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Comparative analysis of protective garments system with fleece and spacer based removable inserts

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Original scientific paper
Received: November 3, 2025
Accepted: March 16, 2026
https://doi.org/10.65776/ep.20.3.1

Abstract

The measurement results for the thermal insulation of the outer shell, removable thermal inserts, and protective garments system (PGS), as well as a comparative analysis of the thermal insulation, are presented. Both protective garments systems are made from the same materials. One removable thermal insert is made of fleece, while the other is made of spacer material. Tests of the thermal properties of the protective garments system were conducted using a thermal manikin. These studies have shown that the primary contributors to thermal insulation are the removable thermal inserts, while the outer shell, made of laminate, serves a protective function against wind and moisture. From the measured thermal insulation values and established results, it is evident that the outer shells of both protective garments systems have values slightly greater than 1 Clo, while the removable thermal inserts in the protective garments system have significantly higher thermal insulation values of 1.45 and 1.78 Clo. Thus, the total thermal insulation increases to about 2.3 Clo, indicating that removable thermal inserts can more than double the thermal insulation of the protective garments system.

Keywords*: protective garments system, thermal insulation, thermal mannequin*

1. Introduction

Garment plays a key role in maintaining thermal balance and significantly affects thermal comfort. Gagge et al. published a paper in 1941 proposing the unit of measurement Clo (1 Clo = 0.155 m^{2}K W^{-1}) for determining the thermal insulation of garment [1, 2], which was later used as an important parameter in thermal comfort models [3, 4]. Clo is defined as a unit for measuring the thermal insulation value of garment, where 1 Clo refers to a person who feels thermally comfortable when sitting in a ventilated room with an ambient temperature of 21 °C, an air flow of 0.1 m s^{-1}, and a relative humidity of less than 50% [2]. Thermal comfort is a psychological state of satisfaction with the ambient temperature, that is, a state in which it is neither too cold nor too hot. As this is a subjective feeling associated with a person's response to the environment, such as sensations of cold or heat, quantitatively defining thermal comfort is challenging [6]. Since the body surface area is most sensitive to environmental changes, wind speed, humidity, thermal radiation, and other environmental factors can affect the amount of body heat loss. Therefore, body surface temperature should be considered an important parameter for assessing the level of thermal comfort in humans [7]. A sense of comfort is related to gender, body mass index (BMI), age, activity level, and garment [7, 8]

Li et al. analysed heat transfer through multilayer garment systems that have a layer of corrugated geometry and different air permeability levels of materials. The aim was to establish how the combination of corrugation and permeability affects thermal insulation and the overall effect on heat transfer. The results showed that heat drainage is more efficient in corrugated forms than in flat configurations. Moreover, the thermal flux decreased as permeability increased until a critical minimum was reached, after which the thermal flux started to rise sharply [9].

Testing the thermal properties of garment requires a comprehensive approach, including analysis of several interconnected thermal and physiological parameters. Despite significant progress in the development of measuring instruments and methods, further improvement is still needed. A particular challenge is the integration of different measuring systems and methods to enable simultaneous monitoring of several thermal and physiological characteristics, which would provide a more realistic view of the interaction between the body, garment, and the environment. Therefore, an integrated measuring system for evaluating the thermophysiological properties of garment was developed, installed, and patented at the *Faculty of Textile Technology* in the *Laboratory for Thermal Insulation Properties of Clothing*. The integrated system consists of five measuring methods and devices: hot plate, multipurpose differential conductometer, thermal mannequin, device for measuring temperature gradients, and device for measuring physiological parameters of the human body for precise evaluation of the thermal comfort of clothing. The integrated system have been developed, calibrated, patented [10]. The thermal properties of PGS on a thermal mannequin were investigated in this paper. Although numerous studies examine thermal comfort or thermal resistance of individual textile layers, there is a lack of system-level analyses that quantify the incremental contribution of removable thermal inserts relative to the outer shell under controlled dynamic conditions. Existing research typically relies on single-method measurements, which do not capture interactions between layers during motion nor the redistribution of heat and air within multilayer clothing systems. For this reason, the thermal properties of complete PGS were investigated, with emphasis on understanding how differences in insert architecture (fleece and spacer) influence overall insulation when combined with an identical laminated outer shell.

2. Measurement system and materials

A segmented metal mould, anatomically designed to simulate the human body and known as the thermal mannequin, consists of 24 human body segments with builtin electric heaters, temperature sensors, 14 microcontroller interfaces, and a pneumatic system for arm and leg movements (**Fig. 1.**).

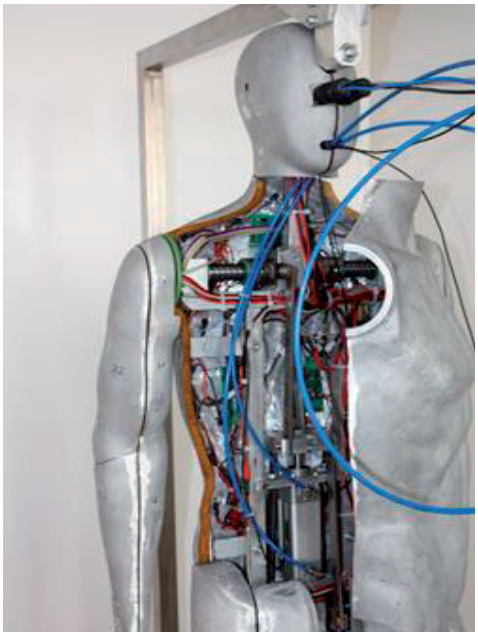

Fig. 1. Thermal mannequin [11]

The thermal mannequin shown in Fig. 1 is designed and installed at the Faculty of Textile Technology and forms part of a fully integrated measurement system comprising several unique devices for testing the thermal insulation properties of garment. All devices have been developed and patented by scientists from the Faculty.

The thermal mannequin [11] is installed in the thermal insulation chamber, and software is used to manage the mannequin (selection of segments and determination of the temperature of individual segments), measure the thermal properties of garment on the mannequin, and control the air conditioning chamber (setting the environmental temperature, air flow rate, and monitoring atmospheric humidity) **(Fig.2)**.

For each sample, measurements were taken over a 20 minute period, with readings recorded every 5 seconds, resulting in 240 data points per sample, which were then averaged to obtain the mean thermal insulation. Before the measurements began, the samples were placed in the thermal insulation chamber containing the thermal manikin and stabilised under the same ambient conditions (temperature, air velocity, humidity) as the thermal manikin.

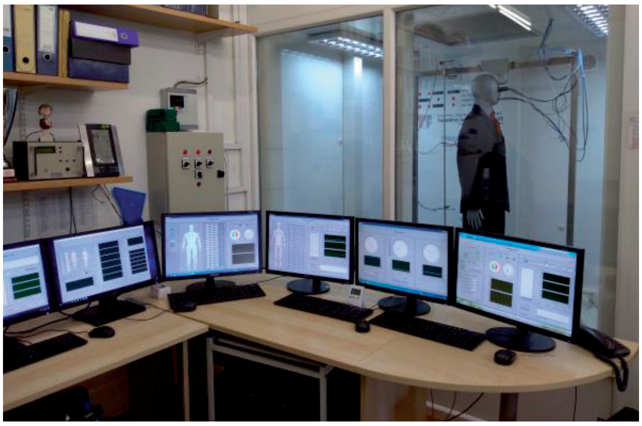

Fig. 2. Thermal mannequin installed in the thermal insulation chamber and computer software displays

The thermal mannequin is used to obtain static and dynamic measurements consistent with the simulation of human walking. Once garment is placed on the thermal mannequin, its thermal properties under dynamic conditions are determined in a manner that simulates the wearer's gait, with both arms and legs moving in opposite phases. The limbs are moved using a pneumatic linkage system integrated into the thermal mannequin. The movement speed of the limbs can be varied over a wide range and precisely adjusted by the air damper to achieve a movement speed of 45 ± 2 double steps per minute and 45 ± 2 double arm movements per minute for walking, in accordance with the standard EN ISO 15831:2004. The method for controlling, regulating, measuring, and calculating the thermal systems on the garment was introduced using a segmented metal casting modelled after the human body, with the capability to activate and deactivate all segments (of the entire casting) or any group of segments, and to introduce and set measurement parameters in accordance with standards for experimental research. When stable environmental conditions (temperature, relative humidity, and air velocity) are achieved in the climatic chamber, the value of the device constant for the thermal mannequin should be determined, and can be obtained according to the following equation [12]:

$$R_{ct0} = \frac{(T_s - T_a) \cdot A}{H_0}$$

where: R_{ct0} – resultant total thermal insulation of the measuring device, including the thermal insulation of the boundary air layer, $m^2K\ W^{-1}$; A – total surface area of thermal manikin, m^2; T_s – mean skin surface temperature of thermal manikin, °C; T_a – air temperature within the climatecontrolled chamber, °C; and H_0—total heating power supplied to the thermal manikin, W

The evaluation of the thermal properties of the garment using the thermal manikin is performed by placing the selected garment or ensemble around its body in either static or dynamic mode. In dynamic measurement, the thermal manikin simulates the wearer walking, with both the legs and arms moving in phase reversal, at a specified number of movements per minute and a specified stride length. The measurements can be performed under static or dynamic environmental conditions simulated in the climatic chamber. After determining thermal comfort, indicated by the stabilisation of parameter values (numerical and shown in diagrams), measurements are taken and the thermal insulation is calculated using following equation [12]:

$$R_{ct} = \frac{(T_s - T_a) \cdot A}{H} - R_{ct0}$$

where: H – location where the electrical power required to maintain the temperature of the measuring surface on which the measurement sample is positioned is provided.

Technical characteristics of the builtin materials for the outer shell and removable thermal insert are presented in **Table 1**.

Protective garments system (jacket) made of outer shell and removable thermal insert **(Fig.3)**.

a)

b)

Fig. 3. Model sketch of protective garment system: a) outer shell (IM1+IM2); b) removable thermal insert (TU1: IM3+IM4 and TU2: IM3+IM5)

Table 1. Review of the analysed technical characteristics of the sample of builtin material.

Technical characteristics	Material	Value
Raw material composition	IM1	PES 100%
	IM2	PES 100%
	IM3	PES 100%
	IM4	PA 100%
	IM5	PES 100%
Mass per unit area	IM1	168.90 gm^{-2}
	IM2	54.60 gm^{-2}
	IM3	298.80 gm^{-2}
	IM4	231.00 gm^{-2}
	IM5	76.8 gm^{-2}
Water vapor permeability	IM1	3135.7 $gm^{-2}24h^{-1}$
	IM2	3469.70 $gm^{-2}24h^{-1}$
	IM3	4341.80 $gm^{-2}24h^{-1}$
	IM4	3648.30 $gm^{-2}24h^{-1}$
	IM5	4500 $gm^{-2}24h^{-1}$
Air permeability	IM1	mean value: 0.036 $m^3m^{-2}min^{-1}$ from right side to reverse side: 0.007 $m^3m^{-2}min^{-1}$ from reverse side to right side: 0.064 $m^3m^{-2}min^{-1}$
	IM2	expressive
	IM3	mean value: 19.33 $m^3m^{-2}min^{-1}$ from right side to reverse side: 19 $m^3m^{-2}min^{-1}$ from reverse side to right side: 19.66 $m^3m^{-2}min^{-1}$
	IM4	expressly
	IM5	mean value: 4.03 $m^3m^{-2}min^{-1}$ from right side to reverse side: 3.91 $m^3m^{-2}min^{-1}$ from reverse side to right side: 4.15 $m^3m^{-2}min^{-1}$
Raw material composition of the membrane	IM1	PU 100%

For the protective garments system PGS1.1, the following embedded materials have been selected:

- for the outer shell (OS1) as the outer layer, a laminated fabric with a PU membrane labelled IM1 was chosen, and for the lining material, a mesh polyester lining labelled IM2.
- for the removable thermal insert (TU1), the polyester fleece material labelled IM3 (on the outside of the removable thermal insert) and the polyamide spacer material labelled IM4 (on the inside of the removable thermal insert) were selected

For protective garments system PGS1.2, the following embedded materials have been selected:

- for the outer shell – as in PGS1.1.
- for the removable thermal insert (TU2), the polyester fleece material labelled IM3 (on the outside of the removable thermal insert) and the lining material labelled IM5 (on the inside of the removable thermal insert) were selected

It is important to emphasise that mesh lining IM2 and spacer material IM4 are fabrics with large interyarn openings, resulting in very high air permeability (expressive). They do not function as air barriers and contribute negligibly to system level thermal insulation. Their purpose in the PGS is aesthetic, to cover seams and protect the removable insert surface, not thermal.

3. Results

When measuring thermal insulation, the temperature of the heated surfaces of the models was 34.0 °C and the ambient temperature was 20 °C. The airflow rate in the chamber was 0.4 m s^{-1} and the relative humidity was 32%. The measured total thermal insulation in static mode of the undressed model, together with the boundary layer of air adjacent to the surface (R_{ct0}), was 0.09116 m^2 K W^{-1}.

A graphical representation of the results is shown in **Fig.4** and **Fig. 5**.

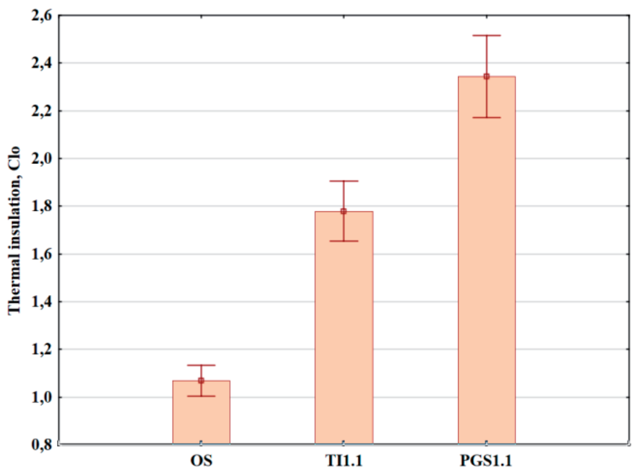

Fig. 4. Graphical representation of measurement results of thermal insulation in static mode of the outer shell (OS), removable thermal insert TI1.1, and protective garments system PGS1.1

Based on the measured data set, the thermal insulation of the outer shell is at the basic level, as in the protective garments system PGS1.1, because the same outer shell was used, with a thermal insulation value of 1.03 Clo **(Fig. 4)**. The thermal insulation of the removable thermal insert is 1.78 Clo. The thermal insulation value of the protective garments system PGS1.2 is 2.36 Clo.

Based on the measured data set, a graphical representation of the results was produced, showing that the thermal insulation of the outer shell is at a basic level of 1.03 Clo **(Fig. 5)**. The thermal insulation of the removable thermal insert is 1.45 Clo thus providing adequate protection against cold. The thermal insulation value of the protective garment system, created by combining the outer shell OS1 and the removable thermal insert TU1, is 2.26 Clo.

In **Fig. 4** and **Fig. 5**, a sharp increase in thermal insulation values is observed when the outer shell is combined with the heat insert.

The research confirms that removable thermal inserts are the main contributors to the thermal insulation of protective garments system, while the outer shell plays a secondary role, primarily providing protection against wind and moisture. Measurements conducted on a thermal mannequin under controlled environmental conditions showed that combining an outer shell with a removable thermal insert significantly increases the overall thermal insulation of the protective garments system. Specifically, the protective garments system PGS1.1, which includes a removable thermal insert (TU1) made of polyester fleece material labelled IM3 (on the outside of the insert) and polyamide spacer material labelled IM4 (on the inside of the insert), was selected and achieved a thermal insulation of 2.36 Clo. PGS1.2, with a removable thermal insert (TU2) made of polyester fleece material labelled IM3 (on the outside of the insert) and lining material labelled IM5 (on the inside of the insert), was also selected and reached 2.26 Clo.

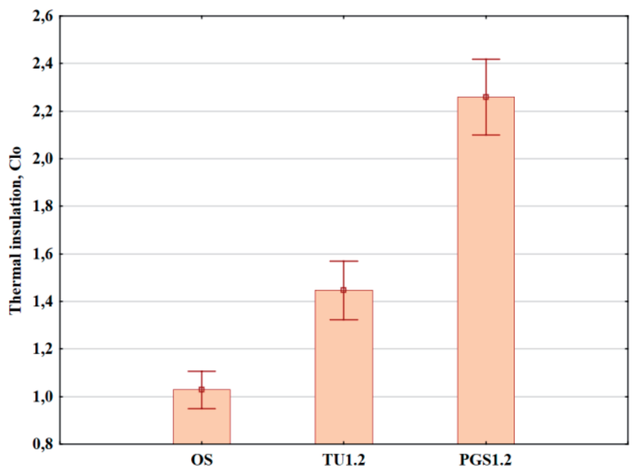

Fig. 5. Graphical representation of measurement results of thermal insulation in static mode of the outer shell (OS), removable thermal insert TI1.2, and protective garments system PGS1.2

Based on a oneway numerical analysis of variance (ANOVA), no statistically significant difference was found between the results for PGS 1.1 and PGS1.2. These results suggest that the values for the two groups do not differ significantly, indicating a similar level of variability within the analysed data.

4. Discussion

The measured differences in systemlevel insulation can be explained by how the removable inserts manage air and convection within the clothing assembly. Both the fleece and the spacer introduce a thicker region of relatively quiescent air, which is the main contributor to thermal resistance. Their porous microgeometries interrupt bulk airflow and reduce convective coupling between the skinside and shellside microclimates, so insulation remains high even when the wearer's motion is simulated on the thermal manikin. The laminated outer shell, common to both systems, primarily stabilises the external boundary layer as a wind and moisture shield; by itself, it does not provide an air volume comparable to that created by the inserts. The mesh lining, with large apertures and very high air permeability, does not act as a wind barrier and adds negligible resistance; it is present for constructional and aesthetic reasons, chiefly to cover seams and protect the insert surface. These mechanisms are consistent with the presented results: the shell alone provides a lower Clo, while combining the shell with either insert raises the overall insulation to the observed system values, with only a small difference between the fleece- and spacerbased variants within the measured variability.

5. Conclusion

The research confirms that removable thermal inserts are the main contributors to the thermal insulation of protective garments system, while the outer shell plays a secondary role, primarily providing protection against wind and moisture. Measurements conducted on a thermal insulation of the protective garments system. Specifically, the protective garments system PGS1.1, which includes a removable thermal insert made of a combination of fleece material and spacer material, achieved a thermal insulation of 2.36 Clo, while PGS1.2, with a removable thermal insert made of a combination of fleece and lining material, reached 2.26 Clo. Measurements of the thermal insulation of protective garments system on a thermal mannequin in controlled environmental conditions showed that combining an outer shell with a removable thermal insert significantly improves thermal insulation. It can be concluded that adding removable thermal inserts to protective clothing can more than double its thermal insulation. Given that the cost of removable thermal inserts is significantly lower than that of the outer shell, their use in protective clothing is also highly justified from a cost perspective. Specifically, the protective garments system PGS1.1, which includes a removable thermal insert made of a combination of fleece material and spacer material, achieved a thermal insulation of 2.36 Clo, while PGS1.2, with a removable thermal insert made of a combination of fleece and lining material, reached 2.26 Clo. Measurements of the thermal insulation of protective garments system on a thermal mannequin in controlled environmental conditions showed that combining an outer shell with a removable thermal insert significantly improves thermal insulation. It can be concluded that adding removable thermal inserts to protective clothing can more than double its thermal insulation. Given that the cost of removable thermal inserts is significantly lower than that of the outer shell, their use in protective clothing is also highly justified from a cost perspective.

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Impact of silicone products on the properties of reference polyester fabrics

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Abstract

The paper examined the effect of the washing and after-treatment on the properties of red, blue, and white reference polyester fabrics. Washing performed with a reference detergent at 60°C was followed by after-treatment with silicone products (A, B) from two manufacturers, both modified polydimethylsiloxanes (PDMS). Untreated, washed, and washed then after-treated polyester fabrics were evaluated by spectral parameters and surface properties. Washing and after-treatment did not reduce the whiteness of the white fabric, which can be considered a favorable property of the silicone products analyzed. The influence of the silicone products on the colour fastness of blue and red polyester fabrics was confirmed, with product B having a stronger effect than product A. It was found that the after-treatment with both PDMS products exhibited a reduction in the surface friction coefficient in comparison to washed with detergent. Finally, the colour fastness and the fabric surface kurtosis parameter (Rku) showed a difference between the blue and red polyester samples, as well as between the effects of silicone products A and B.

Keywords*: polyester fabric, detergent, polydimethylsiloxane (PDMS), spectral parameters, surface properties*

1. Introduction

Sustainability in textile technology requires a thorough understanding and appropriate testing principles, using objective evaluation methods to assess technological benefits and environmental impact. One of the global problems in the past decades is the presence of microplastics (MPs), typically less than 5 mm in size and microfibrils (MFs), in the environment (effluents, air, soil, rocks) [1].

Textiles are a significant source of MFs presence into the environment matrices; however, research findings indicate that synthetic fibres release approximately 34.8% of MFs into water when washed [2-4]. The tendency for formation of fragments and its release from textile sources depends on the properties of the textile material, the conditions of the technological process, wash and use cycles.

The action of factors in the Sinner cycle alters the characteristics of textiles and removes finishes and preparations, leading to changes in the surface (an unpleasant and harsh touch, formation of fuzz, fibre breakage, and detachment) [5,6]. Fig 1 present surface changes and detachment of MFs from polyester fabric upon washing parameters and abrasion.

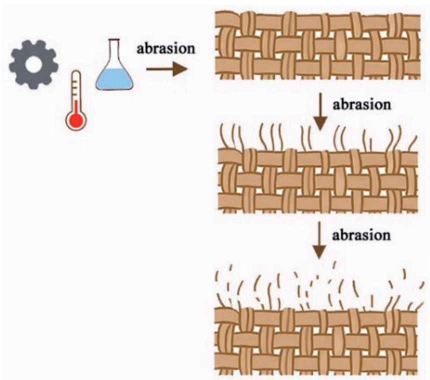


Fig. 1. Schematic representation of the proposed source of MFs

Combating MPs and MFs pollution requires both remediation and preventive measures [6]. As remediation is essential, given the current state of technology, it may take a long time to achieve. Prevention should be implemented urgently to reduce the proportion of released fibres. Possible measures to reduce the release of MPs from synthetic textiles include modifying structural properties, functionalizing with additives (such as biopolymers or softeners), and optimizing washing conditions [7,8].

These measures can reduce friction between individual fibres and between fibres and metal parts of washing machines. Besides low mechanical action, which could reduce this release, softeners can also contribute to less fragmentation and release of MPs and MFs into environmental matrices [9].

The role of softeners is to enhance multiple textile properties, including softness, hydrophilicity or hydrophobicity, easier ironing, reduced wrinkling, faster drying, a pleasant scent and freshness, fibre care and smoothing, antistatic effects, colour retention, and anti-allergic effects [10].

Silicone-based softeners are becoming increasingly important due to their excellent characteristics. They are used in the finishing of lyocell textiles, as products that positively affect yarn fibrillation, maintain the peach-skin effect (peach skin surface), and reduce fragmentation and fibrillation during home washing [11]. They are classified as stable semi-permanent products because they retain a soft and pleasant feel even after multiple washes. The many advantages of polysiloxanes over other compounds can be attributed to the nature of the siloxane bond, which is thermodynamically one of the most stable. They are elastic due to free rotation in Si–O bonds, especially when small organic groups, such as methyl, attached to the silicon atom [12].

Silicones are available in various forms, such as silicone fluids, polydimethylsiloxane (PDMS), aminosilicones/amidosilicones, and silicone emulsions. Aminofunctional silicones are positively charged and interact effectively with negatively charged materials, decreasing the coefficient of friction and producing a smoother surface [13]. Silicones, classified as derivatives of polydimethylsiloxane (PDMS), are organically modified inorganic macromolecules of silicon with various molecular weights, sizes, and chemical properties. The presence of both organic and inorganic components gives rise to their multi-phased chemistries, as either covalent or ionic linkages connect their hybrid molecular chains [14]. It was reported that environmentally friendly polydimethylsiloxane (PDMS), used as a finish for polyamide, reduces the release of MPs by lowering friction [15]. The number of MPs fragmented in both dry and wet states from PDMS-coated polyamide was reduced by 93% compared with the untreated sample [16].

Fabric surface friction plays a critical role in determining tactile behavior, drape performance, abrasion resistance, material handling, comfort, and processing efficiency [17]. The fabric surface friction coefficient (SFC) represents the quantitative measure of resistance encountered during relative sliding motion between a fabric surface and a contacting body [18]. It reflects the combined effects of fibre morphology, yarn structural characteristics, fabric geometry, and surface modifications, and serves as a key parameter for describing the tribological behavior of textile materials.

The friction of a fabric on itself or on another fabric has a significant effect on fabric performance features such as abrasion, wear and shrinkage, as well as on the user's tactile comfort [19].

Although common associated with surface roughness, friction is a non-intrinsic property influenced by multiple structural and material factors, including fibre type, yarn hairiness and twist, weave architecture, fabric density, finishing treatments and aging [20]. A comprehensive understanding of these interdependent parameters enables the precise engineering of woven fabrics with tailored functional, aesthetic, and mechanical performance.

It is important to note that abrasion resistance is closely linked to the quality of the fabric surface, as abrasion primarily affects the outer layer, i.e., the surface. Key factors, such as raw material composition, yarn type and parameters, weave, and warp and weft count influence most fabric properties, including abrasion resistance. However, there is a noticeable lack of research focused on fabric surface quality, particularly surface topography, and its effect on fabric behaviour during abrasion.

Since abrasion primarily affects the surface of a woven fabric and its resistance depends on surface quality and geometry, it can be assumed that the coefficient of friction and surface topography parameters are interrelated and jointly influence the abrasion damage mechanism, degradation and fragmentation of fibres from the fabric surface in wet and dry conditions [19, 21].

This research examines the effect of detergent after the first, second, and third wash cycles, as well as two after-treatment silicone products (PDMS) applied after the first, second, and third cycles, on the properties of three reference polyester fabrics, comparing the properties of pristine and processed polyester fabrics. The selected reference fabrics, before and after treatments, were evaluated using their spectral properties, and abrasion resistance. As the spectral properties provide a visual criterion, the primary focus is on the relevance of certain surface geometry parameters – the maximum height of the roughness profile (*Rz*), the height of the highest peak (*Rp*), the depth of the deepest valley (*Rv*), the total roughness height (*Rt*), and kurtosis (*Rku*)—for the assessment of the abrasion resistance of fabrics.

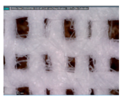
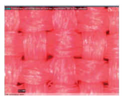
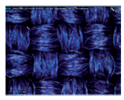
2. Experimental

The study varied the following parameters: type of polyester material (structural parameters and colour), functional additives (two silicone products), sequence of operations (washing and washing with after-treatment), and number of cycles (0, 1 and 3).

Material

The research was conducted on three reference polyester fabrics supplied by Center for Testmaterials (CFT), Table 1.

Table 1. Specification of polyester fabrics

	Fabrics		
Colour	white (B)	red (C)	blue (P)
Q (g/m^2)	156.0	187.0	189.2
Density (threads/cm) warp/weft	27.7/20	23.2/23.75	22.8/23.4
Thickness (mm)	0.35	0.45	0.448
Yarn fineness (tex) warp/weft	30.4/31.9	36.5/37.0	35.9/35.0
Weave	plain weave		
Digital image magnified 200x			
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Washing

Polyester fabrics were subjected to a washing process using reference ECE A detergents (D) for three cycles.

The washing process was carried out in a reference washing machine, Wascator FOM 71 CLS, according to HRN ISO 6330, programme 2A at 60 °C. Polyester fabrics in dimensions 31 × 31 cm, supplemented with 900 g of polyester/cotton ballast, were washed with ECE A detergent (1.25 g/L) at a bath ratio of 1:7 for three cycles. One sample each of white, red, and blue polyester fabrics was separated after the first washing cycle. The remaining samples were subjected to the subsequent two washing cycles.

The composition of the detergent is specified in Table 2.

Table 2. Composition of ECE A reference detergent

Ingredient	w (%)
Linear sodium alkyl benzene sulfonate	9.7
Ethoxylated fatty alcohol C12-18 (7 EO)	5.2
Sodium soap	3.6
Anti foam DC2-4248S	4.5
Sodium aluminium silicate zeolite 4A	32.5
Sodium carbonate	11.8
Sodium salt of a copolymer from acrylic and maleic acid	5.2
Sodium silicate (SiO_2:Na_2O = 3.3:1)	3.4
Carboxymethylcellulose	1.3
Diethylene triamine penta (methylene phosphonic acid)	0.8
Sodium sulfate	9.8
Water	12.2

After-treatment

The after-treatment process was performed with two silicone products (A and B), each applied at a concentration of 5.7 g/L and a liquor ratio of 1:8 during the final rinsing step of the wash cycle. The application was carried out in the washing machine, ensuring uniform distribution of the silicone products on the fabric samples through mechanical agitation during the final rinse.

The first product (A) was a self solubilising micro silicone emulsion (pH ~ 5) from DyStar GmbH. The second product (B) was a finely dispersed water-based silicone emulsion (pH 4.5) from Wacker GmbH.

After the first and third wash cycles, both washed and washed after-treated samples were dried using a Lagoon TD6-7 dryer (Electrolux) under a synthetic medium programme.

Table 3 lists the characteristics of pristine and treated polyester fabrics.

Table 3. Designation of polyester reference fabrics

Labels	Description of polyester fabrics
N	Pristine white, blue and red coloured
D	Washed white, blue and red coloured
A	Washed and after-treated white, blue and red coloured with silicone product A
B	Washed and after-treated white, blue and red coloured with silicone product B
Number of cycles	1, 3

Washed (D), washed and after-treated (A and B) polyester fabrics, after each cycle, were dried in a Lagoon TD6-7, Electrolux, at 60 °C.

Methods

The spectral parameters of polyester reference fabrics were determined using the DataColor SF300 spectrophotometer with a 2.2 cm aperture, D65 illumination, and d/8 ° geometry. The whiteness (W_{CIE}), tint value (TV), and tint deviation (TD) of pristine and treated polyester reference fabrics was evaluated according to AATCC test method 110. The impact of reference detergent and silicone products on the color change of blue and red polyester fabrics was assessed by fastness grade according to the evaluation protocol of HRN EN ISO 105-C06.

The analysis of polyester fabrics was carried out by touch evaluation using the SDL Atlas Fabric Touch Tester (FTT), Rock Hill, SC, USA.

Before testing, three specimens of the same samples were conditioned in a standard atmosphere at 20 °C ± 2 °C and 65 % ± 4 % relative humidity. The software generates a report containing 13 FTT index data points in .xls format [22].

Since the FTT provides only numerical assessment values and averaged results, additional data processing was performed to obtain detailed information on fabric surface characteristics. The raw surface roughness profile data (x–z coordinates) were exported from the FTT device and analyzed using external statistical software. The roughness parameters *Rq* and *Rku* were calculated from the primary surface profile, without applying any cut-off wavelength using Gaussian filtering.

3. Results and discussion

The spectral parameters of samples are important visual criteria for appearance of textiles. The whiteness degree (W_{CIE}), tint value (TV), tint deviation (TD) were selected as a whiteness quality criteria. So, the impact of washing with detergent and washing with detergent combined with after-treatment with silicone products during one and three cycles on whiteness are shown in Table 4.

Table 4. Whiteness of white polyester fabric

Sample	W_{CIE}	σ	V[%]	TV	TD
N	66.5	0.52	0.79	-0.4	-
D-1	65.7	0.16	0.25	-0.5	-
D-3	66.0	0.25	0.38	-0.6	R1
A-1	66.7	0.28	0.42	-0.5	R1
A-3	67.1	0.12	0.19	-0.6	R1
B-1	67.9	0.26	0.39	-0.4	-
B-3	70.4	0.12	0.18	-0.4	-

The whiteness degree of the pristine white reference polyester fabric is 66.5. Results presented in Table 4 show that the detergent due to absence of fluorescent whitening agents in the formulation had a slight impact on the whiteness degree. Finely dispersed silicone product B enhanced the whiteness of the white polyester fabric from 1 to 3 units. This may indicate a comparative advantage in the cumulative effect of product B compared to product A. Tint deviation (TD) of white fabric after three washing cycles as well as after one and three after-treatment cycles with softener A is shifted to slight red (R1).

Colour fastness grades of red and blue polyester fabric after exposure to detergent and silicone products are presented in Table 5.

Table 5. Fastness grades of washed and after-treated washed blue and red coloured fabrics

	Fastness grade, ISOA05	
Sample	Red fabric	Blue fabric
D-1	5	5
D-3	5	4-5
A-1	4-5	4
A-3	4-5	3-4
B-1	4	3
B-3	4	3

The fastness grades of red and blue reference fabrics after the first washing cycle are excellent (grade 5) and equal, while three washing cycles caused a slight decrease in the fastness grade of the blue sample (4-5). Change in fastness grade of blue polyester fabric after three washing cycles can be attributed to dyeing parameters and impact of the reference powder detergent. Since the influence of the detergent was recorded, a change due to film-forming properties of silicone products in after-treatments is expected. The results show that the second silicone product (B) had a stronger effect on colour than silicone product A.

The film-forming properties of the silicone can be utilized for improving fibre integrity, making it harder for the fabric to shed microfibers.

Among all FTT-measured parameters: bending, surface friction, surface roughness, compression, and thermal conductivity, the washing and after-treatment with silicone products showed the greatest influence on the friction-related properties of the fabric surface.

The comparison of the surface friction coefficients of the three investigated fabrics (Figs 2-4), measured using the Fabric Touch Tester, and reveals clear differences associated with washing and after-treatments. The unwashed samples exhibit the lowest friction values, which can be attributed to the highly ordered structure of the yarns and fabric surface prior to exposure to mechanical and chemical stresses.

All other properties were predominantly affected by the washing process itself, driven mainly by parameters of Sinner's circle and associated physical changes rather than after-treatment with silicone products.

Figs 2, 3 and 4 show surface friction coefficient (SFC) of pristine (N), washed (D) and after-treated (A, B) white, red and blue polyester fabric samples.

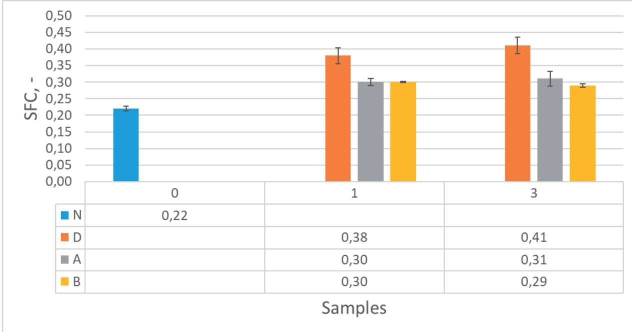

Fig. 2. Surface friction coefficient of the white fabric sample

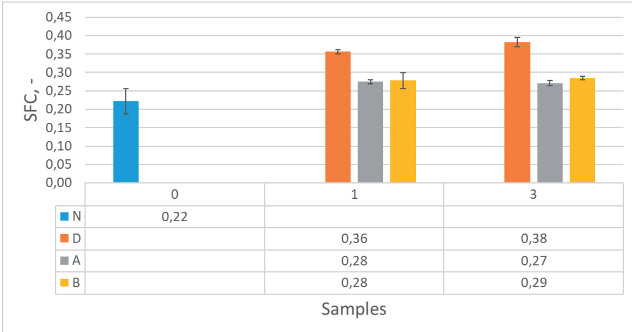

Fig. 3. Surface friction coefficient of the red fabric sample

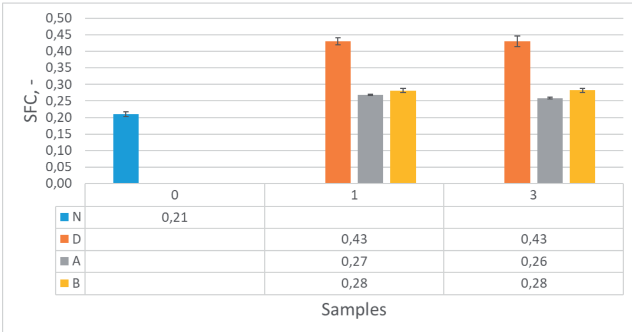

Fig. 4. Surface friction coefficient of the blue fabric sample

Washing with a reference detergent led to a pronounced increase in the surface friction coefficient. The most substantial rise occurred after the first washing cycle, whereas the increase observed after the third cycle is less pronounced. This behavior suggests that the majority of surface degradation and disruption of fibre alignment occurs during the initial washing process. The combined effects of mechanical stress, water as well as high temperature, contribute to increased surface irregularity and consequently higher friction values.

Based on the measured mean values, samples washed and subsequently after-treated with silicone products exhibited lower surface friction coefficients compared to samples washed solely with detergent. This indicates a consistent trend toward reduced surface friction after silicone after-treatment.. This reduction reflects the film-forming properties of polyester samples after-treated with silicone products.

A thin film on the surface decrease interfibre friction, and partially restore surface smoothness. No significant differences were detected between white, blue and red samples after one cycle treatment with silicone products, A and B. After three after-treatment cycles, the surface friction coefficients of samples treated with silicone products A and B were very similar, with negligible differences..

Root mean square of roughness profile (*Rq*) represents the of the surface height deviations relative to the mean line of the measured fabric roughness profile reflecting the general roughness level of the woven structure. Higher *Rq* values indicate increased surface irregularity and amplitude roughness, typically associated with coarse yarns, pronounced weave relief, or a high density of protruding fibers. Lower *Rq* values correspond to smoother, more homogeneous surfaces, where the profile shows fewer pronounced height differences. Rq is common used value for evaluating surface texture uniformity, tactile behavior, tribological performance (friction and wear), thermal–mechanical interactions, and the influence of various finishing processes on fabric morphology.

The graph (Fig 5) presents the *Rq* values of woven fabric samples, obtained after filtering the primary surface roughness profile.

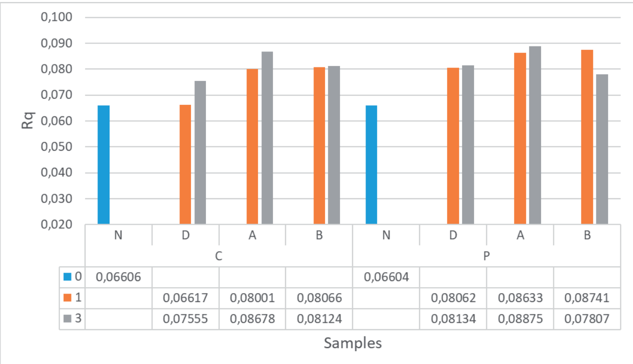

Fig. 5. Root mean square roughness of the surface of fabric samples

Only the red (C) and blue (P) fabric samples are shown, as the white sample exhibited highly unstable and inconsistent roughness values. This instability resulted from its pronounced deformability during repeated washing cycles, due to its loose structure, which caused the surface to undergo non-uniform distortion from chaotic mechanical loads during washing. Consequently, the roughness data for the white sample could not be reliably interpreted and were therefore excluded from the comparison.

For the remaining samples, a slight increase in surface roughness (Rq) is observed after washing, Fig 5. This indicates that mechanical stress during washing produces a modest rise in the vertical irregularities of the fabric surface. Regarding the effect of washing with detergent and after-treatment with silicone products, the results show no meaningful differences between the washed samples. Specifically, the silicone products did not exhibit a significant impact on surface roughness, which contrasts with their previously noted influence on the frictional properties of the same fabrics.

The applied silicone forms a very thin, continuous film on the surface of fibres and yarns, rather than modifying the fabric's macro- or meso-scale surface structure. This film smooths the fibre- and yarn-level surface asperities by filling micro-irregularities and reducing surface energy, which directly influences interfacial interactions during sliding contact. As a result, the coefficient of friction, defined as the ratio between tangential frictional force and normal load, is reduced due to decreased adhesion at the contact interface. In contrast, surface roughness parameters such as *Rq* describe the geometrical topography of the surface, which in textile materials is predominantly governed by fabric construction parameters (weave, yarn fineness, and crimp). Since the silicone product does not alter the fabric structure or weave geometry, the overall topographical profile measured at the fabric scale remains unchanged, leading to statistically similar Rq values before and after treatment.

The apparent decoupling between friction and roughness arises from the different physical origins of these properties. Tactile friction is highly sensitive to surface chemistry and micro-scale fibre smoothness, whereas surface roughness (*Rq*) primarily reflects structural and geometrical features of the fabric. This distinction explains why a nanoscale or microscale silicone film can markedly modify frictional behaviour without inducing measurable changes in surface topography. Fabric surface kurtosis (*Rku*) quantifies the surface height distribution, describing the sharpness of peaks or flatness of the fabric topography relative to a Gaussian (normal) distribution. It characterizes the shape of the roughness profile distribution, distinguishing between different types of surface irregularities. Rku is crucial for understanding woven fabric contact mechanics, as the shape of asperity peaks governs the real contact area, enabling differentiation between spiky and flattened roughness distributions.

High *Rku* indicates a leptokurtic surface with sharp, narrow, and pronounced peaks and valleys. In woven fabrics, such conditions arise from fine fibre ends, mechanical hairiness, or uncut protruding fibres that create localized high-intensity asperities. Low *Rku* indicates a flat surface with broad, flattened asperities and fewer extreme deviations.

Surface profile kurtosis affects friction, dye uptake, surface coating adhesion and the initiation of wear or pilling. The graph in Fig 6 presents the *Rku* values of red and blue samples before and after of washing and after-treatments cycles.

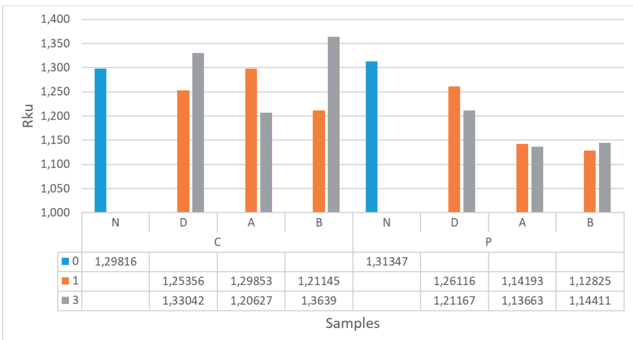

Fig. 6. Fabric samples surface profile kurtosis

The results show clear differences between the red and blue samples regarding how detergent and silicone products influence the surface profile shape. For the blue sample (P), the profile became less peaked (more rounded) after treatment with silicone products A and B. This reduction in kurtosis indicates that the surface asperities became broader and less sharp, suggesting a mild smoothing effect induced by the silicone products. The red sample (C) did not exhibit this behavior. Instead, its surface profile became sharper after the third washing cycle with detergent and after-treatment with silicone product B. These increases in Rku indicate that the fabric developed narrower and more pronounced asperities, likely due to differential fiber movement or surface restructuring during repeated cycles. For the red sample treated with silicone product A, a notable rounding of the profile was observed only after the third cycle, indicating a delayed after-treatment effect compared to the blue sample.

4. Conclusions

Two silicone products (A and B) based on PDMS were evaluated for the after-treatment of white, red, and blue polyester reference fabrics to improve abrasion resistance. After-treatment cycles with silicone product B had a stronger impact on the color of red and blue polyester samples in comparison to silicone product A.

The surface friction coefficient (SFC) of after-treated white, red, and blue polyester reference fabrics was compared to that of fabrics washed with detergent only, indicating the formation of a thin surface film that reduces interfibre friction.

Differences in the surface of white, blue, and red polyester fabrics treated with PDMS-derived silicone products (A, B) are not confirmed when observing the SFC and roughness profile (*Rq*) of blue and red polyester fabrics.

Fabric surface kurtosis (*Rku*) as a parameter showed differences between washed and after-treated red and blue polyester fabrics with silicone products.

Based on these results, it can be assumed that certain surface geometry parameters—such as the maximum height of the roughness profile (Rz), the height of the highest peak (Rp), the depth of the deepest valley (Rv), the total roughness height (Rt), and kurtosis (Rku)—can be effectively used to assess the abrasion resistance of fabrics.

A more realistic assessment of the impact of both silicone product films on white, blue, and red reference polyester fabrics, compared to untreated and washed fabrics on abrasion resistance, will be obtained by measuring the fragmentation and number of shedded MFs in the wastewater from the washing process, as a subject of further research.

The research is part of research activities of Institutional research projects ZORA and FUNK-TEX, funded by NextGenerationEU from 581 sources - The Recovery and Resilience Facility (RRF).

Acknowledgement

The author would like to thank DyStar GmbH and Wacker GmbH for donating the silicone-based products.

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