non-melanoma skin cancer and 132 000 cases of melanoma skin cancer occur globally each year. As the ozone layer is depleting, the atmosphere is losing its natural protective capability, and therefore more and more solar UV rays reach the Earth’s surface. The people that are most prone to this risk are those that spend large parts of the day outdoors (workers). Fabric is the most basic and one of the best means of sun protection, however not all fabrics offer sufficient UV protection. In hot weather conditions, the use of UV-resistant fabrics/clothing is not enough. At the same time, a thermophysiological wear comfort is also desired, so clothing should be made from fabrics that protect the body against penetration and absorption of infra-red (IR) radiation, but also allow moisture to evaporate from the body into the environment. At first glance, these two project demands appear to be in a contradiction. As such, there is a growing need to develop an optimal type of fabric structure that could offer sufficient protection against both UV and IR radiations. First and foremost, the basic knowledge regarding the influence of fabric constructional parameters on UV and IR protection properties should be fully understood at the very beginning, in order to develop the material itself, which will then offer sufficient or optimal UV and IR protection. The proposed paper describes this influence of fabric constructional parameters on IR and UV protection levels of woven fabrics and shows the results of the research focused on the influence of the woven fabrics' constructional parameters, e.g. type of weave and fabric relative density (as primary constructional parameters), on IR and UV radiation transmittance of 100% cotton woven fabrics.

SOLAR RADIATION – SUNLIGHT

The Sun emits different electromagnetic waves, however only three main components of solar radiation reach the Earth's surface: ultraviolet radiation (UV radiation), visible light radiation (light), and infrared radiation (IR radiation) (Figure 1). These electromagnetic waves refer to sunlight, which is filtered through Earth's atmosphere.

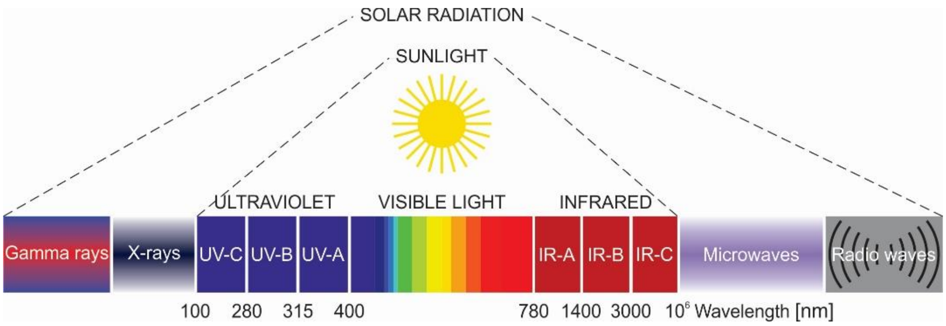

Figure 1. Solar radiation and sunlight spectrum

According to the CIE the spectral distribution of solar radiation at the surface of the Earth contains about 6.1 percent of ultraviolet light consisting of 0.5 percent of UVB (290-320 nm) and 5.6 percent of UVA (320-400 nm), 51.8 percent of visible light (from 400-780 nm), and 42.1 percent infrared light (from 780 nm to 1 mm) [7, 8]. Solar irradiance on the Earth's surface, e.g. the power per unit area received from the Sun, depends on the tilt of the measuring surface, the height of the Sun above the horizon, and atmospheric conditions. When the direct sunlight is not blocked by clouds, it is experienced as sunshine, e.g. a combination of bright light and radiant heat. The visible portion of the sun is visible to the human eye, whereas the IR and UV portion of the sun is not visible. We cannot feel the UV radiation, while the IR radiation can be felt as thermal radiation.

UV radiation and its effect on human health

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 the soft X-rays, in the range of 10 nm to 400 nm, and energies from 3 eV to 124 eV. The UVR spectrum is further 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. 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 UVB radiation as well.

There are significant differences between the UVA, UVB and UVC radiation regarding their effects on human health (Table 1). UVA radiation is also known as the glass-transmission region, while ordinary glass blocks over 90% of the radiation below 300 nm and allows the radiation above 350 nm to pass through. UVA radiation is believed to contribute to premature ageing and wrinkling of the skin, because 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 absorbs UVA radiation and dissipates the energy as harmless heat, thus blocking the UV from damaging any skin tissue. Today, it is also well established that UVA radiation can generate highly reactive chemical intermediates, which indirectly damage the DNA, and in this way induces skin cancer. UVA is the main cause of immunosuppression against a variety of infectious diseases (tuberculosis, leprosy, malaria, measles, chicken pot, herpes and fungal disease), rather than UVB, but its 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 cancer, sunburn and cataracts. It damages the fundamental building element – DNA directly at the molecular level as well as collagen fibres and vitamin A in the skin [9].

Because of the ozone layer, indeed only UVA and UVB reach the Earth's surface; 95 percent of natural UV radiation is in the UVA range. The biological reactions induced by UV radiation are complex. Because of the absorption spectrum of the skin, UVA – even though it has less energy than UVB – penetrates deeper and causes not only epidermal damage but also dermal changes. Nonetheless, UVB has the most carcinogenic effect. UVA enhances the carcinogenic effect through immunosuppression and by inducing the formation of reactive oxygen species (ROS). These in turn damage deoxyribonucleic acid (DNA), cell membranes and enzymes. The end result is damage to the epidermal keratinocytes and the dermal connective tissue (Figure 2). The negative effects of UV radiation on the skin depend on the type, duration and intensity of the UV exposure, and can lead to acute erythema (sunburn), or with cumulative exposure, to chronic actinic damage (extrinsic photoaging) [10].

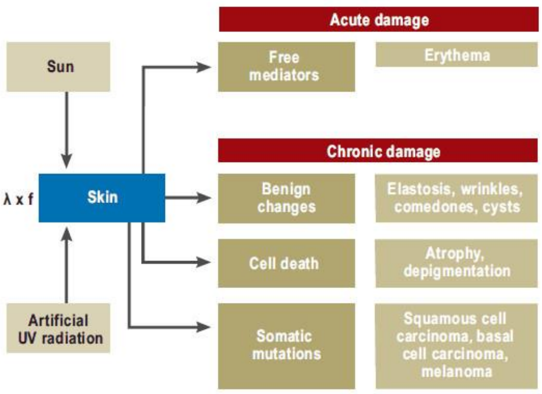

Figure 2. Consequences of excessive UV exposure on human skin

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

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.	It has 2 times bigger mean energy than visible radiation.	It has 4.1 times bigger mean energy than visible radiation.
Its intensity represents the 7,9% of solar radiation.	Its intensity represents the 1,5% of solar radiation.	-
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 destroys DNA and causes skin cancer.	Directly destroys 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 the skin.	Dangerous to the eyes.	Dangerous to the eyes.

IR radiation and its effect on human health

Infrared radiation (IR) is electromagnetic radiation with longer wavelengths than those of visible light, and is therefore generally invisible to the human eye, but people can still feel it as heat. The IR spectrum is subdivided into IRA, IRB, and IRC region by The International Commission on Illumination (CIE), or into NIR, MIR, FIR region by ISO 20473.

Research shows that more than 90 percent of full solar radiation spectrum is in the VIS – IR range. Within IR radiation, roughly 30 percent of the total solar energy is IRA, which penetrates deeply into the human skin. In the last decade, several researches have indicated that not only has UV radiation some negative effects on human health, but VIS and IR radiation appear to have such effects as well, particularly near-infrared radiation (IRA radiation, 760-1440nm). While IRB and IRC radiation does not penetrate deeply into the skin, more than 65 percent of IRA reaches the dermis and alter the collagen equilibrium of the dermal extracellular matrix, thus influencing the photo-ageing process (formation of coarse wrinkles, uneven skin pigmentation, loss of elasticity, disturbance of skin barrier functions) [11]. Therefore, effective sun protection should not exclusively focus on UV, but also include protection against IRA.

Abbreviation	Wavelength	Frequency
IR-A	700 nm – 1400 nm	215 THz - 430 THz
IR-B	1400 nm – 3000 nm	100 THz - 215 THz
IR- C	3000 nm – 1 mm	300 THz - 100 THz

(a)

Designation	Abbreviation	Wavelength
Near - Infrared	NIR	0.78 – 3 µm
Mid - Infrared	MIR	3 – 50 µm
Far - Infrared	FIR	50 – 1000 µm

(b)

Figure 3. The division of infrared radiation by CIE (a) and ISO (b)

Distribution of solar radiation through the fabric

When solar radiation reaches textile material in the form of woven, knitted or compound fabric, there are several possible pathways (Figure 4): it can be transmitted, absorbed, or reflected by the fabric [12]. Part of the radiation is already reflected or scattered by the fibrous material at the fabric surface, part is absorbed by the fibrous material and converted into heat. Another part of the radiation passes directly through the pores between the yarns in the fabric and between the fibres in the yarns (direct transmission) or indirectly through the fibrous material (indirect transmission). Several factors have an important role by determining the effectiveness of fabric to protect us against solar radiation. In the case of woven fabric, these factors can be grouped as shown in Figure 5.

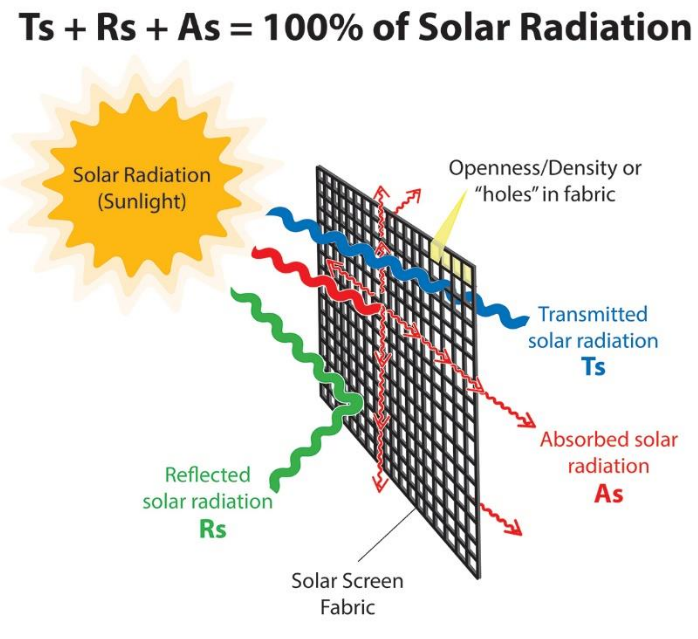

Figure 4. Distribution of solar radiation when it reaches the fabric

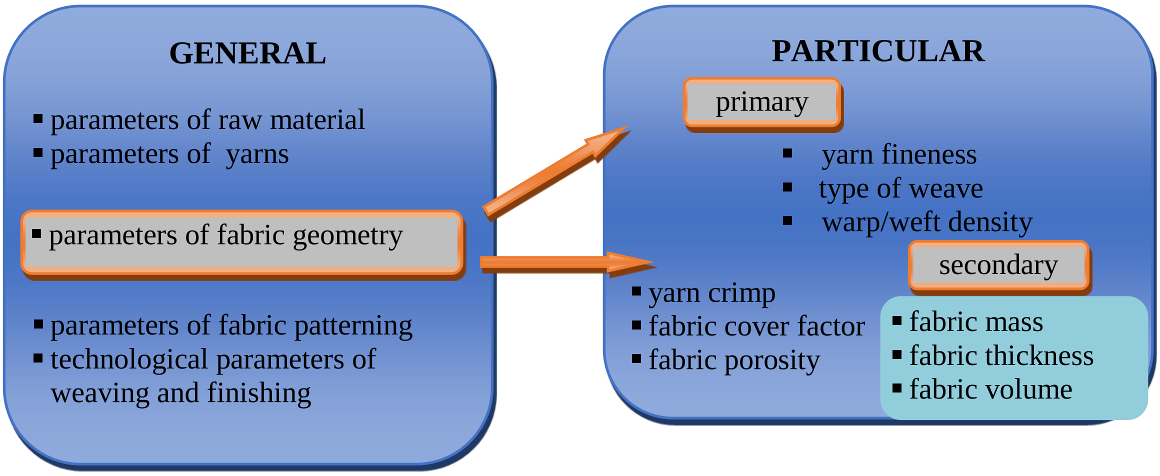

Figure 5. Woven fabric constructional parameters having an effect on solar radiation

MATERIALS AND METHODS

The woven fabrics were engineered according to Kienbaum's setting theory (Table 2) and manufactured using Picanol weaving machine. All woven fabrics were made from 100% cotton carded yarns with following constructional parameters: fineness: 36 tex, number of twist: 630 z, yarn diameter: 0.236 mm, volume coefficient: 6.606, bulk density of fibers: 1.5, yarn packing factor: 0.55, yarn flexibility factor: 0.8, yarn volume mass: 0.825 g/cm^3. It should be noted that samples where in a raw state in order to eliminate the influence of finishing treatments on solar radiation-protective function of fabrics. The basic fabric density was the same for all samples (4.645 threads per cm). The fabric relative density was calculated according to Equations 1-5:

$$t = \sqrt{t_1 \cdot t_2} \tag{1}$$

$$t_1 = \frac{G_1}{G_{\lim}} \cdot 100 \quad t_2 = \frac{G_2}{G_{\lim}} \cdot 100 \tag{2}$$

$$G_{\lim} = g \cdot V \cdot \sqrt{\frac{1000}{T}} \tag{3}$$

$$g = 5{,}117 \cdot \sqrt{\rho_{fib} \cdot i} \tag{4}$$

$$V = \frac{1.732 \cdot R}{R + \frac{a \cdot (2.6 - 0.6 \cdot z)}{f} \cdot 0.732} \tag{5}$$

wherein t is fabric relative density or fabric tightness in percentages, G is actual density in threads per cm, Glim is limit density of fabrics with the same threads and the same weave parameters in warp and weft directions, in threads per cm, g is basic density in threads per cm, V is weave factor, T is yarn fineness in tex, , ρ_{fib} is bulk density of fibers in gcm^{-3}, i is yarn packing factor, R is number of threads in weave repeat, a is the number of passages of yarn in one 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.

Table 2 The constructional parameters of tested woven samples

Fabric Code	Yarn Fineness (Tex)	Type of Weave	Warp Density (ends/cm)	Weft Density (pick/cm)	Level of Fabric Relative Density	Fabric Relative Density (%)
1	36	plain	19.9	9.6	I	62
2	36	plain	20.8	12.0	II	71
3	36	plain	20.8	16.4	III	83
4	36	twill	26.4	12.7	I	63
5	36	twill	27.1	16.0	II	72
6	36	twill	26.9	21.7	III	83
7	36	satin	29.9	12.9	I	58
8	36	satin	29.6	16.5	II	65
9	36	satin	29.9	23.6	III	79

Testing samples of different weaves – namely plain (10-01 01-01-00), twill (20-02 02-01-01), and satin (31-01 04-01-02) were prepared at three levels of fabric relative density: 55% - 65% (minimum), 65% - 75% (average), and 75% - 85% (maximum). The warp density of tested samples was around 20, 27, and 30 threads/cm for plain, twill and satin fabrics, respectively. The weft density of fabrics was set between10-16, 13-22, and 13-24 threads/cm for plain, twill and satin fabrics, respectively. Afterwards, the warp and weft densities were measured again in accordance with the ISO 7211-2. For measuring UV and IR transmittance, an UV/VIS/NIR spectrophotometer Lambda 900 was used in the range between 210 and 1200 nm. The device was equipped with a double beam optical system and two detectors with an integrating sphere unit (60 mm with Spectralon coating), which is able to evaluate the total spectral transmittance of the scattering material. A photomultiplier tube (PMT) detector was used for the UV (and visible) region and a low-temperature sulfide lead (PbS) detector for the NIR region. By using a spectrophotometer, the percent transmittance of solar radiation (both direct and diffuse), was measured at wavelength intervals of 10 nm in the 210-1200 nm spectral range.

RESULT AND DISCUSSION

Figures 6 and 7 present the results of solar radiation transmission through tested cotton woven fabrics over the wavelength between 200-1200 nm.

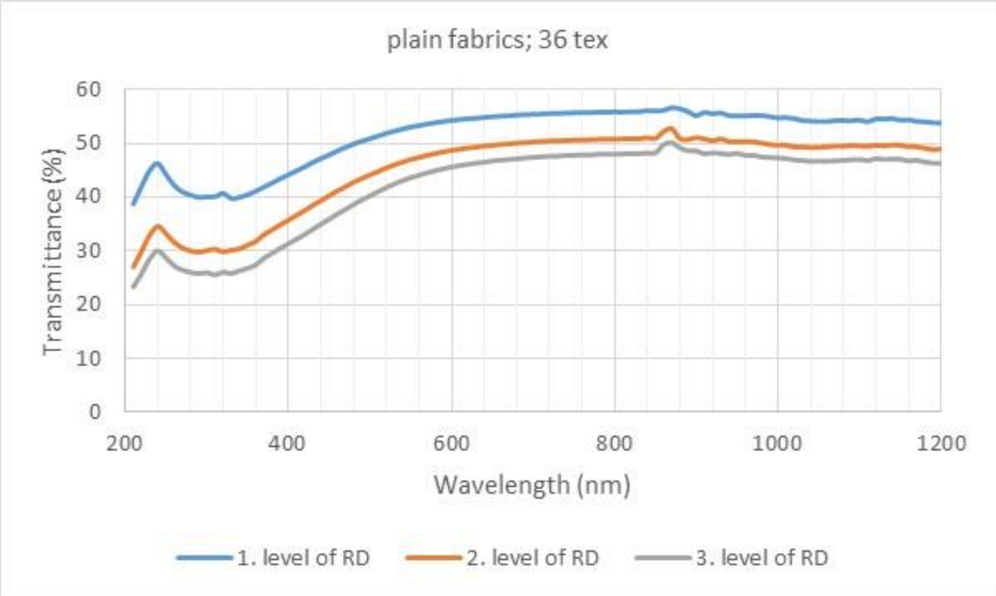

Figure 6. Transmittance curves of plain-woven fabrics at different levels of fabric relative density as function of the wavelength

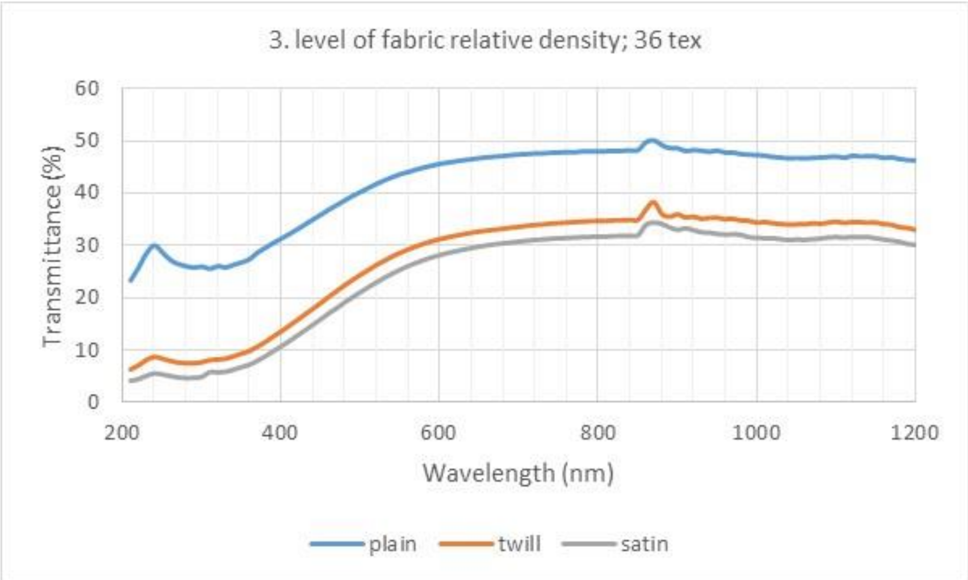

Figure 7. Transmittance curves of woven fabrics by 3. level of fabric relative density at different type of weave as function of the wavelength

The transmission of UV radiation through plain-woven fabrics was lower than IR transmission at all levels of fabric relative density. The maximal UV transmittance was 46.2% (at 240 nm), 34.7% (at 390 nm) and 30.6% (at 390nm) while the maximal IR transmittance was 56,5%, 52.6% and 50.2% (all at 870 nm) at 1., 2. and 3. level of fabric relative density, respectively. The similar conclusions are valid for twill and satin fabrics regarding the level of fabric relative density (fabric tightness). UV an IR transmittance decrease with the higher level of fabric relative density. Higher fabric relative density means lower open area (open porosity), thus resulting in less space for direct transmission of UV radiation through the open pores of woven fabric (pores between the yarns in the fabric). The UV/IR transmittance may also occur through the pores between the fibers in the yarns and through the fibers itself, but the open porosity (fabric tightness/fabric relative density) is considered to have bigger influence. If we compare the results regarding the type of weave, we can conclude (Figure 7) that satin fabrics allow less solar radiation to go through the fabric than twill and plain fabrics at the same level of fabric relative density. We should have in mind that satin fabrics have higher ends/picks by the same level of fabric relative density, and consequently lower open area.

CONCLUSIONS

The average warp/weft density was 18.6/24.3/26.8 for plain, twill and satin fabrics at 3. level of fabric relative density, respectively. The maximal UV transmittance was 30.5%, 12.6% and 9.7% (all at 390 nm), while the maximal IR transmittance was 50.2%, 38.3% and 34.3% at 3. level of fabric relative density for plain, twill and satin fabrics, respectively. Similar conclusions can be made for fabrics at 2. and 3. level of fabric relative density.

REFERENCES

[1] Hatch, K. L. (1993). Textile science. New York, West Publishing Company.
[2] Cesarini, J. P. (2001). Impact of ultraviolet radiation on humans. Indoor and built Environment, 10(5), 310-316.
[3] Ferrini, R. L., Perlman, M., & Hill, L. (1998). American College of Preventive Medicine practice policy statement: skin protection from ultraviolet light exposure. American journal of preventive medicine, 14(1), 83-86.
[4] Gies, P. H., Roy, C. R., Toomey, S., & McLennan, A. (1998). Protection against solar ultraviolet radiation. Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis, 422(1), 15-22.
[5] Reichrath, J. (2007). Sunlight, skin cancer and vitamin D: What are the conclusions of recent findings that protection against solar ultraviolet (UV) radiation causes 25-hydroxyvitamin D deficiency in solid organ-transplant recipients, xeroderma pigmentosum, and other risk groups?. The Journal of steroid biochemistry and molecular biology, 103(3-5), 664-667.
[6] Apalla, Z., Lallas, A., Sotiriou, E., Lazaridou, E., & Ioannides, D. Epidemiological trends in skin cancer. Dermatology Practical & Conceptual. 2017; 7 (2): 1–6.
[7] CIE (Commission Internationale de l'Eclairage): Solar spectral irradiance, CIE Technical Repor (1989), Table 4, Global solar irradiance at sea level No.85.
[8] Zabetakis, A. (2002). Textiles for protection against solar UVR, weather conditions and fire. In Dragčević, Z. (Ed), The International Textile Clothing & Design Conference: Magic World of Textiles, pp. 152-157, Zagreb, Faculty of Textile Technology, University of Zagreb.
[9] Dubrovski, P. D. (Ed.). (2010). Woven fabric engineering. BoD–Books on Demand.

[10] Fartasch, M., Diepgen, T. L., Schmitt, J., & Drexler, H. (2012). The relationship between occupational sun exposure and non-melanoma skin cancer: clinical basics, epidemiology, occupational disease evaluation, and prevention. Deutsches Ärzteblatt International, 109(43), 715.

[11] Schroeder, P., Calles, C., Benesova, T., Macaluso, F., & Krutmann, J. (2010). Photoprotection beyond ultraviolet radiation–effective sun protection has to include protection against infrared A radiation-induced skin damage. Skin pharmacology and physiology, 23(1), 15-17.

[12] How solar screen Ssades work (2018) Retrieved from https://insolroll.com/how-solar-screen-shades-work.