High-tech Sports Clothing With a High Comfort of Use Made from Multi-layer Composite Materials

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Abstract
Materials designed for the manufacture of sports clothing must meet many different requirements regarding barrier characteristics, comfort of use and service life. To satisfy such requirements, the materials used must consist of specially designed multi-layer textile-polymer composite systems with appropriately selected properties for each layer. The internal layer, or one of the internal layers, consists mostly of special polymeric membranes that provide high water-tightness and windproof capability. At the same time, this layer should show good respiration properties determined by water vapour permeability. As part of the studies carried out in the Institute of Textile Materials Engineering, a set of component materials have been developed and made for particular layers, as have model multi-layer composite materials for sports clothing to be used under different climatic conditions. The paper presents some examples of component materials and model multi-layer composite systems made from them, as well as the test results. The analysis of the results was used to establish relationships between the component materials and the resultant composite materials. The test results presented confirm that the multi-layer composite materials are characterised by both very good protective and hygienic properties.

Key words: *sports clothing, comfort of use, multi-layer composite materials, barrier properties, water vapour permeability, resistance of water vapour, thermal resistance, water-tightness, windproof property, microporous coats, polymeric membranes.*

Textiles designed for sports clothing should perform several very different, and even mutually excluding, functions. On the one hand, they must protect their users against heat loss, overheating or soaking, and on the other hand they must meet high requirements in respect of product durability, as well as many other properties contributing to the comfort of use [2]. First of all, such characteristics include:

- protective properties against variable atmospheric conditions existing during the clothes' use, as well as protection against physical damage,
- a high resistance to external influences, including tear strength, resistance to abrasion, shape stability, colour fastness, making-up quality, constancy of protective functions, and other features contributing to the service life of such materials,
- comfort-providing properties, generally described as wellness, including first of all physiological comfort [1]. This includes protection against over-warming or -cooling, owing to high water vapour permeability, i.e. carrying off perspiration, good warmth retention and adequate air permeability. Moreover, the user's feeling is positively affected by soft handle and good shape assumption by the fabric and cloth cut that does not limit the user's ease of movement, as well as the cloth's aesthetic appeal and practical constancy of protective and aesthetic functions throughout the period of use.

It is rather difficult to make all the mentioned features compatible, and optimised solutions can be found only by using composite materials, i.e. multi-layer systems with appropriately selected types and characteristics of the component materials used to manufacture clothing of that type.

Scope of investigation

Within the project undertaken at the Institute of Textile Materials Engineering [6], a complete range of all basic component materials has been developed and constructed, followed by testing to determine their technical parameters and hygienic properties. Based on the results obtained, some model multi-layer composite systems were selected for various final end-uses under different conditions, including during the summer and autumn-winter seasons.

The paper will firstly focus on the test results concerning the physiological comfort of use. and the effects of the structures & properties of exemplary system components (as well as some selected combinations) on developing these properties in model multi-layer systems.

The multi-layer model system

The model systems consist of three layers: an external or top layer, a middle layer that functions as a barrier, and a back layer. usually described as the lining. These layers are joined together, either by the technique of point laminating or while making up the clothing, to form a specific multi-layer composite material [5].

The **top layer** must show good physical and mechanical properties to provide durable protection of the user against all external, mechanical and atmospheric effects, as well as great aesthetic appeal and as high a constancy as possible throughout the whole period of use. This layer, depending on its structure and raw materials, can also fulfil barrier functions, including resistance to wetting and water penetration inside the composite material, as well as windproof capability. A typical example of such a material may be woven fabric made from multi-filament polyester yarns, principally micro-fibres, with a high structure cover factor and high strength, sometimes with an additional waterproof finish or soil-release finish.

The **middle layer**, with barrier properties, can be of two basic types:

a) a water- and windproof layer consisting usually of polymeric membranes or coats on a carrier such as polyester knitted fabric, with high water vapour permeability and low air permeability. Mostly, these are water- and windproof and simultaneously 'breathing' micro-porous hydrophobic polyurethane coats/membranes with a high water vapour permeability or hydrophilic coats/membranes with a compact structure and a generally lower water vapour permeability, but higher water-tightness. Both types of materials are made by the technique of reversible coating and transferred onto light, usually knitted textile carriers. These parameters should be at the following levels:
   - for microporous hydrophobic coats/membranes, the water-tightness should be at a level of 200-250 cm (measured by the hydrostatic method - water head); water vapour permeability of about 2000 $g/m^2.24$ h (measured by the gravimetric method under static conditions) and resistance to water vapour below 10 m^2 Pa/W (measured by the method of sweating a heat-insulated plate under dynamic conditions);
   - for hydrophilic compact coats/membranes, water-tightness up to 1000 cm, water vapour permeability of 1200 $g.m^2.24$ h and resistance of water vapour below 20 m^2.Pa/W.

b) a thermo-insulating layer with a high warmth retention, used in sports clothing to be used under lower temperature conditions (e.g. in the spring/autumn or winter periods). This layer mostly consists of fluffy polyester non-woven fabric or raised knitted fabric of the Polar type. These knitted fabrics have single-sided or two-sided developed piles, usually from polyester microfibres [3]. Their fluffiness provides particularly high warmth retention.

The back layer of the system, fulfilling the role of lining, may for example be a thin polyamide woven/knitted fabric, but Polar knitted fabric or fur fabric is also possible.

Methods for determining the properties of the multi-layer model system

The properties of these particular layers, as well as of entire composite systems, were determined by the following methods:

- Water resistance - according to standard PN-EN 24920:1997 ('Textiles. Spray-test").
- Water-tightness - according to standard PN-EN 20811:1997 ('Textile. Determination of water-tightness. Hydrostatic pressure method').
- Water vapour permeability under static conditions was assessed by measuring the amount of water vapour passing through the sample surface for a specific period of time, under temperature, relative humidity and flow rate conditions as given in test procedure NJC/2/95-IIMW.
- Resistance to water vapour flow and thermal resistance under dynamic conditions were tested with the use

Table 1. *Characteristics of exemplary textile and textile-polymeric materials as individual layers of model composite systems.*

Kind of layer	Type of fabric	Raw material	Basic weight, g/m^2	Thickness, mm
External layer	Woven fabric	Polyester fibre	110	0.24
	Woven fabric/ hydrophobic micro-porous coat	Polyester fibre/ polyurethane coat	150	0.32
Intermediate, watertight layer	Hydrophobic micro-porous membrane/knitted fabric	Coat/polyurethane membrane/polyester fibre	108	0.31
	Hydrophilic membrane/ knitted fabric	Coat/polyurethane membrane/polyester fibre	126	0.35
Intermediate, heat-insulating layer	Non-woven fabric	Polyester fibre	65	7.3
	Polar knitted fabric	Polyester fibre	200	3.5
Back layer	Woven fabric	Polyamide fibre	55	0.11

Table 2. *Basic properties of the example component textile and textile-polymeric materials for particular layers of model composite systems.*

Kind of layer	Type of fabric	Resistance of water vapour R_{et}, m^2Pa/W	Thermal resistance R_{ct}, m^2K/W	Water vapour permeability, g/m^224h	Air permeability, mm/s	Water-tightness, cm	Oleophobicity, degree	Spry-test, degree
External layer	PES woven fabric	4.38	-	1781	62.8	-	5	5
	PES woven fabric/hydrophobic micro-porous coat	5.28	-	1814	0	223	5	5
Intermediate, watertight layer	Hydrophobic membrane/micro-porous PES knitted fabric	7.51	-	1851	0	240		
	Hydrophilic membrane/PES knitted fabric	15.94	-	1585	0	100		
Intermediate, thermo-insulating layer	Non-woven fabric	26.00	0.180	2087	2491	-		
	Polar knitted fabric	22.90	0.092	1846	874	-		
Back layer	Polyamide woven fabric	3.35	-	1864	415	-		

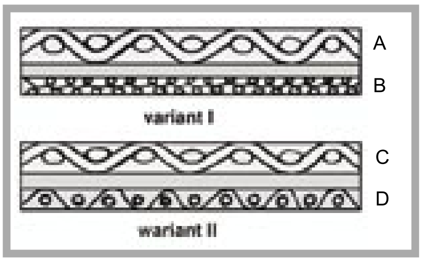

Figure 1. Multi-layer systems designed for summer clothing; A - PES woven fabric, B - membrane/PES knitted fabric, C - PES woven fabric/polymer coat, D - PA woven fabric.

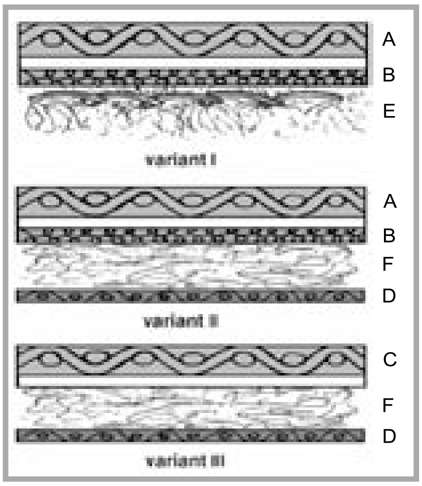

Figure 2. Multi-layer systems designed for spring-autumn and winter clothing; A - PES woven fabric, B - membrane/PES knitted fabric, C - PES woven fabric/polymer coat, D - PA woven fabric, E - Polar PES knitted fabric, F - PES non-woven fabric.

of a Sweating Guarded Hotplate M2559B apparatus from SDL Int. Ltd. equipped with a special microporous plate that simulates human skin [2]. The measurements were carried out according to standard PN-EN 31092:1998/Apl:2004 ('Textiles. Determination of physiological properties. Measurement of thermal resistance and resistance of water vapour flow under conditions of steady state – sweating thermally insulated plate'). The resistance to water vapour R_{et} is defined according to standard [4] as the quotient of pressure difference between both sides of the tested material and the resulting value of evaporation heat flow through a surface unit in the direction of the pressure gradient, while the thermal resistance R_{ct} is defined according to standard [4] as a quotient of temperature difference between two sides of the tested materials and the resulting value of heat flow through the unit surface in the temperature gradient direction.

- Air permeability - according to standard PN-EN ISO 9237:1998. ('Textiles. Determination of air permeability').

The characteristics of the example textile and textile-polymeric component materials used for particular layers of composite systems designed for sports clothing to be used under various ambient conditions are given in Table 1. The basic performance properties, including hygienic characteristics, are listed in Table 2.

Example structures of the multi-layer model composite systems made from component materials with the characteristics given in Table 1 (designed for summer clothing) are shown in Figure 1, and those for spring-autumn clothing in Figure 2.

Test results

The results of testing the physiological comfort of some selected composite materials designed for summer, spring-autumn and winter clothing are given in Tables 3, 4 and 5.

As follows from the data presented, the resistance to water vapour of the multi-layer system is higher than the sum of resistances of particular layers in each case, regardless of the type and number of layers. In the case of thermal resistance, its values depend first of all on the warmth retention of the heat-insulating layer.

Analysis of test results

The research carried out by us enabled to formulate the following statements.

1. Clothing made from multi-layer composite materials containing a hydrophobic polyurethane coat applied on woven fabric or microporous membrane bonded with (or applied on) knitted fabric, shows good water-tightness and a low water vapour resistance or very good water vapour permeability through the composite system, and consequently particularly beneficial hygienic properties and high comfort of use.
2. Clothing made from multi-layer composite materials containing hydrophilic membranes with compact structures is characterised by high water-tightness and high water vapour permeability at the same time.
3. The resistance of water vapour flow through the heat-insulating components is relatively high, being of importance for the total resistance of the whole system. The value of R_{et} depends on the thickness of these components (the amount of air present in the insulating layer). The greater the thickness of component/air layer, the higher the resistance of water vapour, or the lower its permeability.
4. The thermal resistance of multi-layer systems depends mainly on the thermal resistance of the heat-insulating layer. The latter depends, in turn, on the layer thickness. The thicker the layer, the better is the warmth retention.
5. The warmth retention of multi-layer composite material is increased by its polymeric coats/membranes. A relatively higher thermal resistance is shown by the systems containing a compact hydrophilic membrane than those with a hydrophobic microporous coat/membrane.
6. Depending on the structure and application of the multi-layer composite materials, the resistance of water vapour flow R_{et} ranges from 12 m^2Pa/W to 50 m^2Pa/W. Lower values of this parameter, below 30 m^2Pa/W, are shown by systems designed for summer clothing (with no heat-insulating layers). Higher values of 30-50 m^2Pa/W are observed in the systems containing heat-insulating layers, designed for spring-autumn and winter clothing. Considering that there are no standardised requirements for sports clothing, we can only state that the obtained values of the resistance of water vapour (under dynamic conditions) reach the level of requirements established by the PN-EN 343 for protective clothing that, as a rule, contains no thermo-insulating layers, below 40 m^2Pa/W and below 55 m^2Pa/W for clothing containing thermo-insulating layers.

Conclusions

1. The assessment of the protective and physiological properties of composite materials constitutes principles for designing effective multi-layer composite materials designed for the manufacture of high-tech sports clothing.
2. The designing and production of textile products with good physiological comfort and long service life, resistant

Table 3. *Resistance to water vapour of example component materials and composite systems made from them, designed for sports summer clothing.*

No. of composite systems	Type of system	Resistance of water vapour of particular layers R_{et}, m^2Pa/W	Resistance of water vapour of the whole system R_{et}, m^2Pa/W
1	- PES woven fabric - hydrophobic microporous membrane/PES knitted fabric	4.38 7.51	15.80
2	- PES woven fabric - hydrophilic membrane/ PES knitted fabric	4.38 15.92	18.16
3	- PES woven fabric/hydrophobic microporous coat - PA woven fabric	5.28 3.35	12.20

Table 4. *Resistance to water vapour of exemplary component materials and composite systems made from them designed for sports summer clothing.*

No. of composite systems	Type of system	Resistance of water vapour of particular layers R_{et}, m^2Pa/W	Resistance of water vapour of the whole system R_{et}, m^2Pa/W
1	- PES woven fabric - Hydrophobic microporous membrane/PES knitted fabric - Polar	4.38 7.51 22.90	35.89
2	- PES woven fabric - Hydrophilic/PES knitted fabric - Polar	4.38 15.92 22.90	48.08
3	- PES woven fabric - Hydrophobic microporous membrane/PES knitted fabric - PES non-woven fabric - PA woven fabric	5.28 15.92 26.00 3.35	44.38
4	- PES woven fabric - Hydrophilic membrane/PES knitted fabric - PES non-woven fabric - PA woven fabric	4.38 15.92 26.00 3.35	50.76
5	- PES woven fabric/hydrophobic micro-porous coat - Polar	5.28 22.90	37.66
6	- PES woven fabric/hydrophobic micro-porous coat - PES non-woven fabric - PA woven fabric	5.28 26.00 3.35	37.39

Table 5. *Thermal resistance of example model composite systems for winter sports clothing and of their heat-insiting layers.*

No. of composite systems	Type of system	Thickness, mm	Thermal resistance of the heat-insulating layer R_{ct}, m^2K/W	Thermal resistance of the system R_{ct}, m^2K/W]
1	- PES woven fabric - Hydrophobic microporous membrane/PES knitted fabric - Polar	0.24 0.31 3.50 ∑ 4.09	0.092	0.113
2	- PES woven fabric - Hydrophilic/PES knitted fabric - Polar	0.24 0.35 3.50 ∑ 4.09	0.092	0.132
3	- PES woven fabric - Hydrophobic microporous membrane/PES knitted fabric - PES non-woven fabric - PA woven fabric	0.24 0.31 7.30 0.11 ∑ 7.96	0.180	0.219
4	- PES woven fabric - Hydrophilic membrane/PES knitted fabric - PES non-woven fabric - PA woven fabric	0.24 0.35 7.30 0.11 ∑ 8.00	0.180	0.263
5	- PES woven fabric/hydrophobic microporous coat - Polar	0.32 3.50 ∑ 3.82	0.092	0.153
6	- PES woven fabric/ hydrophobic microporous coat - PES non-woven fabric - PA woven fabric	0.32 7.30 0.11 ∑ 7.73	0.180	0.196

to prolonged use and repeated washing, require a selection of specified raw materials, including fibres with developed surface. An appropriate, spatially developed structure of composite materials and a selection of proper polymeric coats/membranes are also required. However, it should be mentioned that considerable effect on the physiological comfort of clothing is also exerted by the conditions of use – namely the atmospheric conditions surrounding, and the physiological properties of the user as an individual.

3. The test results presented may form a basis for designing multi-layer composite materials for the manufacture of sports clothing with tailor-made properties.

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