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APPROACH TO PERFORMANCE RATING OF RETROREFLECTIVE TEXTILE MATERIAL CONSIDERING PRODUCTION TECHNOLOGY AND REFLECTOR SIZE

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Abstract:

The study investigates retroreflective fabrics' efficiency from the point of view of the interaction of their visibility, thermo-physiological comfort properties, and durability (represented by physical-mechanical performance). The effect of the combination of two production technologies (reflective transfer films and screen printing method) and two reflector covering sizes (25% and 85%) was examined. Technique for order of preference by similarity to ideal solution (TOPSIS) method was used to determine the best solution considering the abovementioned tested categories of properties. Retroreflective performance was in congruence with the used design coverage factor of the tested pattern. It was found that retroreflection of the tested pattern produced using screen printing technology was significantly lower than retroreflection of an identical pattern made by a transfer film. On the contrary, in terms of thermo-physiological comfort and physical-mechanical performance of the tested samples, screen printing technology shows significantly better results in almost all tested properties, especially in water vapor permeability, moisture management, and physical-mechanical performance. The solution for the abovementioned contradictory results can be achieved by using a combination of the advantages associated with each of these technology methods. Screen printing can be applied to specific regions of clothing that are exposed to extreme loading or sweating, and the transfer of film elements ensures high visibility with respect to the standards and biomotion principles that are deployed as prevalent benchmarks in the industry.

Keywords:

Visibility, retroreflection, thermo-physiological comfort, durability, multi-criteria decision, TOPSIS

1. Introduction

Reduced visibility is a common cause of many tragic road traffic accidents. Pedestrians and cyclists are often victimized by these accidents because they are the weakest participants in road traffic and the most vulnerable ones [1]. At dawn and night, pedestrians are more at risk than in full sunlight. Research has suggested that pedestrians' apparel and poor visibility are likely to contribute to these accidents significantly [2]. European Commission statistics show that vulnerable road users (pedestrians, cyclists, and powered two-wheelers) account for 70% of road deaths in urban areas [3]. In 2019, pedestrians in the Czech Republic were involved in 3,265 cases of traffic accidents; 87 people were killed, 427 were seriously injured, and 2,687 were slightly injured in these accidents. Taking into account the participation of cyclists, the data reveal that there were 4,034 traffic accidents, with 3,594 getting seriously and slightly injured and 35 people getting killed [4]. According to a comparison-study addressing the development of the fatal consequences of pedestrian visibility outside a village over 5 years, it has been observed that these tragedies most often occur at night [4].

In passive elements, visibility can be increased by a suitable color of clothing and accessories made of fluorescent and reflective materials, thereby increasing the light contrast to the background and extending the distance from which a driver can see a pedestrian or a cyclist [1]. Retroreflection is a phenomenon of light rays striking a surface and being redirected to the source of light while an even distribution is maintained across various incidence and observation angles. If retroreflective materials were used in clothing reflecting light from headlights of vehicles, they would aid the visibility of a person to the driver from a safe distance. This fact would potentially lead to fewer accidents between cars and pedestrians [5]. Retroreflective material used in warning-clothes comes in various forms, such as synthetic resin plates, fabrics, and sheets. Products are often equipped with retroreflective sheets (bead type and micro prism type) that are either patterned or plain [6]. The fulfillment of the requirements of the EN ISO 20471 (High visibility clothing – test method and requirements) standard declares a certain degree of visibility performance.

Monitoring the effect of retroreflection on clothing or the thermo-physiological comfort of clothing is vital from the user's perspective. Good clothing comfort will ensure the willingness of users to wear a given garment with retroreflective elements in the case of leisurewear and will increase workers' performance in the case of work-wear. Most studies forming part of the professional literature focus on providing high-performance retroreflective components and methods of testing. However, in the prevailing literature, the degree of the influence of retroreflective elements on the thermo-physiological comfort of clothing is left largely unexplored [7–-9]. Studies also address the topology of the retroreflective pattern to increase the wearer's visibility [2].

Expert studies often use biomotion as a means to increase the visibility of pedestrians and cyclists at night. The use of reflective markings on the major joints of pedestrians' bodies to facilitate biological motion perception has been proven to significantly enhance pedestrian conspicuity during nighttime. Ankle and knee markings are a simple and very effective way of strengthening bicyclist conspicuity at night [10. 11]. It has been concluded that adding retroreflective strips in the biomotion configuration can significantly improve road worker conspicuity regardless of the road worker's orientation and the driver's age [12]. Finally, a large part of professional research in the field of visibility of pedestrians or cyclists is devoted to the aspect of psychology and human factors influencing the level of visibility of pedestrians [13]. Attention is paid to the effect of different levels of refractive blur and the driver's age on nighttime pedestrian recognition; biomotion retroreflective clothing was found to be effective even under moderately degraded visibility conditions for both young and older drivers [14].

For a clothing system, comfort is a fundamental necessity. In the case of clothing for pedestrians and cyclists as road users, the performance obtained from the protective element of the clothing is often at the expense of poor thermo-physiological comfort. The research in this paper is focused on monitoring the interaction of visibility provided by retroreflection, thermo-physiological comfort, and last but not least, physical-mechanical performance. The physiological comfort of clothing and textiles has been explored in many studies focused on quantitative evaluation of parameters designed to measure this comfort [15–-17]. The physiological comfort of sportswear in cyclists and protective clothing is one of the most significant factors for ensuring the best conditions for the wearers when they are active [18, 19]

2. Experimental

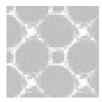
2.1. Materials

The tested material was designed for functional sportswear in order to support total wearing comfort, taking into account the prevailing physical stress and climatic conditions. The tested fabric Coolmax Athletic contains 50% of classic PES and 50% of Coolmax fibers (modified PES, four-channel cross-section), having a weight of 150 g · m^{-2} and thickness of 0.49 mm, and the pattern used is a double jersey with tuck loops. Two production technologies (two reflective transfer films and one screen printing method) and two reflector sizes (covering 25% and 85%) were applied to the tested fabric; see Figure 1.

Retroreflective patterns with two almost inverse patterns were made using retroreflective silver transfer film I C750 (silver, heat transfer polyester adhesive, thickness 0.09 mm, company 3M) and retroreflective transfer film II WL-RF-1001 (silver, heat transfer polyurethane adhesive, thickness 0.1 mm, company Weallight). The third retroreflector was prepared by a screen printing method using printing water-based ink TEXTILAC CAT-EYE containing glass beads with a diameter <50 μm, Th · cm^{-1} max. 43. The reflector design is based on an old high wheel bicycle shape because of an end-use application (cycling jerseys). The sample descriptions are provided in Table 1.

The percentage of fabric coverage by retroreflection element was determined based on the ratio between the area of

Table 1. Sample description.

Production technology	**Reflector size [%]**	
	Covering 85 	**Covering 25** 
Screen printing	A1	A2
Transfer film I	A3	A4
Transfer film II	A5	A6

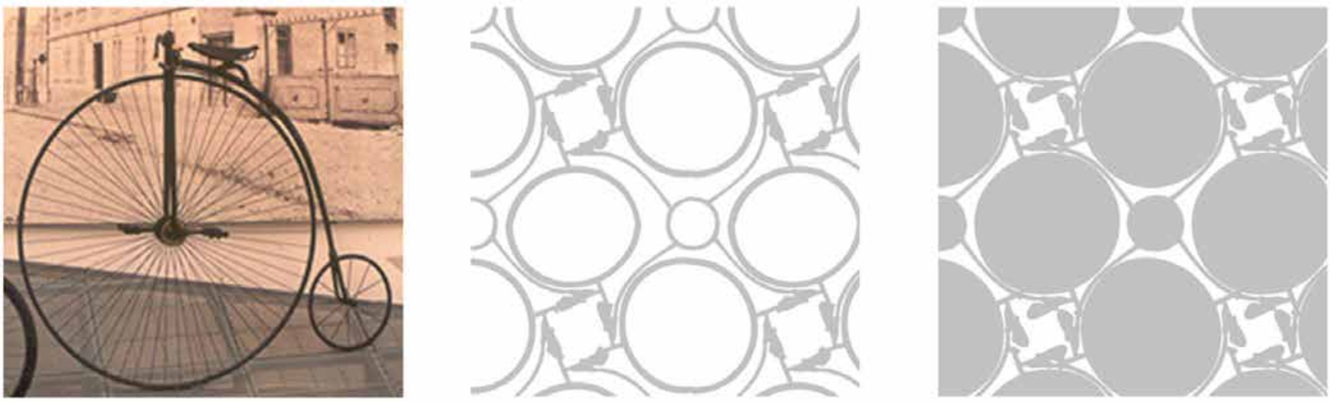


Figure 1. Design of tested samples. (a) motive design of old high wheel bicycle, (b) reflector covering 25%, and (c) covering 85% of the whole area.

the reflective element and the total area of the sample. The percentage of fabric coverage by retroreflection element (25% and 85%) was determined based on the ratio between the reflective area (by reflective elements) and the total area of the sample. It was measured using the image analysis system NIS Element.

Prior to being measured, the samples were washed and air-conditioned for 24 h. The measurement was carried out in an air-conditioned room under a constant relative humidity of 65% and at a temperature of 21 °C.

2.2. Methods

The performance rating of retroreflective fabric that reflects the applied production technology and reflector covered area was investigated in the following three ways:

- thermo-physiological comfort given by thermal properties, moisture management, and water vapor permeability;
- the physical-mechanical performance provided by bending rigidity (B) and abrasion resistance, especially appearance change (AP); and
- retroreflective performance by coefficient of retroreflection (RA).

Figure 2 shows the schema of experiment.

The results of the abovementioned methods were compared and discussed to detect the tested samples' real visibility and comfort behavior. Further, the multiple-criteria decision-making method (MCDM), namely the method of technique for the order of preference by similarity to ideal solution (TOPSIS), was used to ascertain the best solution (sample) from the perspective of physiological comfort, durability (represented by physical-mechanical performance), and visibility. Final values (means) of all tested parameters correspond to five measurements on average.

2.2.1. Evaluation of thermo-physiological comfort properties

Liquid moisture transport

Objective evaluation of liquid moisture transport was tested by standardized measurement with laboratory equipment—moisture management tester (MMT). MMT was developed to quantify dynamic liquid transport properties of knitted and woven fabrics through three dimensions:

- absorption rate – time for absorption of moisture on the fabric's face and back surfaces,
- one-way transportation capability – one-way transfer from the fabric's back surface to its face surface,
- spreading/drying rate – the speed at which liquid moisture spreads across the fabric's back and face surfaces.

MMT works according to AATCC Test Method 195 – 2011. Two parameters, overall moisture management capacity (OMMC) [−] and cumulative one-way transport capacity (OWTC) [%] were used for the evaluation of moisture management.

Water vapor permeability

The FX 3180 Cup Master was used for the measurement of water vapor permeability. This equipment determines the water vapor transmission rate (WVTR) [$g \cdot m^{-2} \cdot 24$ h] parameter

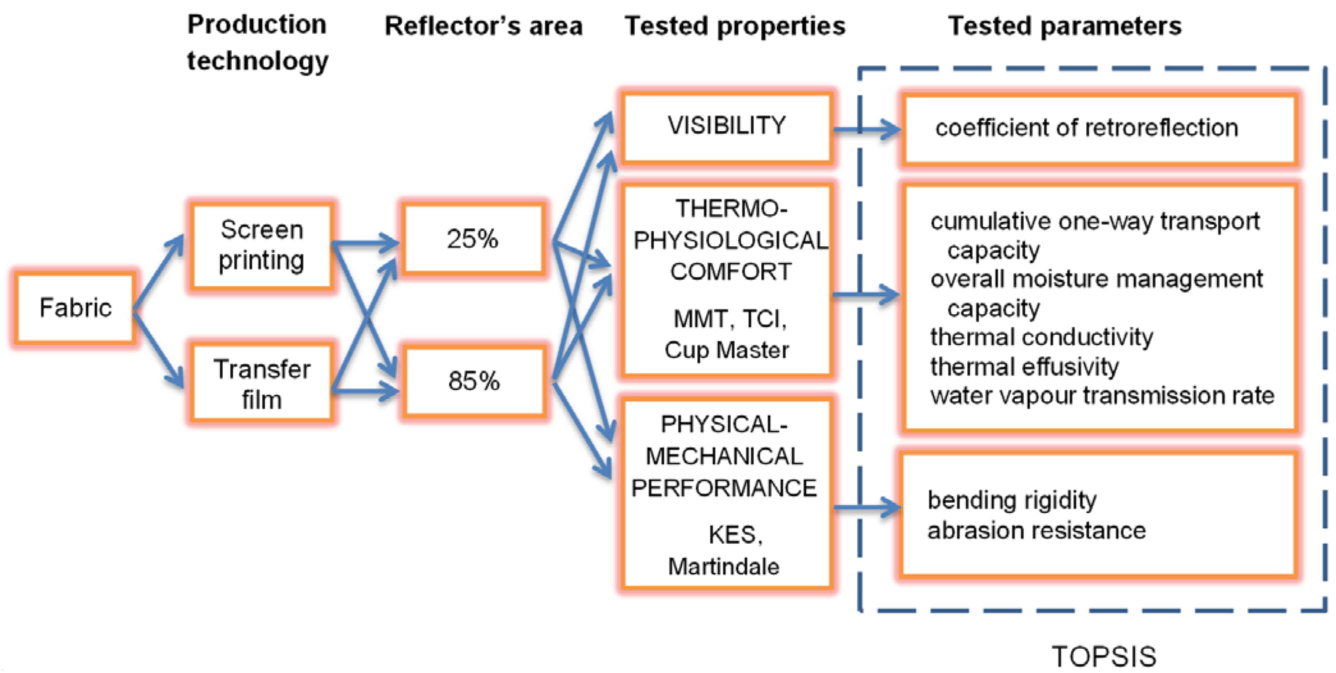


Figure 2. Schema of experiment.

using the gravimetric measuring principle. The measurement was carried out according to the standard JIS L 1099 (2012).

Heat transport

Thermal transport properties were measured using C-Therm thermal conductivity analyzer (TCi). The TCi employs the modified transient plane source (MTPS) technique in characterizing thermal conductivity (TC) [$W \cdot m^{-1} \cdot K^{-1}$] and thermal effusivity (TE) [$W \cdot s^{-1/2} \cdot m^{-2} \cdot K^{-1}$] of materials. The standard test method EN 61326-2-4:2006 was used for this testing by TCi.

2.2.2. Evaluation of Physical-mechanical performance

Abrasion resistance

Determination of the abrasion resistance of the tested samples was carried out by the Martindale method EN ISO 12947-4:2017. The degree of appearance change (AP) [−] of the tested samples was determined to fall within the range 1–5. Degree 1 indicates the most significant AP, and degree 5 the smallest one. Within the test, 36,000 cycles were applied to each sample; the applied pressure was set to 12 kPa.

Bending rigidity

The bending properties, specifically the bending rigidity (represented as parameter B) [$N \cdot m^{-2} \cdot m^{-1}$] of the investigated samples, were defined by the Kawabata evaluation system (KES). The principle of pure bending is applied in the KES-FB2-A pure bending tester, whereby the fabric specimen is bent in an arc of constant curvature, which is changed continuously.

2.2.3. Evaluation of Visibility

Coefficient of retroreflection

The coefficient of retroreflection (RA) [cd · lx−1 · m−2] of the tested reflective materials was measured by the methods based on any one of the following retroreflective intensity testing procedures: ASTM E809-02, and E810-03 (RA) and CIE 54.2:2001 (R’) with the use of headlamp-equipped halogen lamp Osram H4, illuminance meter T10 made by Konica-Minolta, and spectroradiometer PhotoResearch PR 740. Measurement of RA was carried out for different angle rotations of the sample, ρ, ranging from 0° to 180° (step 10°). Following CIE 54.2 Retroreflection: Definition and Measurement, the following parameters were ascertained: observation angle α = 12’ and entrance angle β = ρ - 90°. The distance from the light source to the sample was 10.00 ± 0.02 m, and from the detector to the sample, 10.00 ± 0.02 m. Value of RA in angle ρ = 90° was used for TOPSIS analysis.

2.2.4. Evaluation of the best alternative by TOPSIS

The TOPSIS is one of the classical MCDM methods initially developed by Ching-Lai Hwang and Yoon in 1981 [20]. This method is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution (A^+) and the longest geometric distance from the negative ideal solution (A^-). A MCDM problem is generally expressed in a matrix known as the decision matrix (see Table 2). A decision matrix is a (m×n) matrix in which element x_{ij} indicates the performance of alternative Ai when it is evaluated in terms of decision criterion C_j, where i = 1, 2, 3,…, m, and j = 1, 2, 3,…, n. Numerical weight (w_j) is attached to each criterion based on its relative importance.

Table 2. Decision Matrix for a MCDM problem.

Criteria		C_1	C_2	…	C_n
Weight		w_1	w_2	…	w_n
Alternatives	A_1	x_{11}	x_{12}	…	x_{1n}
	A_2	x_{21}	x_{22}	…	x_{2n}
	…				
	A_m	x_{m1}	x_{m2}	…	x_{mn}

MCDM, multiple-criteria decision-making method.

The weight vector *W* was determined by Saaty’s method [20].

$$W = \{w_1, \dots, w_n\} \tag{1}$$

$$\sum_{j=1}^{n} w_j = 1 \tag{2}$$

where $w_j \in R$

The TOPSIS analysis can be represented in a series of steps as presented below:

Step 1—Calculate the normalized decision matric to make its elements dimensionless and comparable.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}} \quad , j = 1, \dots, m; i = 1, \dots, n \tag{3}$$

Step 2—Calculate the weighted normalized decision matric.

$$v_{ij} = r_{ij} \times w_j \text{ ,} for\ i = 1,2,\dots, m, j = 1,2,\dots \tag{4}$$

where w_j is the priority weight of the j-th criterion,

$$\sum_{j=1}^{n} w_j = 1 \tag{5}$$

Step 3—Calculate the positive ideal solution (A^+) and negative ideal solution (A^-).

$$A^+ = \{v_1^+, \dots, v_n^+\} = \left\{\left(\max_i v_{ij} \ | j \in I\right), \left(\max_i v_{ij} \ | j \in J\right)\right\} \tag{6}$$

$$A^- = \{v_1^-, \dots, v_n^-\} = \left\{\left(\max_i v_{ij} \ | j \in I\right), \left(\max_i v_{ij} \ | j \in J\right)\right\} \tag{7}$$

where A^+ and A^- are the positive ideal solution and the negative ideal solution, respectively.

Step 4—Calculate the distances from each alternative to the positive ideal solution (A^+) and negative ideal solution (A^-).

$$d_i^+ = \sqrt{\sum_{j=1}^{m}\left(v_{ij} - v_j^+\right)^2}, i = 1,2,\ldots,m \quad (8)$$

$$d_i^- = \sqrt{\sum_{j=1}^{m}\left(v_{ij} - v_j^-\right)^2}, i = 1,2,\ldots,m \quad (9)$$

where d_i^+ is the distance between i-th alternative and positive ideal solution (A^+), and d_i^- i is the distance between i-th alternative and negative ideal solution (A^-).

Step 5—Calculate the relative closeness to the ideal best solution.

$$R_i = \frac{d_i^-}{d_i^+ + d_i^-}\ for\ i = 1,2,\ldots,m \quad (10)$$

where $0 \leq R_i \leq 1$

The larger the index value, the better the evaluation of the alternative.

Step 5—Rank the preference order or select the alternative closest to 1. A set of alternatives can now be ranked based on the descending order of the value of R_i.

3. Results and discussion

The values of all measured properties are given in Table 3.

3.1. Evaluation of thermo-physiological comfort properties

3.1.1. Water vapor permeability

The results of water vapor permeability WVTR [g · m^{-2} · 24 h] obtained from the Cup Master FX 3180 are summarized in Figure 3. Some of the findings in line with our expectations and suggested that the higher the reflector area, the lower the WVTR value. Sample values of A3 and A5 (reflector size 85%, film transfer technology) are lower by half in comparison with samples A4 and A6 (reflector size 25%, transfer film technology). The surprising aspect of the data is the tiny difference in the measured values between samples A1 and A2. Both A1 and A2 are produced by the same technology (screen printing) but with a different reflector size (85% and 25%). Also,there is only a slight difference in terms of their water vapor efficiency.

Furthermore, the technology of screen printing supports water vapor permeability significantly more than transfer film technology; see WVTR value of sample A1 in comparison with A3 or A5. Transfer film sample A3 has an approximately 40% lower value of WVTR than the screen printed sample A1. A possible explanation for this might be that glass beads are randomly distributed in fabric structure (see microscopic images in Figure 13). Therefore, there are more free spaces of the bare textile substrate without beads in screen printed samples than in samples produced by transfer film technology. Water vapor moves more effectively through the mentioned free spaces in samples A1 and A2. WVTR efficiency of the mentioned sample A2 decreased by 15% compared to the "pure" sample A0 without any retroreflection elements.

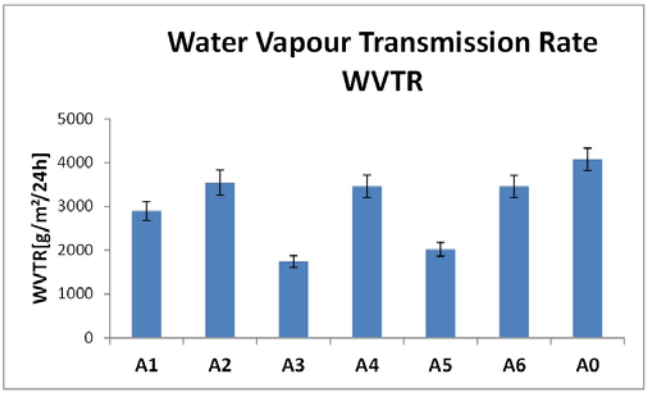


Figure 3. WVTR of tested samples

3.1.2. Liquid moisture transport

Accumulative OWTC is the difference in the accumulative moisture content between the two fabric surfaces (water content on face (bottom) minus water content on the back (top)) in the unit time [21]. As shown in Figure 4, in the performance recorded for sample A2, the best transport of liquid moisture occurs from the back to the face of the fabric, which can provide the drain-off of perspiration away from the skin. Samples A4 and A6—to which a variant covering 25% is applied—show similarly good results. In contrast, the samples with covering of area of 85% also reached negative values, indicating that there was no transport of fluid from one side of the fabric to the other. They also show high variability of results due to inhibition of fluid transfer by the unsupported retroreflective layer. The experiment methodology respects the aspect that test implementation is always at the same motive point, so that the results are not distorted.

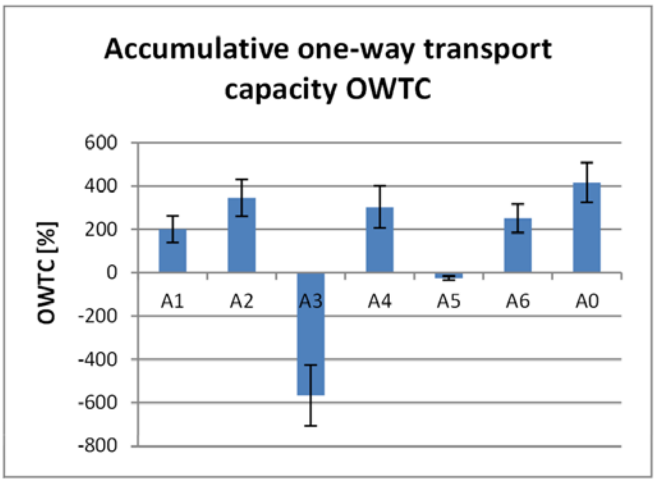


Figure 4. OWTC of tested samples.

Table 3. Properties of tested samples.

	Thermo-physiological comfort					Physical-mechanical performance		Visibility
Sample code	Cumulative one-way transport capacity	Overall moisture management capacity	Thermal effusivity	Thermal conductivity	Water vapor transmission rate	Appearance change	Bending rigidity	Coefficient of retroreflection
	OWTC [%]	**OMMC** [-]	**TE** [$W \cdot s^{-1/2} \cdot m^{-2} \cdot K^{-1}$]	**TC** [$W \cdot m^{-1} \cdot K^{-1}$]	**WVTR** [$g \cdot m^{-2} \cdot 24\ h$]	**AP** [−]	**B** [$N \cdot m^{-2} \cdot m^{-1}$]	**RA** [$cd \cdot lx^{-1} \cdot m^{-2}$]
A1	200 (61)	0.55 (0.12)	198 (6.3)	0.094 (0.002)	2,895 (215)	4 (0.30)	0.21 (0.012)	124 (6.3)
A2	345 (86)	0.60 (0.10)	103 (7.7)	0.063 (0.003)	3,542 (285)	4.5 (0.32)	0.07 (0.005)	40 (2.5)
A3	−566 (−140)	0.32 (0.08)	362 (15.2)	0.151 (0.019)	1,740 (138)	3 (0.25)	0.40 (0.021)	418 (19.8)
A4	303 (98)	0.51 (0.09)	113 (1.5)	0.066 (0.001)	3,456 (259)	3.5 (0.4)	0.11 (0.005)	122 (6.4)
A5	−24 (−9)	0.39 (0.10)	337 (2.9)	0.142 (0.002)	2,020 (160)	2 (0.21)	0.44 (0.022)	457 (21.1)
A6	250 (65)	0.58 (0.12)	114 (1.3)	0.066 (0.001)	3,454 (257)	2.5 (0.3)	0.10 (0.002)	155 (6.5)
A0	416 (92)	0.62 (0.10)	101 (6.4)	0.061 (0.001)	4,075 (255)	5 (0)	0.03 (0.005)	–

*A0 presents a pure sample without retroreflection elements.

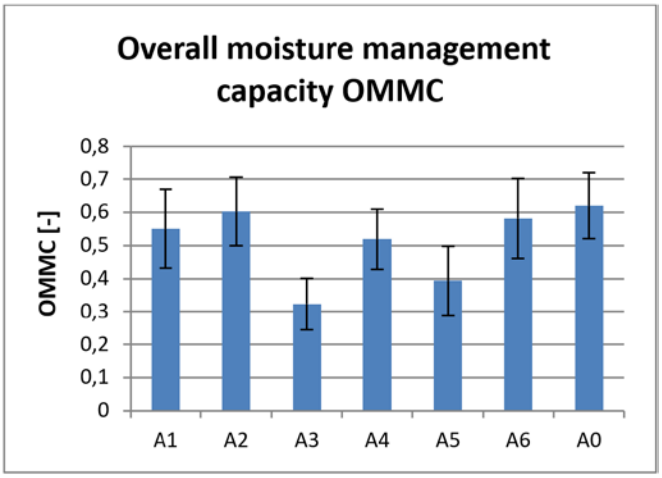


Figure 5. OMMC of tested samples.

OMMC is an index to indicate the overall capability of the fabric to manage the transport of liquid moisture [4]. Overall moisture management properties of the tested fabrics are given in Figure 5. The obtained results correspond to the results of OWTC when the best values were achieved by samples with lower coverage of A2 and A6.

Generally, it can be stated that the size of the covered area significantly reduces the moisture management in the fabric, and covering 25% amounts to achievement of moisture management results that are close to the results of the sample without any coverage by retroreflective printing (sample A0). The best results from the used technologies are achieved by thermal transfer printing (samples A1, A2).

3.1.3. Heat transport

Figures 6 and 7 provide the results obtained from heat transport analysis by C-Therm TCi. Both parameters, TC and TE, indicate the expected impact of reflector covering on area-to-heat-transport behavior of the tested samples, which is a significant increase of values TE and TC for samples of 85% covering area (A1, A3, A5). TE and TC values for A1, A3, and A5 are higher in the range 40–70% than values of samples A2, A4, and A6, which present samples with 25% covering of reflector

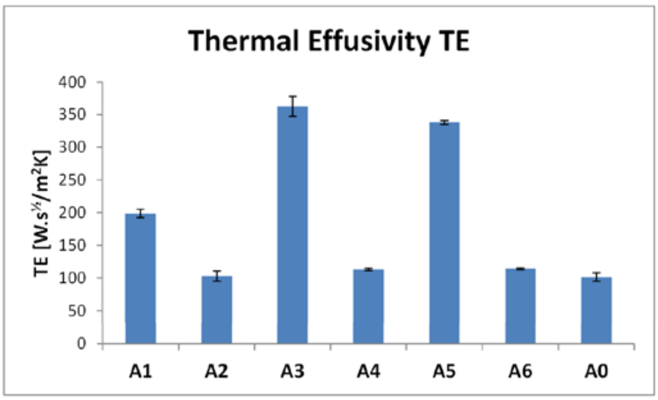


Figure 6. TE of the tested samples.

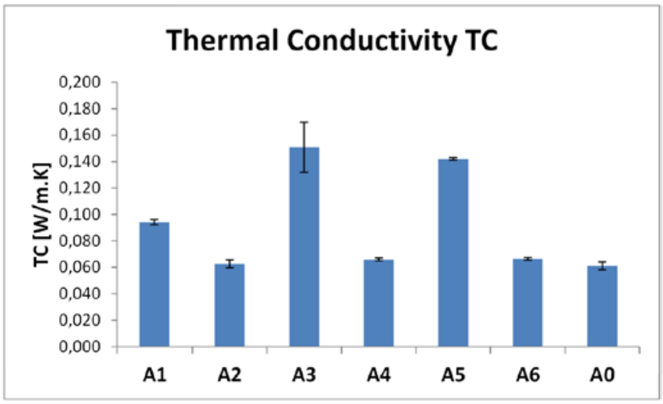


Figure 7. Thermal conductivity TC of tested samples.

area. The high value of the mentioned thermal properties for film transfer samples assume faster cooling of the body. With regard to this outcome, it deserves to be emphasized that rapid cooling as a characteristic of retroreflective fabrics is a highly favorable development, especially during physical activities of cyclists in the summer season. The insulation problem may occur in cold or windy weather when retroreflection elements multiply heat transport from the wearer's body.

Further, in terms of heat transfer, the difference between screen printing technology and film transfer technology was observed, particularly in samples covering an area that equals 85%. Both TC and TE values for sample A1 (screen printing) are nearly 50% lower than sample A3 (transfer film).

Moreover, the thermal properties of transfer film samples remain almost unchanged under low covering conditions (25% covering sample compared with the "pure" sample A0).

3.2. Evaluation of physical-mechanical performance

3.2.1. Bending rigidity and Appearance change

Figure 8 presents experimental data on bending rigidity (B) [N · m−2 · m−1] by KES.

These results agree with the general idea that the large size of a reflector negatively influences the mechanical behavior

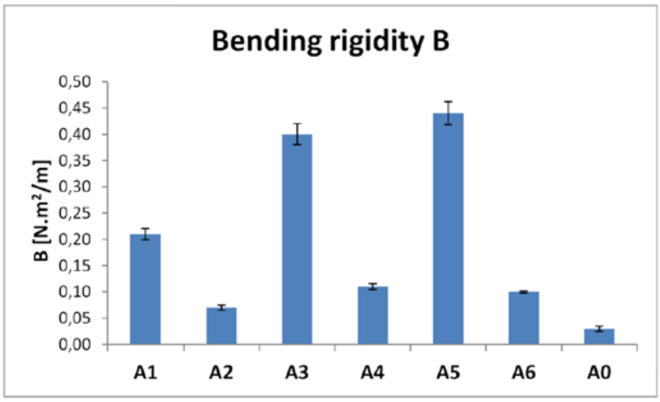


Figure 8. B of the tested samples

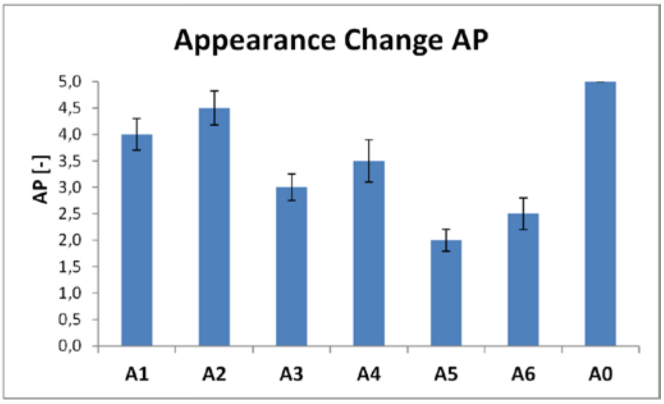


Figure 9. Appearance change AP of tested samples

of retroreflective fabrics, especially bending rigidity. Already in the case of 25% reflector covering area (samples A2, A4, and A6), the stiffness is two to three times higher than the value of sample A0 (without retroreflection elements), for 85% covering size that is more than 10-fold when compared with the pure sample A0.

However, the observed difference between the used screen printing technology and film transfer technology was significant in this study. Interestingly, in screen printing technology, half of the B value against film transfer technology was observed. Therefore, these results suggest that screen printing samples provide better sensorial wear comfort than the rest of the tested materials.

3.2.2. Abrasion resistance

The AP [−] of the tested samples is shown in Figure 8. This parameter was tested within abrasion resistance by the Martindale system. Significant AP of the tested samples is a matter of concern, namely for transfer film after 36,000 cycles (it corresponds to 10 test hours); see Figures 10 and 11. The value of AP for film transfer technology is decreasing about 2–3° (A3, A4, A5, A6) in contrast to printing technology (A1, A2), where drop-in AP is in the range of 0.5–1°. Overall, these results indicate that the quality of visibility is reduced for transfer film samples compared to screen printing samples. Moreover, the sensorial comfort of screen printing samples is better from the point of view of bending rigidity.

3.3. Evaluation of visibility

The retroreflective elements of a highly visible pattern produced on textiles generally do not have symmetries as homogenous systems; nevertheless, our measurements.

It was found out that screen printing was less effective for both retroreflector designs, as shown on the graph in Figure 11. There is also a visible indication that retroreflective transfer film I - C750 is slightly more effective than film II - WL-RF-1001, with a similar shape of retroreflection distribution.

The explanation of this result is present in the microscopic images presented in Figure 13, where the random distribution of glass beads is visible. Beads are partially nested in fabric structure, and the effective area of retroreflection is reduced by overlapping these beads.

Figure 10. Appearance change AP of tested samples (A1) produced by screen printing technology after test

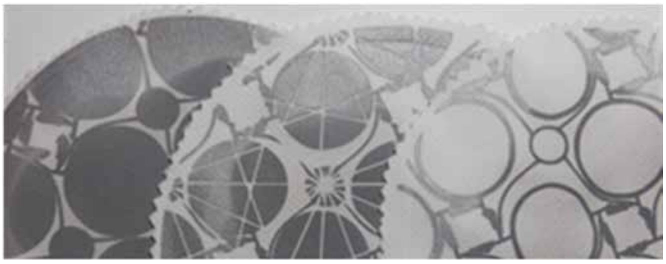


Figure 11. Appearance change AP of tested samples (A3) produced by transfer film technology after test

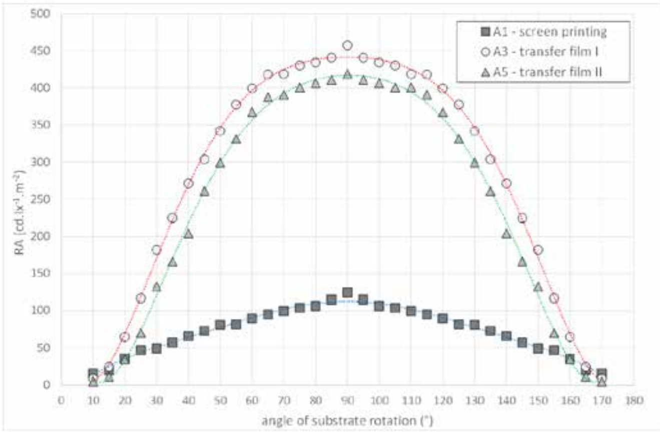


Figure 12. Distribution of coefficient of retroreflection RA of tested samples A1, A3, A5 with 85% pattern coverage [24]

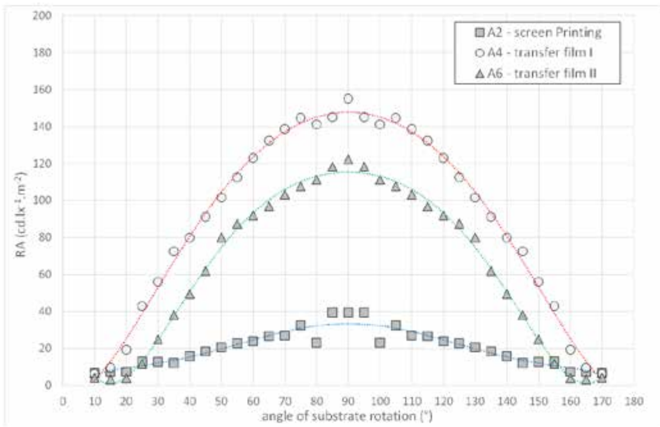


Figure 13. Distribution of coefficient of retroreflection RA of tested samples A2, A4, A6 with 25% pattern coverage [24]

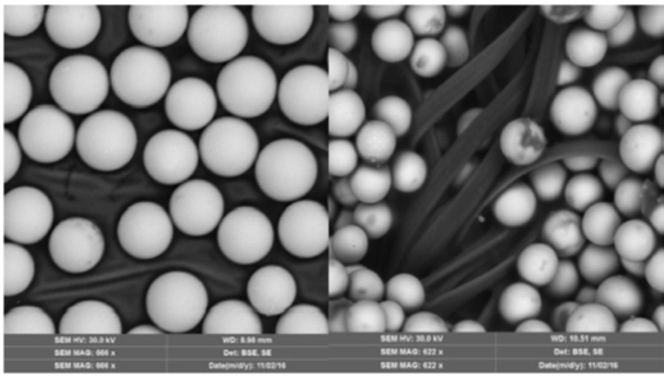


Figure 14. SEM of reflective film 3M C750(left) and screen printed sample(right)[24]

Retroreflective performance of the tested samples shown by the graphs in Figures 12 and 13 documents the similar performance of sample transfer film II with 25% of coverage and screen printed pattern with 85% coverage. The optical indicatrix of the tested retroreflectors on the graph presented in Figure 15 show acceptable retroreflective performance (RA ~ 400 $cd.lx^{-1} \cdot m^{-2}$) at entrance angle ($\beta \pm 30°$). This confirms the expected category of retroreflective transfer film as retroreflectors of high visibility.

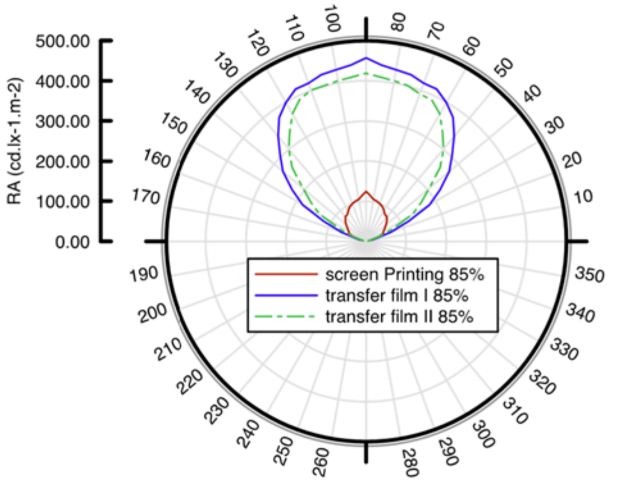


Figure 15. Indicatrix of RA of tested samples with 85% pattern coverage [22]. RA, coefficient of retroreflection.

3.4. TOPSIS analysis

The fundamental step is to set the relative importance of different criteria properly with respect to the objective of the problem before using TOPSIS analysis. This problem was

Table 4. The relational scale for pairwise comparison according to Saaty.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	Activity is very strongly favored, and its dominance is demonstrated
9	Extreme importance	The evidence favoring one activity over another is the highest possible order of affirmation

Table 5. Pair wise comparison matrix of criteria.

Criteria	OWTC	OMMC	TE	TC	WVTR	**AC**	**B**	**RA**	**Weight**
OWTC	1	1	5	5	1/5	5	5	1/9	0.098
OMMC	1	1	5	5	1/5	5	5	1/9	0.098
TE	1/5	1/5	1	1	1/7	1	1	1/9	0.028
TC	1/5	1/5	1	1	1/7	1	1	1/9	0.028
WVTR	5	5	7	7	1	7	7	1/9	0.211
AC	1/5	1/5	1	1	1/7	1	1	1/9	0.028
B	1/5	1/5	1	1	1/7	1	1	1/9	0.028
RA	9	9	9	9	9	9	9	1	0.481
λ_{max}					8.29				
CI					0.041				
CR					0.029				

B, bending rigidity; CI, consistency index; CR, consistency ratio; OWTC, one-way transport capacity; OMMC, overall moisture management capacity; RA, coefficient of retroreflection; TE, thermal effusivity; TC, thermal conductivity; WVTR, water vapor transmission rate.

solved using the Analytical Hierarchy Process (AHP) proposed by Saaty [20]. Pairwise comparisons define the relative importance of one item (property) to the other in meeting the decision goal (total wearing performance). Therefore 9-point Saaty's scale was used for quantifying managerial judgments, which is the standard. The basic scale of intensity of importance 1, 3, 5, 7, and 9 was used to simplify the calculation process, except immediate values 2, 4, 6, and 8 between the above scales values; see Table 4. A pairwise comparison matrix was constructed by using a scale of relative importance, and judgment was made, as shown in Table 5.

The obtained values of weights for eight criteria: OWTC, OMMC, TE, TC, WVTR, AC, B, and RA were found to be 0.098, 0.098, 0.028, 0.028, 0.211, 0.028, 0.028, and 0.481 respectively. Consistency analysis indicated that the matrix's judgment was considered consistent and acceptable (CR < 0.1).

The TOPSIS method (Eqs (1)–(8)) was used for the fabrics' selection process using weights obtained from pairwise comparison and measurement results of tested properties (thermo-physiological comfort, physical-mechanical performance, and visibility); see Table 3. The weighted normalized decision matrix, positive ideal solution (A^+), and negative ideal solution (A^-) are shown in Table 6.

The relative closeness and final ranking of the tested fabrics are shown in Table **7**. The calculated values associated with Sample A5 indicate that it was the best choice in terms of combining the performance of thermo-physiological comfort, physical-mechanical properties, and visibility. Sample A5 represents the fabric produced using the technology of retroreflective transfer film (film transfer technology – C750; company 3M) with reflector covering 85%. The sample A3 (film transfer technology – WLRF1001; company Weallight, covering 85%) was very close to the efficiency of sample A5, in contrast to sample A1, which has the same reflector area but a different applied technology of retroreflection. Both RA (weight is 0.48) and water vapor permeability (weight is 0.21) parameters play dominant roles in choosing the best solution (see Table 8). For the reasons mentioned above, samples with reflector size equal to 85% and transfer film technology are ranked first out of the six chosen samples, although sample A1 shows better results in most tested parameters, i.e., it is more complex. It is necessary to set the proper order of the importance of evaluated properties (their weights) before using TOPSIS analysis; however, it is not easy. Determination of this order depends on the intended purpose. In the present study, the weights were determined mainly with regard to the criterion of health protection within public transport, or in other words the need to ensure enhanced safety for pedestrians and cyclists by improving road users' visibility (RA parameter). So, the importance attributed to thermo-physiological comfort

Table 6. Weighted normalized decision matrix, A^+, and A^-.

Sample code	OWTC	OMMC	TE	TC	WVTR	AC	B	RA
A1	0.050	0.043	0.010	0.010	0.085	0.014	0.009	0.090
A2	0.048	0.048	0.005	0.007	0.104	0.015	0.003	0.029
A3	0.005	0.025	0.018	0.017	0.051	0.010	0.017	0.303
A4	0.045	0.041	0.006	0.007	0.101	0.012	0.005	0.087
A5	0.031	0.031	0.017	0.016	0.059	0.007	0.019	0.332
A6	0.042	0.046	0.006	0.007	0.101	0.009	0.004	0.113
A^+	0.050	0.048	0.018	0.017	0.104	0.015	0.003	0.332
A^-	0.005	0.025	0.005	0.007	0.051	0.007	0.019	0.029

A^+, positive ideal solution; A^-, negative ideal solution; B, bending rigidity; OWTC, one-way transport capacity; OMMC, overall moisture management capacity; RA, coefficient of retroreflection; TE, thermal effusivity; TC, thermal conductivity; WVTR, water vapor transmission rate.

Table 7. Final ranking of sample alternatives and relative closeness R

Sample code	d^+	d^-	Relative closeness R	Rank
A1	0.242	0.085	0.261	5
A2	0.303	0.073	0.195	6
A3	0.079	0.274	0.776	2
A4	0.245	0.089	0.267	4
A5	0.054	0.304	0.849	1
A6	0.220	0.107	0.328	3

d^+, distance between i-th alternative and positive ideal solution; d^-, distance between i-th alternative and negative ideal solution.

was considered to a slightly lesser extent, whereas physical-mechanical performance was the least considered. It has been verified that TOPSIS analysis is an appropriate tool for choosing the best solution if we are able to define the intended purpose of our investigation.

4. CONCLUSION

In this study, the impact of technology and retroreflector size is examined to ascertain the complex power of functional knitted fabric in terms of the combination of thermo-physiological wear comfort and visibility. Two technologies (screen printing and transfer film) and two reflector covering sizes (25% and 85%) were applied to the tested material. Subsequently, these samples were investigated in the following three fundamental ways. The first way dealt with examination of the thermo-physiological behavior of the tested samples, as determined based on thermal transport, moisture management, and water vapor transport properties. The second way focused on their physical-mechanical performance presented by bending rigidity and appearance change by abrasion test. Last but not least was the ways: test of visibility given by the coefficient of retroreflection. Furthermore, TOPSIS analysis was used to select the best solution from all the abovementioned points of view.

This study has confirmed that generally, both thermo-physiological and sensorial wearing comfort decrease with the reflector size; on the other hand, increase in visibility has been observed. The different advantages and disadvantages of both applied technologies have been demonstrated in this study.

Unlike film transfer technology, the screen printing method proves to be better for almost all tested properties (mainly water vapor permeability, moisture management, and physical-mechanical performance) except visibility. Simple screen printing of suitable glass spheres gives only 27% of the retroreflective factor of the retroreflective transfer film system. Film transfer technology ensures high visibility that meets the requirements of the standard EN ISO 20471 (for high visibility clothing); unfortunately, the places of application are stiffer, non-permeable, and have a low resistance of abrasion given by AP. Sample A5 was determined as the best using the TOPSIS analysis. Both the RA and water vapor permeability parameters, namely their weights, play dominant roles in choosing the best solution.

To summarize, the question remains as to what size of coverage area is acceptable from the point of view of optimal thermal comfort for different weather conditions/seasons.

The presented results suggest that the solution can be achieved through a combination of the advantages associated with both the technology methods (screen + film transfer) to ensure sufficient wear comfort as well as high visibility corresponding to the standards. Retroreflection transfer film can be used for the main RA elements, as required by visibility standards for sportswear clothing (including the principle of biomotion within sleeves). Screen printing elements can be applied to specific regions of apparel that are exposed to extreme loading, especially those regions that are prone to sweating.

Although the current study is based on a small group of tested materials and a moderate amount of the reflector-tested size (about 50%) is missing, the findings suggest the importance of taking into consideration different fabric properties in order to evaluate the total wear comfort of sportswear clothing in relation to its visibility.

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