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Comfort Properties of Functional Double Bed Knitted Fabric for Firefighters Underwear

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ABSTRACT

The comfort properties of fabrics are closely related to their structural parameters. Various material and construction changes affect thermal insulation, permeability properties, wetting and water vapour permeability, which are the most important properties related to the comfort of textiles. Thermal comfort evaluation plays a crucial role in the development of textiles and is mainly carried out in the three aspects of breathability, heat transfer and moisture transfer. The aim of the research is to investigate the comfort and flame retardant properties of knitted fabrics made of four different materials: three conventional (cotton, Tencel and Micromodal) and one flame retardant material (blend of Tencel, polyacrylate, Modacryl-Tayrilan) that can be used for firefighter underwear. All materials were knitted in three different constructions of double jersey. It was found that the blend of Tencel, polyacrylate and Modacryl-Tayrilan is a truly flame retardant material suitable for firefighter underwear and has good comfort properties.

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1. INTRODUCTION

The physical aspects of comfort are related to human perception and subjective sensation of discomfort and/or pain. Physical comfort is largely a subjective factor, although it is influenced by receptors that are universal to the human body. A person's physiological comfort is related to maintaining the heat balance between the body's heat production and heat loss. Subjective factors that determine physiological comfort are the thermal perceptions of the individual's sensory perceptions and physical activity. Although physiological comfort depends on individual reactions and perceptions, it is closely related to the design and production of textiles and clothing in technical terms: from the selection of materials and yarn production, fabric production and its finishing, to the production of garments for various purposes or the application of textiles in indoor environments [1].

Therefore, the comfort of clothing can be divided into two approaches: subjective (reflection of all sensations perceived by the user) and objective (comfort is interpreted on the basis of physical condition and described by appropriate physical measurements and principles). The comfort properties of fabrics are closely related to their structural parameters. Various material and construction changes (different structure, change of density, also change of dimensional stability) influence thermal insulation, permeability properties, wetting and water vapour permeability, which are the most important properties related to the comfort of textiles [2,3].

The evaluation of thermal comfort capacity plays a critical role in the development of fabrics, and it is mainly conducted in the three aspects of: breathability, heat and moisture transfer properties. Breathability is related to the size and number of pores within the fabrics. With the increase of the number and size of pores, air and moisture permeability increases. In a warm and humid environment, better breathability leads to a pleasant state of

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psychological and physical harmony of the human being with the clothing–body microclimate [4,5].

Knitted fabrics and knitwear are characterised by relatively simple production technology, low cost, high clothing comfort and a wide range of products. Knitting technology meets the rapidly changing requirements of the clothing market. Knitted fabrics are not only stretchy and offer freedom of movement, but also have a good handle and are very comfortable to wear due to their good air permeability and thermal conductivity. For this reason, knitted fabrics are often preferred for sportswear, casual wear and underwear [6].

The geometry of the knitted structure and the resulting performance characteristics of knitted fabrics are very complex and highly interdependent. Knitted fabrics can be highly extensible due to complex deformation mechanisms. Compared to woven structures, simple knitted structures do not exhibit good dimensional stability because they do not recover well from stretching and are subject to relaxation shrinkage, which begins as soon as the fabric is removed from the knitting machine and does not stop until the product has been washed or dry cleaned several times. Hydrophilic fibres such as cotton and wool may also undergo dimensional changes due to contact with water [7]. Stretching and relaxation affect the porosity of knitted structures, which in turn affects their comfort properties.

The thickness of the fabric is the most important variable that determines the rate of heat transfer and thus the so-called “warmth” of the fabric. The thickness of the fabric affects the air permeability and moisture absorption capacity. Air permeability is related to fabric cover factor, i.e. the ratio between the area covered by the yarn and the area covered by the fabric. The air permeability of knitted fabrics is generally much higher than that of woven fabrics. Since most textile fibres have very similar thermal conductivity coefficients, two main structural factors determine the thermal conductivity of fabrics: thickness and the extent to which the structure traps stationary air. Knitted fabrics are inherently much thicker than comparable woven fabrics, and the knitted loop encloses a cell in the fabric structure where air can be trapped under the right conditions. The combination of high thickness and a high volume of trapped air results in fabrics with low thermal conductivity, provided they are protected from wind pressure by windproof outer layers or shell fabrics [7]. Since different knitted structures have different thickness due to the spatial arrangement of the different loop elements (loop, tuck, miss, etc.) as well as the different porosity, a different amount of air can be trapped within the knitted structure, which affects the thermal conductivity.

The liquid transfer through textiles is usually a two-step process. First, the liquid wets the surface of the fabric and is absorbed by capillary action into the yarn and, in the case of hydrophilic polymers, into the fibre structure. Second, the liquid moves through the structure by a combination of diffusion and capillary wicking. Over time, the liquid that has migrated along the yarn capillaries evaporates and then diffuses into the air spaces of the fabric. If there is an air pressure gradient in the fabric, the liquid molecules in the air spaces will move through and out of the fabric. The more permeable the fabric, the higher the air flow for a given pressure gradient and therefore the greater the rate of liquid transfer [7]. Due to the porosity of the knitted structure on the one hand, and the geometry of the loop (the direction of the loop limbs) on the other, differences in liquid transfer in wale and course direction can be expected.

Against this complex background, knitted fabrics offer advantages in three main areas. First, the stretch properties of knitted fabrics provide better conformability and prevent excessive pressure and/or shear from occurring between the garment and the body surface. This is particularly important for underwear. Second, knitted fabrics offer significant insulation benefits. Third, knitted fabrics are good at wicking sweat away from the skin surface. This property enhances the advantage of natural stretchability in active sports applications [7]. It has been proven that different knitted structures have different comfort properties. Therefore, in order to achieve the ideal wearing comfort of clothing, it is necessary to consider the intended use of the garment when selecting fabrics [6].

2. FIREFIGHTERS CLOTHING

2.1 Complexity of Firefighters Clothing

Comfort features are especially important in extreme conditions, such as those experienced by firefighters. When selecting underwear for them, it is important that the knitted fabric be flame retardant, have good absorption properties that allow excess moisture and perspiration to evaporate, and have good thermal conductivity properties that affect thermal comfort [3-4, 8-9].

The effectiveness of firefighters depends, among other things, on the choice of protective clothing, which must meet the prescribed standards. It is of utmost importance that this clothing be fire, heat, and water vapour resistant, air permeable, and comfortable due to the hot environment, while providing unrestricted freedom of movement. The most common cause of serious injury and death to firefighters on the job is not skin injuries, but injuries related to heart attack or stroke due to excessive heat exposure [8]. Protective clothing is therefore essential for firefighters as they are exposed to a number of hazards. It should provide adequate protection from the expected hazards on the one hand and be comfortable on the other. When semi-permeable or impermeable moisture barriers are used for protective clothing, good protection from hazards is provided, but heat and moisture exchange between the human body and the environment is difficult.

This often leads to an increase in thermophysiological discomfort for firefighters working in hot environments for extended periods of time [10]. Since firefighter clothing design is a compromise between protection and comfort, it is important to improve the thermal and moisture comfort of clothing as much as the full thermal protection of firefighter clothing allows [11].

Typical protective clothing for firefighters consists of three or four different layers. The outer layer protects against all types of thermal hazards and mechanical impacts. It is made of flame-resistant material, usually produced by flame-retardant finishing or by using inherently flame-resistant materials. The fibers in flame resistant textiles are usually blended with other fibers to reduce production costs and improve comfort properties. The thermal barrier is an insulating layer that protects against heat. The moisture barrier protects against water and other fluids. It is the middle layer that prevents water vapor at high temperatures, chemicals and other pathogens from entering the clothing. The inner layer is used to increase thermal protection and protect the last layer from abrasion. It is a thermal liner that provides thermal protection to the wearer with its nonwoven or porous padding structure. Firefighter underwear is worn between the jacket and the skin, and a station uniform is also worn between the underwear and the firefighter jacket [12, 13].

Studies of the comfort properties of firefighter protective clothing are complex due to the inhomogeneous internal structure, coupled heat and moisture transfer, and other physical processes occurring at different space and time scales [13].

2.2. State of Research

Firefighters personal protective clothing is the only source of firefighter protection during firefighting operations. Protective clothing should provide adequate protection and be comfortable to wear. The requirements of protection and wearing comfort are always opposite in different protective clothing, including firefighters. The selection of appropriate materials, the design of the garments, and the final evaluation of the results play a critical role in predicting the performance and comfort of clothing. Several studies have been conducted to improve the performance and comfort of protective clothing for firefighters [14]. Few of these studies are related to underwear.

Onofrei et al [13] conducted studies to optimize the performance of firefighters protective clothing in terms of thermal comfort and protection of the skin from thermal injury due to exposure to low intensity thermal radiation. They developed a numerical model of heat transfer in protective clothing under low-intensity radiant heat exposure using Comsol Multiphysics® software. Three-layer fabrics were studied, and a 100% aramid knit coated with polyurethane was used for the moisture barrier. The model was limited to dry fabrics. The predicted temperature values agreed well with the corresponding experimental measurements.

Van den Eijnde et al [15] quantitatively investigated in vivo whether the skin barrier is compromised when wearing a fire jacket, which is an important trigger for increased percutaneous penetration. Immediately after wearing a firefighter jacket, transepidermal water loss values were significantly increased. This was indicative of an occlusive effect of the firefighter jacket. The skin barrier was fully restored at 30 minutes after occlusion with cellophane or wearing a firefighter jacket.

Wakatsuki et al [16] investigated whether synthetic underwear plays a significant role in moisture and metabolic heat transfer within firefighters clothing by measuring total heat loss. The total heat loss measurements were performed in accordance with the ASTM F-1868, Part C standard. Three types of firefighters clothing, one station garment, and five types of underwear were used for the test. The test was conducted for each garment and combination of garments. Underwear made of 100% cotton, cotton/polyester, and polyester/polyurethane blends were tested. The results showed that the heat loss of synthetic underwear was greater than the heat loss of underwear made of natural fibers.

Waatsuki et al [17] investigated how the wet condition of firefighters clothing compared to the dry condition during routine firefighting operations in a building caused faster heat transfer from pain sensation to second-degree skin burns. Cotton underwear generally worn by Japanese firefighters was studied. The results showed that the condition of the station clothing and the underwear when wet had a significant effect on the condition of the station clothing, while the effect of the underwear was small.

Petrusic et al [3] studied the liquid and water vapor transfer through different types of underwear and the innermost layers of the firefighter’s emergency jacket (linings). The moisture vapor transfer characteristics of single and double layer fabrics were investigated using the evaporative dish method. The results showed that the moisture management of the tested single- and double-layer fabrics was related to their composition and general physical properties. The composition of both the underwear and the inner lining has a decisive influence on the transport of liquid through two-layer fabrics. The transfer of water vapor is mainly determined by the physical properties of the fabric. The combination of natural and synthetic fibers results in fabrics that perform best in terms of moisture management. Interlock and pique knits made of cotton, cotton/modacrylic and aramid/viscose blends were studied.

More recently, Eryuruk et al [18] investigated the thermal comfort and moisture management of a firefighter garment with a new fire-resistant underwear. They analyzed the performance characteristics of single-layer fabrics (underwear, outer shell, moisture barrier, and thermal barrier) and their three- and four-layer combinations to better understand comfort and protective performance. The underwear fabrics studied were single jersey made of flame retardant viscose/para-aramid blend. The structure of the underwear fabric was found to have the highest capacity for fluid management and one-way transfer, allowing it to be classified as a "fast absorbing and quick- drying fabric." The general conclusion of the very complex and thorough study was that the heat and moisture transfer properties of fabrics decrease as the number of fabric layers increases. On the other hand, the use of new fire-resistant underwear fabrics has a positive effect, as they improve the heat and moisture transport properties of the layered fabric structure.

Also in 2022, Stygiene et al [19] investigated the flammability and thermal comfort of two-layer knitted fabrics. Two groups of aramid and flame retardant viscose knitted fabrics with different combination patterns and surface structures (porosity and flatness) were designed and manufactured (different variants of double tuck structures). Aramid fiber spun yarns formed the inner layer in contact with human skin, and aramid/flame retardant viscose formed the outer layer. The results showed that all the fabrics tested were non-flammable, breathable and air-permeable, and could be classified as moisture management fabrics. The knitted fabrics with embossed porous surface to the skin had higher overall moisture management capacity. The thermoregulatory comfort properties were mainly influenced by the structure of the fabrics, while the burning behavior was independent of the structure and the flame retardancy was mediated by the fiber content of the knitted fabrics.

2.3 Research Objective

Since underwear is an important part of firefighters' clothing system, the aim of the research was to investigate the comfort and flame retardant properties of knitted fabrics potentially suitable for knitted firefighters' underwear. Based on previous studies, several influencing parameters were considered for experimental design.

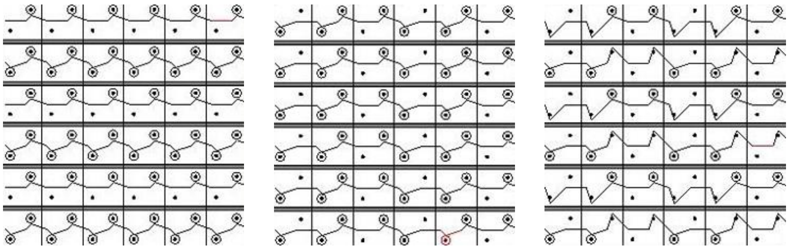
- Knitted structures and yarn composition significantly influence thermal comfort properties. Good thermal and moisture transport properties promote the cooling property of the fabric [5].
- Air permeability is a function of knitted fabric thickness, tightness factor, and porosity [20].
- Weight and material combinations are important parameters to optimize both functional and comfort properties [12].
- Firefighters' ensembles combined with inner garments made of cellulose (linen) can provide a better thermal and clingy sensation when working in high temperature environments [11].

Previous studies have mainly investigated knitted fabrics for firefighters' underwear made of cotton, flame retardant viscose and aramid, and their blends. Single, interlock, and single and double tuck structures have been primarily investigated. In contrast to the previous studies summarized above, the present study investigated half-Milano knit structures (flat surface) and 2x2 rib and 2x2 cardigan rib structures (textured surface) made of flame retardant modacrylic blends in comparison with natural (cotton) and regenerated cellulosic fibers (Lyocell, Micromodal).

3. MATERIAL AND METHOD

3.1 Material

To investigate comfort and flame-retardant properties, knitted fabrics of four different materials (combed cotton, Tencel, Micromodal, and a blend of 15% Polyacrylate, 30% Tencel, and 55% Modacryl-tayrilane (T334)) were made in three different double-jersey types (Figure 1, Table 1), so a total of 12 knitted fabrics were designed and produced on the Shima Sheiki SES 122 RT knitting machine, gauge 12 E, using the same yarn feed tension, cam setting, and take-down tension for all knitted samples. The design of the technical pattern and the creation of the control programme were carried out by Shima Seiki SDS-ONE. All knitting yarns had the same linear density of 15 tex.



Half-Milano - DJ1 2x2 rib - DJ2 2x2 cardigan rib - DJ3

Figure 1. Yarn path notation of the investigated knitted structures

Table 1. Designation of knitted samples

Sample code	Material	Material code	Knitted structure	Structure code
1	100 % Combed cotton	CO	Half-Milano	DJ1
2	15 % Polyacrylate 30 % Tencel 55 % Modacryl-Tayrilan	T334	Half-Milano	DJ1
3	100 % Tencel	Tencel	Half-Milano	DJ1
4	100 % Micromodal	Micromodal	Half-Milano	DJ1
5	100 % Combed cotton	CO	2x2 rib	DJ2
6	15 % Polyacrylate 30 % Tencel 55 % Modacryl-Tayrilan	T334	2x2 rib	DJ2
7	100 % Tencel	Tencel	2x2 rib	DJ2
8	100 % Micromodal	Micromodal	2x2 rib	DJ2
9	100 % Combed cotton	CO	2x2 cardigan rib	DJ3
10	15 % Polyacrylate 30 % Tencel 55 % Modacryl-Tayrilan	T334	2x2 cardigan rib	DJ3
11	100 % Tencel	Tencel	2x2 cardigan rib	DJ3
12	100 % Micromodal	Micromodal	2x2 cardigan rib	DJ3

3.2 Method

Physical properties of knitted fabrics

For the study, the physical properties of horizontal and vertical density before and after washing, dimensional stability, mass per unit area (SIST EN 12127: 1999 - Determination of mass per unit area using small samples) and thickness (SIST EN ISO 5084 - Determination of thickness of textiles and textile products) were measured according to the standards. The knitted fabrics were washed at 40°C with a mild detergent without optical brighteners and dried on a flat surface according to the standard ISO 6330 - Domestic washing and drying procedures for textile testing. All permeability properties of knitted fabrics were measured after washing, because knitted fabrics for underwear are always washed before use.

Permeability properties of knitted fabrics

Air permeability was measured using the Air Tronic, (Mesdan-Lab, Italia) with a test area of 50 cm^2 and a pressure drop of 20 Pa. Five measurements were made for each sample. The low pressure drop was chosen because knitted fabrics are very porous and breathable and this preasure was the most appropriate for measuring air permeability of all the knitted fabrics tested.

The water method was used to measure the water vapour permeability. It was measured according to the American standard ASTM: E96-00 - Standard Test Methods for Water Vapor Transmission of Materials [21]. In the water method, the dish contains distilled water, and the weights determine the rate of vapour movement through the sample from the water to the controlled atmosphere. Standard atmosphere conditions were used, 20°C±2 and 65±4% relative humidity. This test simulates the flow (velocity) of water vapour from the skin surface through the clothing layers to the environment.

Two parallels were made for each sample. 7 ml of distilled water was poured into the dish, covered with the sample, and a lid with a hole in the centre was placed. The prepared samples were left to stand at room temperature and humidity for one hour and weighed. Then the samples were placed in the chamber under standard conditions (20°C±2 and 65±4% relative humidity) and weighed again after twenty-four hours.

The water vapour transmission rate (WVT) was calculated using the following equation:

$$WVT = \frac{m}{S \cdot t} \tag{1}$$

where m is weight change before and after climatization (g), S is test area of samples (m^2) – the diameter of the hole in the lid is 3 cm, and T is time during weight change (h).

The thermal conductivity of the samples was measured using a comparative method using standard DIN 52 612-1 - Testing of thermal insulating Materials; Determination of thermal conductivity by the Guarded Hot Plate Apparatus; Test Procedure and Evaluation. The measurement of thermal conductivity is based on the transport of heat flow from a warmer to a colder region, from the bottom of the apparatus to the top. The massive frame of the apparatus has the insulating plate on top and bottom. On the plate on the bottom the tick copper plate is placed, with temperature 60°C. On that plate, the reference glass plate with known thermal conductivity is put, then a thin cooper plate. After that a sample is placed and finally, a cooler cooper plate with pemperature 20°C is added. On the top it is insulating plate. Between the blocks the sample with an area of 100 cm^2 is put. Both blocks and three measuring cooper plates are connected to the temperature measuring device via thermoelements. The entire system is isolated. The heat flow passes through the reference glass plate and fabrics tested sample. The resulting temperature differences were measure with thermoelements in three cooper plates, where temepratures T_1, T_2, T_3 were read from the apparatus. Equation (2) is used to calculate the thermal conductivity λ_x. The thermal conductivity is inversely proportional to the temperature differences between the blocks [22].

$$\lambda_x = \lambda_n \cdot \frac{d_x}{d_n} \cdot \frac{(T_3 \cdot T_2)}{(T_2 \cdot T_1)} \tag{2}$$

where λ_x is the thermal conductivity of a sample, λ_n is the thermal conductivity of the glass plate (λ_n = 1.0319 W/mK), d_x is the thickness of the sample, d_n is the thickness of the reference glass plate (4 mm), T_2 is the temperature of the cooler thick copper plate, T_3 is the temperature of the middle thin copper plate and T_4 is the temperature of the warmer thin copper plate.

Wetting was evaluated using the sinking test method based on the standard method EN 14697:2005 - Textiles - Terry towels and terry towel fabrics - Specification and methods of test, Annex B - Determination of the time of absorption. The time required for a piece of fabric to sink completely out of the surface layer of water in a beaker was measured. For this purpose, a 3 × 3 cm piece was cut out of the fabric and placed on the surface layer of water in a 500 ml beaker. The wetting time was estimated with a stopwatch as the time interval between the moment of immersion and the moment when the sample had sunk below the water level. Each experiment was performed at least three times [23, 24].

Flame retardancy of knitted fabrics

Flammability tests were performed in accordance with the standard ISO 15025 - Protective clothing – Protection against flame – Method of test for limited flame spread. A 20 × 16 cm sample was placed vertically in a combustion chamber. The vertical flammability test was used because it is used for testing garments that are normally worn vertically. The samples were exposed to a direct flame for 10 seconds, then the burner was removed and the burning time was observed. Three measurements were made for each sample.

Statistical evaluation

The experimental results (physical properties, dimensional stability, air permeability, thermal conductivity, water vapour permeability, wetting, and the results of the flame retardancy test) were statistically analysed using the multifactor ANOVA at a significance level of 0,05. Two independent variables - factors were selected for the statistical analysis: the knitted structure and the material used for knitted fabrics. The material factor had four levels and the knitted structure factor had three levels (Table 2). The experimental results were evaluated to determine which of the design parameters (factors) was statistically important and to what extent.

4. RESULTS AND DISCUSSION

4.1 Physical Properties of Tested Knitted Fabrics

The results of the measurement of physical properties are shown in Table 3. The results of the statistical evaluation of the multifactorial ANOVA for the physical properties - horizontal and vertical density, shrinkage in horizontal and vertical direction - are presented in Tables 4, 5, 6 and 7.

Table 2. Experimental design diagram

Factor	Level
Material	100 % Combed cotton (CO)
	100 % Tencel (Tencel)
	100 % Micromodal (Micromodal)
	15 % Polyacrylate, 30 % Tencel, 55 % Modacryl-Tayrilan (T334)
Structure	half-Milano (DJ1)
	2x2 rib (DJ2)
	2x2 cardigan rib (DJ3)

Table 3. Physical properties of tested knitted samples (fabric horizontal and vertical desnity, fabric shrinkage after washing, fabric thickness and mass per unit area)

Sample	Fabric density before washing				Fabric shrinkage after washing (%)		Fabric thickness (mm)		Fabric mass per unit area (g/m^2)	
	Dh (wales/5 cm)		Dv (courses/5 cm)							
	$\overline{x}$	CV (%)	$\overline{x}$	CV (%)	horizontal	vertical	$\overline{x}$	CV (%)	$\overline{x}$	CV (%)
1	65.2	1.50	33.0	3.83	-13.30	-25.34	1.58	0.92	395.4	1.24
2	66.8	1.46	30.8	2.42	-2.91	-12.50	1.35	2.47	326.1	3.21
3	65.2	1.50	31.4	3.24	-5.23	-22.28	1.43	2.55	342.4	2.81
4	67.2	1.45	33.4	2.39	-3.45	-17.73	1.30	2.80	350.6	1.47
5	81.2	0.49	42.4	3.19	7.98	-24.01	1.95	3.86	365.6	5.97
6	85.2	0.46	48.0	3.48	15.14	-1.64	1.79	5.39	361.7	1.86
7	85.6	2.03	49.4	2.74	46.58	-2.76	1.40	7.54	277.1	6.67
8	87.2	4.88	46.6	3.98	34.98	-0.43	1.11	10.86	268.3	2.84
9	47.2	3.64	38.8	1.92	-5.22	-9.35	1.80	3.12	340.1	5.12
10	55.8	1.75	35.4	1.38	27.98	-14.90	1.50	5.49	292.3	3.94
11	46.6	3.21	38.2	1.04	7.37	-11.98	1.38	3.41	280.1	4.66
12	52.0	0.00	35.4	1.38	17.12	-18.81	1.21	5.83	272.8	3.63

All knitted fabrics were made with the same set density (yarn feed tension, cam setting, and take-down tension), but have different degrees of relaxation after knitting due to differences in knitted structure. This affects the different horizontal (Dh) and vertical density (Dv) of the knitted samples. The vertical density of the knitted fabric is a reflection of the cam setting (couliereing depth), which was the same in all samples studied, and the knitted structure (arrangement of the loop elements, i.e. different loop types). The half-Milano structure (DJ1) consists of an alternating course of short and a course long loops. The 2x2 rib (DJ2) consists only of courses of regular loops, and the 2x2 cardigan rib (DJ3) consists of courses of long loops. Both rib structures shrink strongly in the cross direction after knitting. Using the multifactor ANOVA, it was confirmed that the knitted structure in the horizontal (structure is 75 times more important) and vertical (structure is 126 times more important) directions is a much more important factor than the material (Table 4, Table 5), as shown by the F-ratio. Multifactor ANOVA also shows that the two factors Material and Structure are statistically significant at 95% confidence level.

After washing, some samples shrank and others expanded. The multifactor ANOVA confirmed that the structure has almost 4 times more influence on the dimensional stability of the knitted samples than the material in the horizontal direction and 2 times more influence in the vertical direction (Table 6 and Table 7).

The highest shrinkage was observed in the cotton samples in both directions, horizontal and vertical. In the horizontal direction, there is a statistically significant difference between cotton and all other materials, Tencel, Micromodal and a blend of Tencel, Polyacrylate and Modacryl-Tayrilan. These three materials are more dimensionally stable than cotton knitted samples and have statistically the same properties. In the vertical direction, there is no statistically significant difference between the samples made of Tencel and Micromodal, as both are regenerated cellulose fibres, while there is a statistically significant difference between the samples made of cotton and a blend of Tencel, Polyacrylate and Modacryl-Tayrilan (T334), as this blend contains synthetic fibres that are more dimensionally stable than cotton.

Statistically significant differences are found between all three structures in the horizontal and vertical directions. The highest change in dimensional stability is obtained for the structure half-Milano (DJ1), which consists of an alternating course of short and a course of long loops, and the lowest for the structure 2x2 rib (DJ2), which consists only of short loops, both in the horizontal and vertical directions. Long loops are created during knitting process by bending and stretching the yarn and relax after knitting, resulting in greater shrinkage compared to short loops.

The cotton samples were the thickest and had the highest mass per square meter. Micromodal samples had the least thickness and mass per square meter. Again, shrinkage during washing affected the thickness and mass per unit area of the samples tested.

4.2 Permeability Properties of Tested Knitted Fabrics

The permeability properties of fabrics are very important for the comfort of the user, especially under extreme conditions. Table 8 and Figures 2 to 5 show the permeability properties (air permeability, thermal conductivity, water vapour permeability and wetting) of the tested knitted samples. Tables 9 to 12 show the statistical evaluation of the multifactorial ANOVA.

Table 4. Effect of material and structure on horizontal density (Dh) of knitted fabrics

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	237,9	3	79,31	24,16	0,0000
B:Structure	11863,6	2	5931,8	1806,64	0,0000
Interactions					
AB	158,3	6	26,38	8,03	0,0000
RESIDUAL	157,6	48	3,28		
TOTAL	12417,4	59			

Table 5. Effect of material and structure on vertical density (Dv) of knitted fabrics

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	25,8	3	8,6	5,52	0,0024
B:Structure	2166,43	2	1083,22	695,11	0,0000
Interactions					
AB	183,7	6	30,62	19,65	0,0000
RESIDUAL	74,8	48	1,56		
TOTAL	2450,73	59			

Table 6. Effect of material and structure on shrinkage in horizontal direction

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	4078,5	3	1359,5	78,24	0,0000
B:Structure	10539,3	2	5269,67	303,26	0,0000
Interactions					
AB	4021,36	6	670,226	38,57	0,0000
RESIDUAL	834,07	48	17,3765		
TOTAL	19473,3	59			

Table 7. Effect of material and structure on shrinkage in vertical direction

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	820,45	3	273,48	23,34	0,0000
B:Structure	1511,6	2	755,81	64,50	0,0000
Interactions					
AB	1807,88	6	301,31	25,71	0,0000
RESIDUAL	562,49	48	11,72		
TOTAL	4702,4	59			

SS – Sum of squares, Df - Degrees of freedom, MS - Mean squares

From Figure 2 and the multifactor analysis ANOVA (Table 9), which was performed based on the obtained test results shown in Table 8, it can be concluded that the air permeability properties depend on both the material used and the knitted structure. Both factors have a statistically significant effect on air permeability, as the p-value is less than 0.5. The material used is twice as important factor as the structure, as shown by the F-ratio. ANOVA also confirms that the materials are significantly different from each other. Cotton knitted samples have the lowest air permeability because they shrink the most after washing. Fabrics made from a blend of Tencel, Polyacrylate and Modacryl-Tayrilan have the second lowest air permeability.

Tencel fabrics have the highest air permeability because these fabrics extend after washing and therefore have a more open structure than cotton fabrics and fabrics made from a blend of Tencel, Polyacrylate and Modacryl-Tayrilan.

The half-Milano (DJ1) structure has the lowest air permeability among all three structures, due to the compact structure composed of a course knitted on all nedles of both needle beds and a course knitted on a single needle bed. That makes the half-Milano (DJ1) structure clearly different from the 2x2 rib (DJ2) and 2x2 cardigan rib (DJ3) structures, which statistically have the same effect on air permeability, as well as the more porous structure. 2x2 cardigan rib (DJ3) structure is composed of long loops and tucks which make it less compact than regular 2x2 rib structure (DJ2).

The results also clearly show that washing, i.e. (textile) care, has an important influence on the dimensional changes of the knitted structure, i.e. its compactness, which in turn affects the air permeability of the knitted fabric and its comfort properties.

Thermal conductivity is an important property that shows how heat passes through the material. The thermal insulation of textiles depends not only on the thermal conductivity of the material used, but also on the volume of air contained in the textile, which depends on its structure and thickness.

The multifactor ANOVA shows (Table 9) that both factors: material used and structure are statistically significant, with the p-value for both factors being 0.0. The material used is almost 15 times more important than the structure, as shown by the F-ratio.

The results show (Figure 3) that knitted cotton samples have the highest thermal conductivity (about 0.16 W/mK), while knitted Tencel, Polyacrylate and Modacrylic-Tayrilan samples have the lowest thermal conductivity (about 0.1 W/mK), and knitted Tencel and Micromodal samples have almost the same thermal conductivity (about 0.12 W/mK). ANOVA confirms that there is no statistically significant difference between knitted farbrics made from Tencel and Micromodal, as both are regenerated cellulose fibres.

Using the multifactor ANOVA, it was also confirmed that there is a statistically significant difference between all three structures. Knitted samples with structure half-Milano (DJ1) have the highest thermal conductivity and knitted samples with structure 2x2 cardigan rib (DJ3) have the lowest thermal conductivity. The 2x2 cardigan rib (DJ3) knit is thicker than the half-Milano (DJ1) and at the same time more voluminous, therefore it encloses more air in its structure.

The statistical analysis of the results of water vapour permeability with the multifactor ANOVA (Table 11) shows that the material used and the structure are statistically significant factors, since the p-value is less than 0.05. It was also confirmed that the material used is a twice as important factor as the structure factor, since the F-ratio of the material factor is twice that of the structure factor.

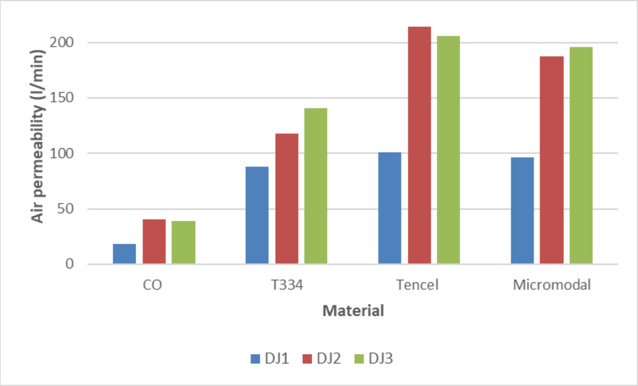


Figure 2. Air permeability test results of the knitted samples

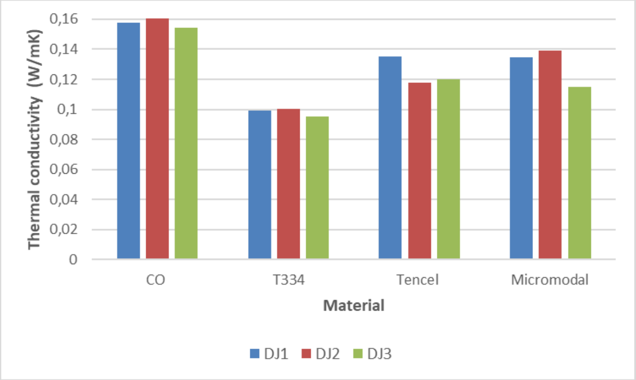


Figure 3. Thermal conductivity test results of the knitted samples

The results on water vapour permeability presented in Table 8 and Figure 4 show that knitted samples made of Micromodal have the highest water vapour permeability, while knitted fabrics made of Tencel, blend of Tencel, Polyacrylate and Modacryl-Tayrilan and cotton have the lowest. The fibre fineness of Micromodal affects the water vapour transport through the knitted structure. The results show that there is no statistical difference between Tencel, blend of Tencel, Polyacrylate and Modacryl-Tayrilan and cotton, which means that the water vapour permeability is statistically the same for these samples.

Samples knitted in structure half-Milano (DJ1) have the lowest water vapour permeability because they are the most compact due to the arrangement of the half-Milano loops, while samples knitted in structure 2x2 cardigan rib (DJ3) have the highest water vapour permeability due to the arrangement of the loops and tucks. ANOVA confirms that there are statistically significant differences between structures half-Milano (DJ1) and 2x2 cardigan rib (DJ3).

Table 8 and Figure 5 show the results of the wetting test. Statistically, only the material factor has a significant effect on the wetting of the knitted fabric, as the p-value is less than 0.05, and the structure of the knitted fabric is not statistically significant as shown in Table 12. In the study, 100% combed raw cotton was used, which is difficult to wet out and therefore was not considered in the presentation of the results and the discussion (Figure 5). Statistical analysis shows that there is no significant difference between Micromodal and Tencel, as both are regenerated cellulose fibres. It takes about 4 to 5 seconds for these materials to wet and sink in. There is a significant difference between the blend of Tencel, Polyacrylate and Modacryl-Tayrilan and Micromodal and Tencel. The blend of Tencel, Polyacrylate and Modacryl-Tayrilan takes 7 to 8 seconds to get wet and sink in. Depending on the type of knitted structure, it can be seen that structures with a more open surface such as 2x2 cardigan rib (DJ3), which consists of loops and tucks, are wetted more quickly than more compact structures.

Table 8. Permeability properties (air permeability, thermal conductivity, water vapour permeability, wetting) and flame retardency of tested knitted samples

Sample	**Air permeability** (20 Pa, 50 cm²)		**Thermal conductivity** (W/m K)		**Water vapour permeability** (g/m^2h)		**Wetting** (s)		**Flame retardancy** (s) **horizontal**		**Flame retardancy** (s) **vertical**	
	$\bar{x}$	CV	$\bar{x}$	CV	$\bar{x}$	CV	$\bar{x}$	CV	$\bar{x}$	CV	$\bar{x}$	CV
1	18,56	6,02	0,15	4,10	82,19	2,12	/	/	80	3,28	72	3,66
2	88,20	4,79	0,09	0,98	78,60	2,21	7,012	7,22				
3	101,30	8,06	0,13	2,94	71,36	14,31	4,528	2,42	80	2,70	51	7,95
4	96,56	6,38	0,13	3,65	78,96	0,45	4,652	4,33	72	1,96	80	6,26
5	40,76	7,66	0,16	1,33	75,13	2,85	/	/	65	10,10	71	6,09
6	117,74	7,70	0,10	2,85	73,45	5,92	8,442	16,82				
7	214,34	1,19	0,11	0,96	75,52	2,35	3,538	4,62	46	5,38	48	7,80
8	187,54	1,35	0,11	3,20	97,29	6,19	3,828	4,04	63	4,88	59	8,39
9	39,16	14,24	0,15	0,59	85,25	4,27	/	/	51	6,1	57	2,20
10	140,86	7,34	0,09	0,58	80,45	5,16	6,690	11,33				

11	205,50	7,88	0,11	3,09	83,70	3,20	4,210	10,85	52	6,3	57	3,63
12	195,82	3,48	0,11	2,94	85,48	4,46	4,200	1,48	64	5,84	71	4,60

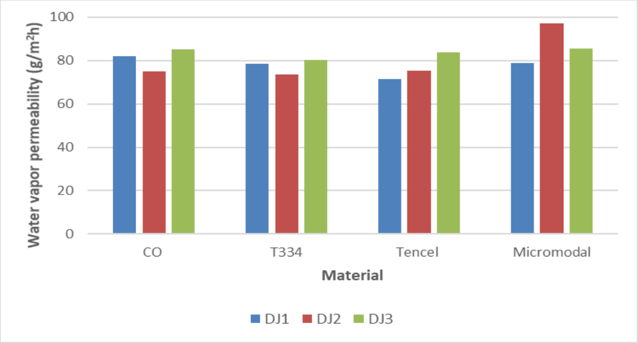


Figure 4. Water vapour permeability test results of the knitted samples

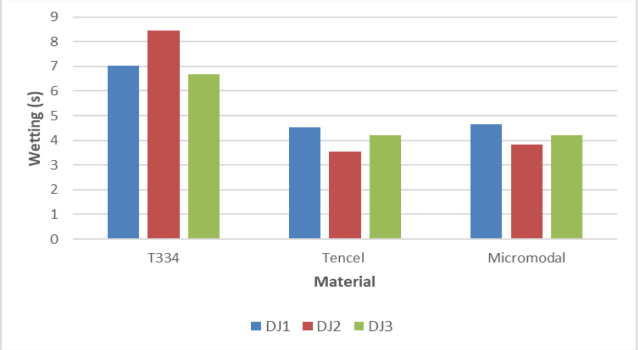


Figure 5. Wetting time test results of the knitted samples

Table 9. Effect of material and structure on air permeability of knitted fabrics

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	181506,	3	60502,1	858,69	0,0000
B:Structure	59344,4	2	29672,2	421,13	0,0000
Interactions					
AB	19009,4	6	3168,24	44,97	0,0000
RESIDUAL	3382,0	48	70,4584		
TOTAL	263242,	59			

Table 10. Effect of material and structure on thermal conductivity of knitted fabrics

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	0,0155	3	0,0052	436,16	0,0000
B:Structure	0,0007	2	0,0003	29,36	0,0000
Interactions					
AB	0,0009	6	0,0002	12,71	0,0000
RESIDUAL	0,0003	24	0,00002		
TOTAL	0,0174	35			

Table 11. Effect of material and structure on water vapour permeability of knitted fabrics.

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	522,02	3	174,06	12,03	0,0001
B:Structure	189,73	2	94,87	6,56	0,0061
Interactions					
AB	631,87	6	105,31	7,28	0,0003
RESIDUAL	303,86	21	14,47		
TOTAL	1532,94	32			

Table 12. Effect of material and structure wetting of knitted fabrics.

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	20,79	2	10,39	17,42	0,0106
B:Structure	0,20	2	0,102	0,17	0,8484
RESIDUAL	2,39	4	0,596		
TOTAL	23,38	8			

SS – Sum of squares, Df - Degrees of freedom, MS - Mean squares

4.3 Flame Retardancy of Tested Knitted Fabrics

The results of the vertical flame retardancy test (Table 8, Figures 6 and 7) show that the blend of Tencel, Polyacrylate and Modacryl-Tayrilan is a truly flame retardant material. This was to be expected since the LOI of the blend is between 32 and 34. The other conventional materials used (cotton, Tencel and Micromodal) are flammable but were included in the study because they are often used for underwear due to their good comfort properties. They were also investigated in some previous studies of underwear for firefighters [3, 16].

The analysis of the results with the multifactor ANOVA, presented in Tables 13 and 14, shows for the other three conventional materials (cotton, Tencel and Micromodal) that both factors, the material used and the structure, are statistically significant in the horizontal direction, while in the vertical direction only the material used is statistically significant. In the horizontal direction, the structure is statistically three times more important than the material used, as shown by the F-ratio.

There is also a statistically significant difference between structures half-Milano (DJ1) and 2x2 rib (DJ2) and 2x2 cardigan rib (DJ3), while there is no statistically significant difference between structures 2x2 rib (DJ2) and 2x2 cardigan rib (DJ3). Half-Milano (DJ1) is a compact rib structure with no visible vertical ribs, while 2x2 rib (DJ2) and 2x2 cardigan rib (DJ3) are both true vertical rib structures. Samples in structure 2x2 cardigan rib (DJ3) burn the fastest, and samples in structure 2x2 rib (DJ2) burn almost as fast as in 2x2 cardigan rib (DJ3). Knitted samples in structure half-Milano (DJ1) burn the slowest. Samples 2x2 rib (DJ2) and 2x2 cardigan rib (DJ3) have distinct ribs - stripes in the vertical direction, which affects the spread of the flame in the vertical direction.

The results show that of the conventional, non-flame retardant materials, the knitted samples made of Micromodal burn the slowest in the horizontal direction, while samples made of cotton and Tencel burn faster, with no statistically significant difference.

Also, in the vertical direction, samples made of

Micromodal burn the slowest and Tencel the fastest among the conventional, non-flame retardant materials. It was found that there are statistically significant differences between all three materials used (cotton, Tencel and Micromodal). However, in the vertical direction, there are no significant differences between the structures.

Table 13. Effect of material and structure on flame retardancy in horizontal direction of knitted fabrics

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	1205,56	2	602,78	5,96	0,0103
B:Structure	3853,56	2	1926,78	19,06	0,0000
Interactions					
AB	666,89	4	166,72	1,65	0,2056
RESIDUAL	1820,0	18	101,11		
TOTAL	7546,0	26			

Table 14. Effect of material and structure on flame retardancy in vertical direction of knitted fabrics

Source	*SS*	*Df*	*MS*	*F-Ratio*	*P-Value*
Main effects					
A:Material	2048,3	2	1024,15	12,97	0,0003
B:Structure	125,41	2	62,70	0,79	0,4672
Interactions					
AB	1441,48	4	360,37	4,56	0,0101
RESIDUAL	1421,33	18	78,96		
TOTAL	5036,52	26			

SS – Sum of squares, Df - Degrees of freedom, MS - Mean squares

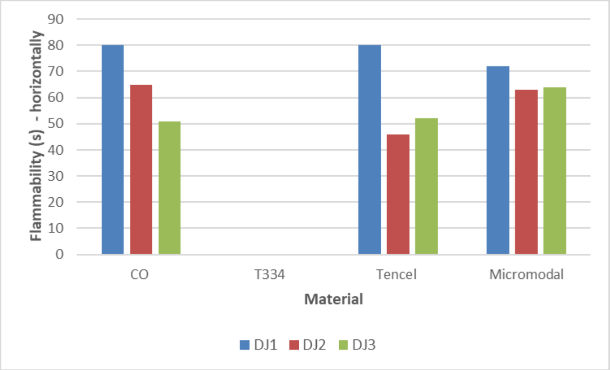


Figure 6. Flammability test results in horizontal direction of the knitted samples

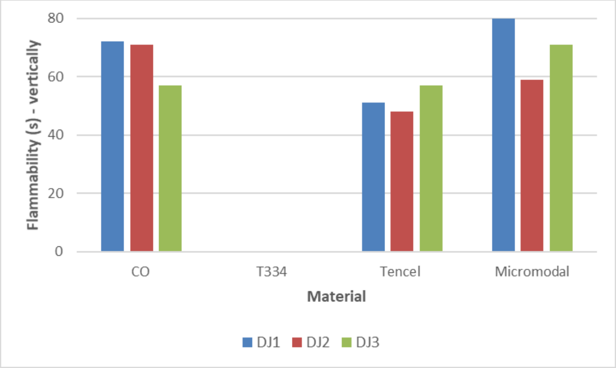


Figure 7. Flammability test results in vertical direction of the knitted samples

The acceptability of firefighters' protective clothing depends on both protective performance and wearer comfort. However, these two requirements are contradictory. Clothing should protect against flames and prevent heat from entering the body from the outside. When firefighters are exposed to heat stress, their bodies respond by activating sweat glands, i.e., the mechanism of evaporative cooling. Protective clothing protects firefighters from heat and moisture from the environment while preventing their flow in the opposite direction, away from the body into the environment. It should allow the outflow of excessive metabolic heat, indicating low thermal resistance and high water vapour permeability. At the same time, any protective clothing must keep moisture away from the firefighters skin to prevent skin burns and provide comfort. The problem with air-permeable fabrics is that they can allow water to penetrate the structure. Materials designed to facilitate metabolic heat loss are not necessarily the same as those required for thermal insulation and waterproofing. Therefore, these requirements can lead to a paradox between comfort and protection. In hot environments, the heat and moisture transfer characteristics of protective clothing have the greatest impact on firefighter performance and safety. Optimising these transfer phenomena from the skin through the protective clothing could improve the comfort of the wearers and thus their performance. Effective protective clothing should minimise heat stress while providing protection [14, 25, 26].

It should be taken into account that knitted underwear is very stretchable; it expands on the body and with stretching its structure changes along with porosity (horizontal and vertical structure density), thickness and mass per unit area, which affects comfort and permeability properties. At the same time, knitted garments shrink after washing, and the shrinkage is most noticeable after the first washing cycle, i.e. between the purchase and first wearing cycle. Therefore, it is of utmost importance that the knitted underwear is designed shrinkage-free and that the correct garment size is chosen to prevent excessive change in the knitted structure during wearing.

It should also be remembered that the underwear is only one layer of the complex firefighting protective clothing and comes into contact with the skin; it must protect the skin and at the same time be comfortable to touch and wear.

5. CONCLUSIONS

The results of the study show how the materials used for the knitted fabrics and their structure affect the permeability and flammability of the fabrics and how the properties of the conventional materials such as cotton, Tencel and Micromodal differ from a flame retardant material blend of Tencel, Polyacrylate and Modacryl-Tayrilan, that could be used for the firefigthers underwear.

The study first examined the physical properties of the knitted fabrics with different material composition and structure. It was found that the structure is statistically the most important influencing factor in the analysis of horizontal and vertical density of knitted fabrics. The structure of knitted fabrics is also statistically more important in the analysis of dimensional stability of knitted fabrics after washing. The highest change in dimensional stability was found in the cotton fabrics in both horizontal and vertical directions. The knitted fabrics made of the blend of Tencel, Polyacrylate and Modacryl-Tayrilan are more dimensionally stable than the knitted fabrics made of Micromodal and Tencel. The highest change in dimensional stability is obtained for structure half-Milano (DJ1) and the lowest for structure 2×2 rib (DJ2) in both horizontal and vertical directions.

On the air permeability of the samples, both factors have statistically significant effects, but the material used is statistically more significant. All four materials (cotton, Tencel, Micromodal and blend of Tencel, Polyacrylate and Modacryl-Tayrilan) are statistically significantly different from each other. Cotton knitted fabrics have the lowest air permeability and Tencel knitted fabrics have the highest.

In the analysis of thermal conductivity, it was found that the material used and the structure are statistically significant, but the material used is more important than the structure. Cotton fabrics have the highest thermal conductivity, while the knitted fabrics made of Tencel, Polyacrylate and Modacryl-Tayrilan have the lowest thermal conductivity. Statistical analysis also shows that there is a statistically significant difference between all three knitted structures (half-Milano, 2x2 rib and 2x2 cardigan rib).

A statistically more important factor in the analysis of water vapour permeability is the material used rather than the structure. Micromodal has the highest water vapour permeability, while knitted fabrics made of Tencel, blend of Tencel, Polyacrylate and Modacryl-Tayrilan have the lowest.

A statistically significant factor in the analysis of wetting is only the material. Knitted fabrics made from a blend of Tencel, Polyacrylate, and Modacryl-Tayrilan require more time to sink in than Micromodal and Tencel.

It was found that the blend of Tencel, Polyacrylate and Modacryl-Tayrilan is a flame retardant material suitable for the manufacture of firefighters' underwear. The material used and the structure, are statistically significant factors in the horizontal direction, while in the vertical direction only the material used is statistically significant in the analysis of flammability. The results show that knitted fabrics made of Micromodal burn the slowest in the horizontal direction, while the fabrics made of cotton and Tencel burn the fastest.

From the test results, it can be concluded that the blend of Tencel, polyacrylate and Modacryl-Tayrilan is a truly flame retardant material suitable for firefighters underwear and also has good comfort properties. However, due to the contradiction between comfort and protection properties and the fact that the underwear is only one of the layers in a multi-layer protective clothing system for firefighters, further investigations of the knitted fabrics made of yarn blend with Modacryl-Tayrilan in the studied structures in combination with outerwear layers made of different fire protection materials should be carried out.

Acknowledgement

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