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A NEW SIMPLIFIED MODEL FOR PREDICTING THE UV-PROTECTIVE PROPERTIES OF MONOFILAMENT PET FABRICS

Klara Kostajnšek, Raša Urbas, Krste Dimitrovski

Faculty for Natural Sciences and Engineering, Department of Textiles, Graphic Arts and Design, University of Ljubljana, Aškerčeva 12, 1000 Ljubljana, Slovenia, Telephone: +386 1 200 3200
E-mail: klara.kostajnsek@ntf.uni-lj.si

Abstract:

Knowing the reflection, transmission, and absorption properties of the yarns from which the woven fabric is made, prediction of a fabric's UV-protective properties is simple. Using the geometrical properties of monofilament yarns and fabrics, which were determined optically, and following the cover factor theory, we have determined the areas of fabrics covered with no yarns, only one yarn, and two yarns. From a special selected set of high-module polyethylene terephthalate (PET) monofilament materials (e.g., fabrics), we have elaborated a method for determining the reflection, transmission, and absorption of yarns. By first defining the differently covered areas of fabrics, we were able to use them in a mathematical model for calculating and predicting the UV-protective properties of the fabrics. The calculated and measured values of the UV-protective properties of the selected test fabrics were highly correlated, with a correlation coefficient >0.98.

Keywords:

PET monofilament, yarns, fabrics, UV-protective properties, model, prediction of UV-protective properties

1. Introduction

In recent decades, protection against the harmful radiation of ultraviolet rays (UV) is becoming increasingly important because of the depletion of the ozone layer in the atmosphere. Despite certain positive effects of the UV radiation, excessive exposure to the sun has negative effects on people's health, the level of which depends on the quantity of exposure to individual types of UV radiation (UVA, UVB, and/or UVC). Nowadays, preventive actions for the protection of people from the effects of UV are well known, such as setting a daily limit for exposure to the sun's rays, use of sunscreens and sunglasses, the use of pharmacological agents, and the use of protective clothing and hats. The most effective metioned approache for the protection of the skin is the usage of mechanical protective products, which physically prevent harm from the negative effects of UV rays. One of the best and most appropriate options are different textile products, which are used both as clothes and as protection devices between the rays and the concerned person in the sense of prevention of penetration (e.g., sun umbrellas, canopies, etc.).

Many researchers have investigated the influence of different factors related to the textile materials used for UV protection. They have investigated the influence of type of material [1, 2], fabric constructions [1, 3–5], colors, and different additives [6–10].

The advantage of textile protective products, in comparison with pharmaceutical products (sunscreens, lotions, protective oils, etc.), is that textile products do not have to be applied directly into/on the skin, by which we avoid many allergic and other chemical skin reactions. The advantage of using textile products (i.e., clothes) is also that it is easy to separate the protected surface of the skin from the unprotected part when we use them [1–3].

The presentation of the research done so far is based on a search conducted in the Web of Science database. The search was done in two sets, namely, general (no restrictions on the search) and then also with a restriction in the Material Science textile category.

The search was set according to the title, abstract, and keywords:
1. UV protection,
2. UV protection by textiles, and
3. UV protection by textile structure.

Statistical processing of data shows that only about 4% of the research reports in the Web of Science database includes UV protection in the Material Science textile search category (MST) (270 hits out of 7.433). The number of hits for the search words in points 1 and 2 shows the importance and popularity of the topic, and the number of hits for the search words in point 3 (number of hits ~53, and number of hits for MST category ~22) shows that the number of publications on the topic of protection against UV radiation concerning the structure of textiles is relatively low, which points to a proportionately low number of authors dealing with UV protection of woven textiles from the perspective of construction and prediction, which is the purpose of our research.

One-layered woven fabrics consist of two different parts in their structure, usually described by the open area and the cover factor [1–3]. The extended version of the cover factor theory also presents the area covered by one yarn and the area covered by two yarns in a fabric's structure (Figure 1).

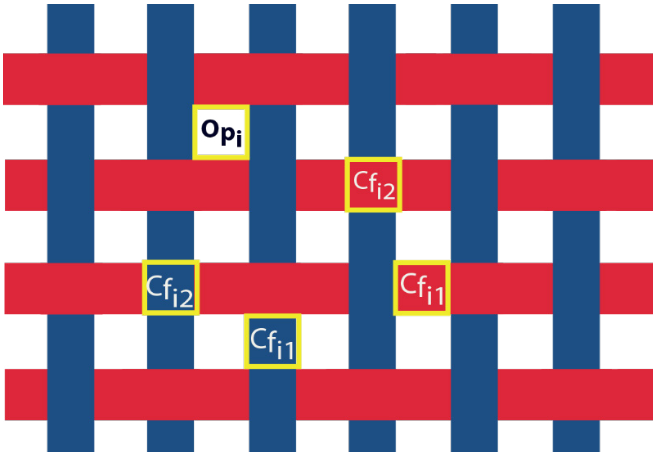

Figure 1. Scheme of woven fabric in plain weave, divided into the areas without yarns – white-colored areas ($Op=\Sigma Op_i$) – and the areas covered with one ($Cf_1=\Sigma Cf_{i1}$) or two yarns ($Cf_2=\Sigma Cf_{i2}$), where i is the number of individual areas in a unit area.

Generally, the theory of the woven fabrics defines the cover factor as a fraction of the surface covered by the yarns. This equals the quotient of the area covered by the yarns divided by the total area of the web construction of the fabric [11], expressed in Equation (1). In this manner, it ranges from the value zero to the value one, and if multiplied by 100, it can be expressed in percentage.

$$Cf = area\,covered\,by\,yarns / total\,area\,of\,web \quad (1)$$

Calculation of the cover factor consists of calculation of the Cf_{wa} (cover factor of warp yarns) and the Cf_{we} (cover factor of weft yarns) as follows:

$$Cf_{wa} = D_{wa} \times d_{we} \text{ and } Cf_{we} = D_{we} \times d_{we},$$

where D_{wa} and D_{we} represent the densities of the warp and the weft, and d_{wa} and d_{we} denote the diameters of the warp and the weft yarns.

The cover factor of a one-layered fabric is expressed by the cover factor of the warp and the weft yarns. Therefore, Equation (1) can be transformed into Equation (2):

$$Cf = Cf_{wa} + Cf_{we} - Cf_{wa} \times Cf_{we} \,. \quad (2)$$

For the purpose of the research, we had to modify and extend the woven fabric cover factor theory into the next form. The fabric cover factor is a sum of areas covered by one yarn (Cf_1) and two yarns (Cf_2), expressed using Equation (3):

$$Cf = Cf_1 + Cf_2 \,. \quad (3)$$

The portion of the fabric covered by two yarns is calculated as follows:

$$Cf_2 = Cf_{wa} \times Cf_{we} \,, \quad (4)$$

and the portion of the yarns covered by one yarn is derived as follows:

$$Cf_1 = Cf - Cf_2 \,. \quad (5)$$

In one of our previous research works [5], we have evaluated the penetration of UV rays through a one-layered monofilament high-module polyethylene terephthalate (PET) material (e.g., fabrics), in order to determine the amount of reflected, absorbed, and transmitted UV rays by one yarn and two yarns (one on top of the other) in the fabric structure. We have calculated the quotient, as shown in Equations (6–8) for each sample.

$$KT_m = (T - Op) / Cf \,; \quad (6)$$

$$KR_m = R / Cf \,; \quad (7)$$

$$KA_m = A / Cf \,, \quad (8)$$

where KT_m, KR_m, and KA_m represent the coefficients of transmission, reflection, and absorption of the material (e.g., fabric); *T* and *R* represent the measured values of transmission and reflection, and *A* represents the calculated absorption as a difference from 100; Cf represents the cover factor of the woven fabric; and Op represents the open area.

The physical meaning of the quotient represents the amount of transmitted, reflected, and absorbed UV rays by the structure of a certain material (e.g., fabric) in case there is no open area in the sample (e.g., Cf equals 1). Actually, in such supposed cases, the quotients should be equal to the measured values.

2. Experimental

2.1. Materials

For the purpose of this research, a set of referential material (e.g., fabric) samples, which are used in practice for the production of screen printing meshes, was chosen. The chosen high-module PET meshes (Sefar AGÒ, Inc.) differ in monofilament diameter, warp and weft density, open area portion, fabric thickness, number of pores, and weave. The actual physical and the construction properties, the calculated cover factors, and the values of the open area portions are presented in Table 1. Measurements were obtained with image analyses performed on a scanning electron microscope (SEM).

Table 1 shows why the chosen fabric samples were suitable for the analysis. Samples 1–4 in plane weave differed in the declared warp and weft density (120, 140, 150, and 165 yarns/cm, respectively), while the monofilament diameter (declared 31 μm) was equal for all the samples (Figure 2).

Samples 5 and 6 were weaved in twill weave and had the same monofilament diameters as the samples 1–4; however, their declared density was higher (180 and 190 yarns/cm) (Figure

Table 1. All declared and measured values of fabric construction parameters and the calculated cover factors and open area portions

Sample	Yarn diameter [μm]		Warp and weft density [yarns/cm]		Number of pores/cm^2	Fabric thickness [μm]	Warp/weft cover factor [%]	Fabric cover factor Cf_m [%]	Open area portion [%]
	*Dec.	**Meas.	*Dec.	**Meas.	**Meas.	**Meas.	**Meas.	**Meas.	**Meas.
1	31	32.90	120	123.54	15262	49	40.64	64.76	35.24
2		34.25	140	144.01	20738	48	49.32	74.32	25.68
3		35.55	150	153.82	23660	47	54.68	79.46	20.54
4		38.55	165	162.79	26500	48	62.76	86.13	13.87
5		34.20	180	182.96	33474	55	62.57	85.99	14.01
6		35.05	190	189.90	36062	55	66.56	88.82	11.18
7	34	38.80	120	122.96	15119	55	47.71	72.66	27.34
8	40	45.50	120	121.01	14643	65	55.06	79.80	20.20

Notes: *Dec. – declared values by producers of the fabrics; **Meas. – measured values.

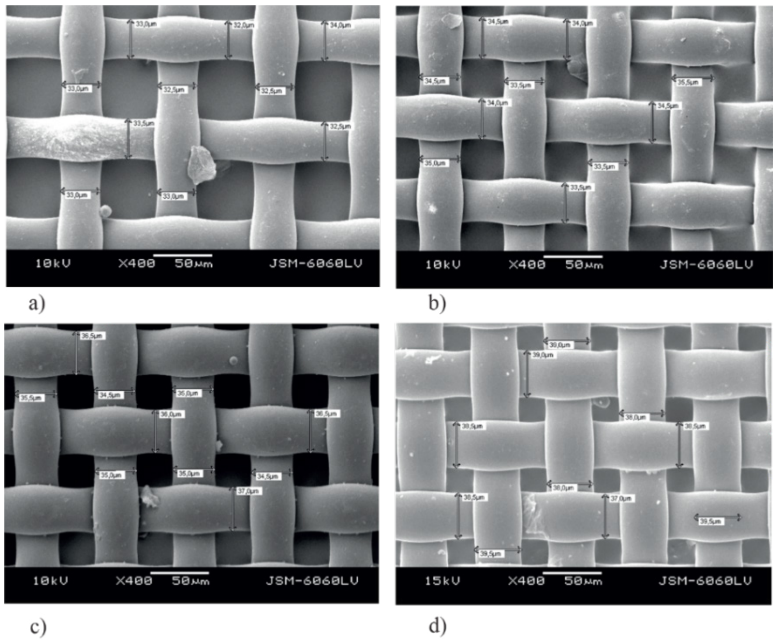

Figure 2. Samples 1 (a), 2 (b), 3 (c), and 4 (d) in plain weave, with equal declared yarn diameter (31 μm) and different densities (120, 140, 150, and 165 yarns/cm) (SEM; 400 × magnification).

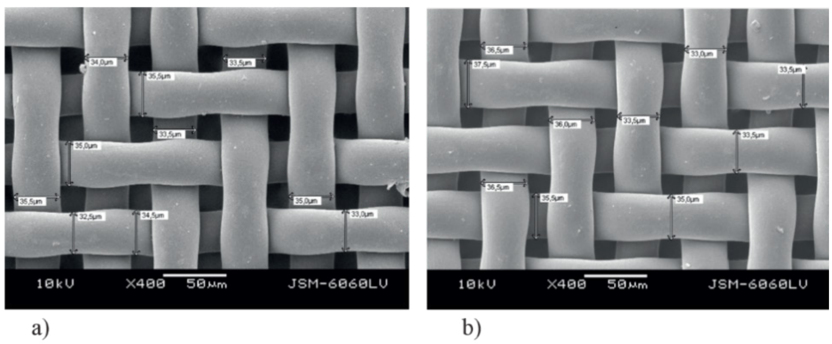

Figure 3. Samples 5 (a) and 6 (b) in twill weave, with equal declared yarn diameter (31 μm) and different densities (180 and 190 yarns/cm) (SEM; 400 × magnification).

3).

Different values of the declared monofilament diameters (31, 34, and 40 μm) were presented by the samples 1 (a), 7 (b), and 8 (c), which had the same declared warp and weft density (120 yarns/cm) (Figure 4).

2.2. Methods

The transmission of the selected samples was measured with Lambda 800 UV–visible spectrophotometer, equipped with PELA-1000 (PerkinElmer, Inc.), which enables measurements of the transmission and the reflection. Measurements were made in accordance with the SIST EN 13758-1 standard, in 2-nm steps, in the range of 700–200 nm. For calculation of the ultraviolet protection factor (UPF), only data within the range 400–290 nm was used.

The average values of the UV transmission (*T*) were calculated using Equation (9), as follows:

$$UV_i = \frac{1}{n}\sum_{290}^{400} T_i(\lambda). \quad (9)$$

The reflection values (*R*) were calculated in the same manner; however, instead of transmission values, the values of the reflection were inserted into the equation.

The obtained values of the transmission (*T*) enabled the calculation of the UPF values and, together with the measured values of reflection (*R*), the absorption (*A*) can be calculated as shown in Equation (10):

$$A = 100 - T - R. \quad (10)$$

3. Results and calculations

The results of the measured properties are presented in Tables 1–5. Table 2 presents the measured values of the transmission and the reflection, together with the calculated values of absorption, UPF, the portion of the areas covered by one and two yarns, and the constants of transmission, reflection, and absorption. The constants of transmission, reflection, and absorption (KT_m, KR_m, and KA_m) are calculated according to Equations (6–8) and the values of Cf and Op are from Table 1.

Using the measured results for Cf_1 and Cf_2 from Table 2, and combining all possible sample pairs (sample 1 and sample 2, 3, 4; sample 2 and samples 3, 4; sample 3 and sample 4) in Equation (11) as a system of two equations with two variables [5], we have succeeded in determining the values of $K_{1(T,R,A)}$ and $K_{2(T,R,A)}$ for particular samples.

$$Cf_1 \times K_{1_{(T,R,A)}} + Cf_2 \times K_{2_{(T,R,A)}} = \text{measured}(T, R, A) \quad (11)$$

These results are shown in Table 3. For further observation, we took into consideration only samples in plain weave, avoiding the small influence of twill weave on the values of K_T, K_R, and K_A, as well as on the complexity in their presentation, in tables [5]. On the other hand, conclusions based on the samples in the plain weave were used in the model and showed that the steps are valid for the samples in the twill weave also.

Analysis of the coefficients K_1 and K_2 showed that there is

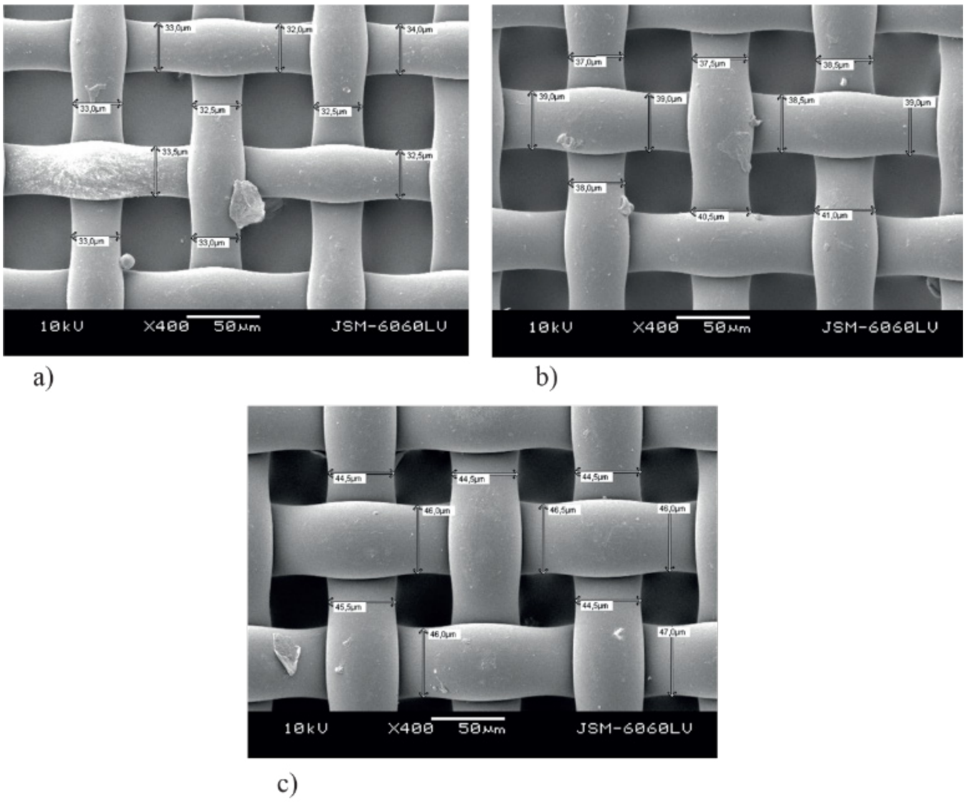

Figure 4. Samples 1 (a), 7 (b) and 8 (c) in plain weave, with equal declared density (120 yarns/cm) and different yarn diameters (31, 34, and 40 μm) (SEM; 400 × magnification).

Table 2. Measured values of the UV transmission (T) and reflection (R), as well as the calculated values of absorption (A) and ultraviolet protection factor (UPF), portion of area covered by one (Cf_1) and two yarns (Cf_2), and the calculated constants of transmission, reflection, and absorption (KT_m, KR_m, and KA_m)

Sample	T [%]	R [%]	A [%]	UPF	Cf_1 [%]	Cf_2 [%]	KT_m	KR_m	KA_m
	*Meas.	*Meas.	**Calc.	**Calc.	**Calc.	**Calc.	**Calc.	**Calc.	**Calc.
1	54.22	13.72	32.06	2.37	48.24	16.52	0.293	0.212	0.495
2	45.95	16.17	37.88	3.08	49.99	24.33	0.273	0.218	0.510
3	41.76	16.53	41.71	3.71	49.56	29.90	0.267	0.208	0.525
4	35.83	18.12	46.05	4.84	46.75	39.38	0.255	0.210	0.535
5	36.02	18.68	45.30	4.78	46.84	39.15	0.256	0.217	0.527
6	33.01	18.81	48.18	5.79	44.52	44.30	0.246	0.212	0.542
7	47.02	15.44	37.54	2.92	49.90	22.76	0.271	0.212	0.517
8	39.25	17.36	43.39	3.87	49.48	30.32	0.239	0.218	0.544

Notes: *Meas. – measured values; **Calc. – calculated values.

Table 3. Calculated values of the transmission (T), reflection (R) and absorption (A) coefficients K_1 and K_2 for the Samples 1–4, 7, and 8 in plain weave

Sample	1–4	1–4	7	7	8	8
Sample coefficient	K_1	K_2	K_1	K_2	K_1	K_2
T	0.335	0.152	0.327	0.148	0.302	0.137
R	0.223	0.193	0.223	0.193	0.223	0.193
A	0.442	0.654	0.450	0.662	0.460	0.680
Sum of coefficients	1.000	0.999	1.000	1.003	0.985	1.010

Table 4. Calculated values of transmission (T) coefficients (K_{1T}, K_{2T}, and K_{1T}^2), absolute values of differences $\Delta(K_{2T} - K_{1T}^2)$, and their connections confirmed with coefficients of correlation

Sample/Sample coefficient	K_{1T}	K_{2T}	K_{1T}^2	$\Delta(K_{2T} - K_{1T}^2)$
1–4	0.335	0.152	0.1122	0.0398
7	0.327	0.148	0.1069	0.0411
8	0.302	0.137	0.0912	0.0458
Correlation coefficient K_{2T}; K_{1T}^2			0.9998	

Table 5. Calculated values (from Equation 10) of the absorption coefficients (K_{1A}, K_{2A}, and $\sqrt{K_{1A}}$), the absolute values of differences Δ (K_{2A} - $\sqrt{K_{1A}}$), and their connections confirmed with coefficients of correlation

Sample	Sample coefficient			$\Delta\left(K_{2A} - \sqrt{K_{1A}}\right)$
1–4	K_{1A}	K_{2A}	$\sqrt{K_{1A}}$	
	0.442	0.654	0.665	–0.0108
7	0.45	0.662	0.671	–0.0088
8	0.46	0.68	0.678	0.0018
Correlation coefficient K_{2A} ; $\sqrt{K_{1A}}$			0.988	

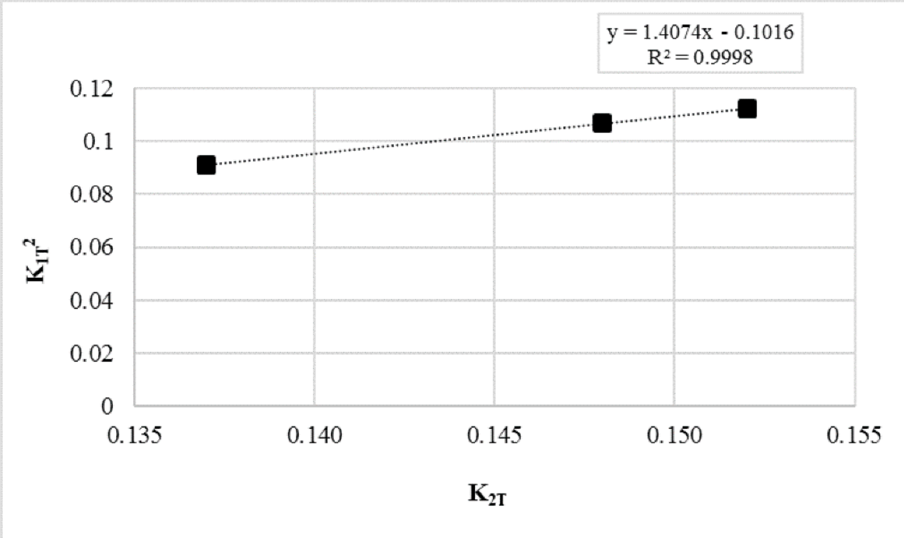

Figure 5. Correlation between K_{2T} and K_{1T}^2.

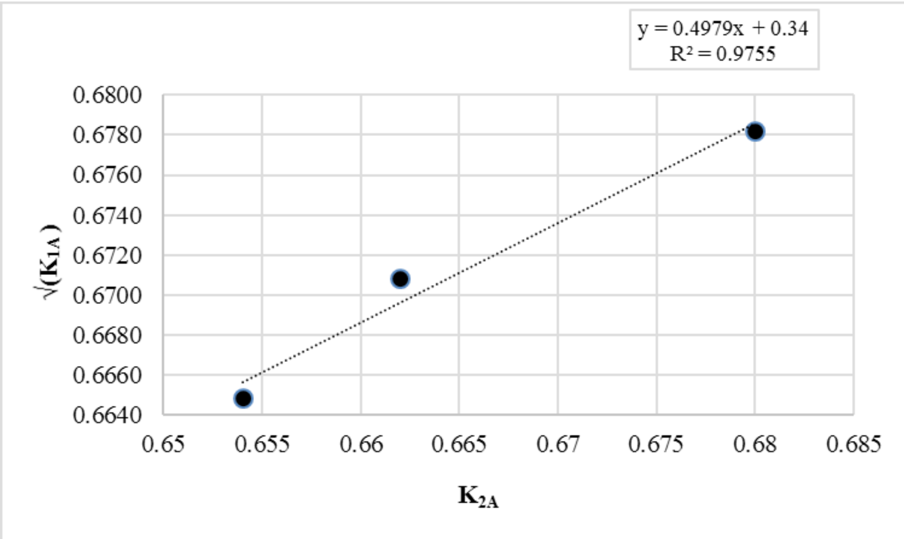

Figure 6. Correlation between K_{2A} and $\sqrt{K_{1A}}$.

a correlation between them. In Tables 4 and 5 and Figures 5 and 6, connections between the coefficients K_1 and K_2 for transmission and absorption are presented.

3.1. Model establishment

Table 5 shows that K_{2A} – the calculated absorption through two yarns based on direct measurement (Column 3 in Table 5) – presents the square root of K_{1A} (Column 4 in Table 5) since the values calculated by the presented correlation differed about <1% (Column 6 in Table 5). In the case of the transmission presented in Table 4, there is also a correlation between K_{1T} and K_{2T} in the form of a power function. In this case, we have obtained almost the same differences between the results of the calculations by the power function and the calculations based on the measurements, with almost a constant difference of about 4%. This coincides with the ~3% difference in reflection of the one-yarn area and two-yarn area between the samples. All these observations gave us the idea to use the recognized correlations for establishing a simplified model for predicting the UV-protective properties of woven fabrics. Accordingly, we have set the next Equations (12–15):

$$R = Cf_1 \times K_{1R} + Cf_2 \times K_{2R} . \qquad (12)$$

For simplifying the calculations, because of the small differences between the reflections from one and two yarns, we next modified Equation (12) as follows:

$$R = Cf \times K_{R(average)}; \qquad (13)$$

$$T = Op + Cf_1 \times K_{1T} + Cf_2 \times K_{1T}^{\;2}; \qquad (14)$$

$$A = Cf_1 \times K_{1A} + Cf_2 \times \sqrt{K_{1A}} . \qquad (15)$$

3.2. Justifying the model

For justifying the established model, we have used the data presented in Table 6 and Equations (13–15) to calculate the predicted transmission, reflection, and absorption of selected monofilament materials (e.g., fabrics).

Table 6. Data used for calculating predicted transmission, reflection, and absorption of the samples

Sample	Op [%]	Cf_1 [%]	Cf_2 [%]	Cf [%]	$^*K_{R(average)}$	$^*K_{1T\ (1–4)\ average}$	$^*K_{1A\ (1–4)\ average}$
1	35.24	48.24	16.52	64.76	0.223	0.335	0.442
2	25.68	49.99	24.33	74.32			
3	20.54	49.56	29.90	79.46			
4	13.87	46.75	39.38	86.13			
5	14.01	46.84	39.15	85.99			
6	11.18	44.52	44.30	88.82			
7	27.34	49.90	22.76	72.66			
8	20.20	49.48	30.32	79.80			

Note: *Average values of $K_{1(T,\ R,\ A).}$

Table 7. Examples of calculated (c) and measured (m) values of transmission (*T*), reflection (*R*), and absorption (*A*), with corresponding correlation coefficients

Sample	T_m [%]	T_c [%]	R_m [%]	R_c [%]	A_m [%]	A_c [%]
1	54.22	53.25	13.72	14.44	32.06	32.31
2	45.95	45.16	16.17	16.57	37.88	38.27
3	41.76	40.50	16.53	17.72	41.71	41.78
4	35.83	33.95	18.12	19.21	46.05	46.84
5	36.02	34.10	18.68	19.18	45.3	46.73
6	33.01	31.07	18.81	19.81	48.18	49.13
7	47.02	46.61	15.44	16.20	37.54	37.19
8	39.25	40.18	17.36	17.80	43.39	42.03
Correlation coefficient	0.993		0.986		0.990	

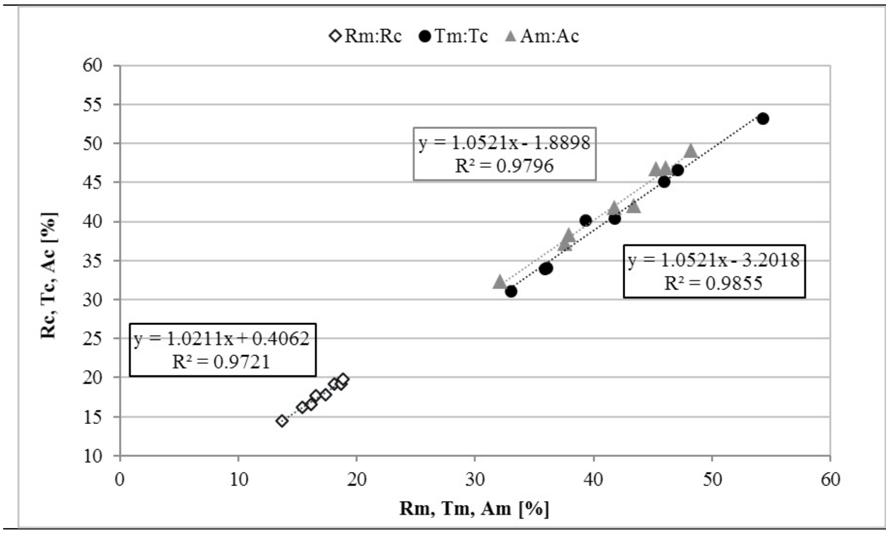

Figure 7. Coefficient of determination between the calculated example and the measured values of sample transmission, reflection, and absorption.

Table 7 presents the calculated values of transmission, reflection, and absorption. Calculations were made using Equations (13–15).

The same results, presented in Figure 7, clearly show a high degree of correlation between the calculated example predicted and the measured values of transmission, reflection, and absorption of samples.

4. CONCLUSIONS

The presented research shows that the established model for the prediction of the UV-protective properties of the monofilament PET fabrics correlates very well with the real measurements. However, practically, all variables inserted into the equations are not easy to be determined. For that reason, selected monofilament fabrics were chosen, since they enabled precise optical determination of all needed material, e.g., fabric construction parameters of the samples. For the broader use of the model, it must be tested on other types of fabrics, made from different types of yarns. This makes the task more difficult, since constructions of other types of yarns and fabrics allow much more deformation in their structure than monofilament yarns in plain and twill weave. For solving the problem, we suggest two approaches:

Getting the relevant construction parameters of fabrics (Op, Cf, Cf_1, Cf_2) through computer-supported image analyses of referential samples [12–14]; and

Indirectly from the measurements of reflection or other permeability properties from the referential samples [15–17].

However, in both cases, the UV-protective properties of used yarns (their K_R, K_T and K_A) are not known. So, we are working on developing a method, different from the one in the paper by Dimitrovski et al. [5], which can allow easier determination of the mentioned properties of the most used yarns of most interests – cotton yarns, PET, cotton blends, coco, poly(lactic acid) (PLA), soya bean, and so on. Our preliminary research in this field shows that the biggest contribution to the UV-protective properties of yarns comes from the fabric, its color, or any other preparation connected to the chemical structure of the yarns' ingredients. It also seems that the influence of yarn fineness and number of twists (within certain interval), attained in the deformability of yarns, their diameter and density, could be neglected.

As a final conclusion, it can be said that the established model for the prediction of the UV-protective properties of the woven fabrics is very simple, easy to use, and logical, giving promising results. The good thing, in general, is that the calculated prediction is not necessary to be very accurate (meaning, not necessary within 1% or 2%). In this way, the manufacturers of the woven fabrics have plenty of possibilities to plan and arrange the UV-protective properties of fabrics within the desired values.

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