Characteristics of Knitted Structures Produced By Engineered Polyester Yarns and Their Blends in Terms of Thermal Comfort

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ABSTRACT
Engineered yarns are used to provide better clothing comfort for summer garments because of their high levels of moisture and water vapor management. The aim of this study was to investigate the characteristics of knitted structures that were produced using different types of polyester yarns in order to achieve better thermal comfort properties for summer clothing. However they are relatively expensive. Therefore, in this study engineered polyester yarns were combined with cotton and lyocell yarns by plying. This way, the pronounced characteristics of these yarns were added to the knitted structure as well. Channeled polyester, hollow polyester, channeled/hollow blended polyester, cotton, and lyocell yarns were plied with each other and themselves. Then, single jersey structures were knitted using these ply yarn combinations and air permeability, thermal resistance, thermal absorptivity, water vapor permeability, moisture management, and drying properties were tested. The results indicate that channeled PES fabrics are advantageous for hot climates and high physical activities with regards to high permeability and moisture transfer and also to fast drying properties. Besides, air permeability and thermal properties improved through the combination of lyocell yarn with engineered polyester yarns. However, the use of lyocell or cotton with engineered yarns resulted in a to a decrease in moisture management properties and an increase in drying times

INTRODUCTION
The demands from textile structures have changed due to the developments in textile technology along with the rise of living standards. Today, textile structures are expected to have improved protection against hot and cold weather, wind, rain, UV radiation and microbial growth, depending on use [1]. Clothing comfort, which can be defined as "a pleasant state of psychological and physical harmony between a human being and the environment" [2], is seen especially as an important property. This includes three main topics: thermophysiological (thermal) comfort, psychological comfort, and sensorial comfort.

It is known that one of the main parameters that affect clothing comfort is fiber type. Natural fibers are more or less hydrophilic and water absorbing, while synthetics are hydrophobic. On the other hand, with the developments in fiber science, special synthetic fibers have been developed with enhanced performances for advanced functional textile materials [3]. Engineered synthetic fibers are the well-known materials in this field, and they are accepted as a good choice for active sportswear.

The aim of this study was to investigate the characteristics of single jersey structures produced using different yarn types to achieve better thermal comfort properties. Channeled and hollow polyester fibers were chosen since they have high levels of clothing comfort [2] and are the most common types for active and summer wear. Channeled polyester fibers improve quick dry and moisture absorption properties by the strong capillary effect, while hollow polyester fibers achieve higher thermal insulation characteristic due to the entrapped air within the fiber structure. However they are relatively expensive. Thus, in the present contribution, engineered polyester yarns were used together with cotton and lyocell yarns to combine the better comfort characteristics of each.

Plying was used to combine the different yarn types. In making plyed yarns from spun strands, the individual strands are usually each twisted in one direction and are then combined and twisted in the opposite direction as shown in *Figure 1*. This gives the yarn much more strength, durability and consistency than that of a single yarn [5]. Moreover, by plying different yarn types, it is possible to add the pronounced characteristics of individual yarns to the fabric structure.

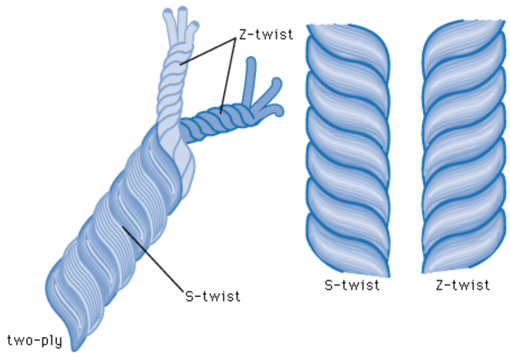


FIGURE 1. Plying of yarns [4].

Previous researches revealed that engineered polyester yarns provide high thermal comfort characteristic. Sarkar, et al. [6] produced 24 fabrics in different weave structures and interchanging patterns, with the same polyester warp yarn and different weft yarns by using cotton, Coolmax®, and Thermolite® fibers. The fabric moisture management properties were determined by using MMT (moisture management test), and to simulate the condition of sweating profusely, a recently developed Transplanar Water Transport Tester was used. According to the results, a slightly higher wetting time was indicated for the fabrics with Thermolite® and Coolmax® weft as compared to the fabrics with cotton weft. Also they developed a new structure called "plant structured fabrics", which had clearly faster liquid water transport and better moisture management property within all tested fabrics. Garments made of such plant structured fabrics facilitate the transport of sweat faster away from the skin to the outer layer of fabric, making the wearer feel drier and more comfortable. Li and Zang [7] studied subjective sensations in different sport conditions with cotton/Coolmax® double faced knitted fabrics. Some of the tested fabrics were developed by Textile Institute of DongHua University for sportswear (including Coolmax®/cotton) and some of the fabrics (including polyester, cotton, polyurethane, and nylon) were chosen from the market for comparative analysis. For the purposes of analyzing thermal, moisture, clinging, stifling, rough, soft, drape, prickle, tight, and overall comfort, they designed a questionnaire including ten comfort properties of knitwear fabric after a four step process: rest/walking/running/rest. According to the results, the overall comfort properties of Coolmax®/cotton double faced fabrics are better than that of the comparative fabrics. Also, some of these fabrics proved to have better heat-moisture sensation. They found that the new developed double-faced fabrics are suitable for heavy sports conditions. Li and Ni [8] studied different blends of Coolmax® and regenerated cellulose fibers, which were pearl fiber, tencel, and modal. Wicking effect, drop-proliferation, regain, water vapor permeability, permeability, and quick dry tests were analyzed. According to the results, natural fibers such as cotton have lower moisture management properties because of their natural curly fiber structure; whereas Coolmax® fiber blended with regenerated fibers have better moisture management properties and could improve wearing comfort. Sampath, et al. [9] studied thermal comfort by analyzing the thermal behavior of moisture management finished (MMF) fabrics knitted by using the yarns of micro-denier polyester filament, spun polyester, polyester/cotton, filament polyester, and cotton. They noted that yarn type had a significant effect on thermal characteristics. Among the five fabric types, it was observed that micro-denier polyester fabrics give faster heat transfer, quicker evaporation of sweat from the skin through the fabric, and cooler feeling at initial touch. They also proved that the MMF treatment has a significant effect on the thermal behavior of micro-denier polyester knitted fabrics. Tarakçıoğlu, et al. [10] investigated the microclimate temperature change depending on the fiber type used in woven structures at extremely hot climates. They concluded that the combination of channeled and hollow polyester fibers provided lower temperature/time curve slopes, thus higher protection capability.

MATERIAL AND METHOD

Engineered 32.8 tex yarns, namely, channeled polyester yarn, hollow polyester yarn, channeled/hollow blended polyester yarn, and 29.5 tex lyocell yarn and 36.9 tex cotton yarn were plied with each other and themselves. Channeled PES, hollow PES, fiber blended channeled and hollow PES, lyocell and cotton yarns were encoded throughout the paper as C, H, CH, T and Co, respectively. The yarns were plied without twist on a DirectTwist 2A machine (Agteks Company). Then single jersey structures were produced by these 10 different plied yarns, as shown in *Table I*, with the same tightness factor on a Mesdan Lab knitting machine with 294 needles.

TABLE I. Yarn combinations.

Samples	Symbols
Channeled PES- Channeled PES	C-C
Hollow PES- Hollow PES	H-H
Channeled/Hollow PES-Channeled/Hollow PES	CH-CH
Channeled PES - Hollow PES	C-H
Channeled PES-Lyocell	C-T
Hollow PES- Lyocell	H-T
Channeled/Hollow PES- Lyocell	CH-T
Channeled PES-Cotton	C-Co
Hollow PES- Cotton	H-Co
Channeled/Hollow PES- Cotton	CH-Co

In order to investigate the effects of moisture management (hydrophilic) finishing on the transfer properties of the engineered polyester fabrics, all the samples were treated with Ultraphil TG® (Hunstman) which is specified for synthetics and their blends.

Air permeability, water vapor permeability, moisture management and thermal properties (thermal conductivity, thermal absorptivity, thermal resistance and thickness) were tested on a Texttest FX3300 (with 100 Pa and 20cm^2 test head, EN ISO 9237), Permetest (ISO 11092), SDL Atlas MMT (AATCC TM 195) and Alambeta devices, respectively; according to the related standards. Drying tests were also performed under standard atmospheric conditions by dripping 1 g of pure water and drying times were recorded.

RESULTS AND DISCUSSION

Air Permeability

Air permeability determines the ability of air flow through the fabric [11]. It is mostly affected by the porosity of the structure and pore characteristics [12-14].

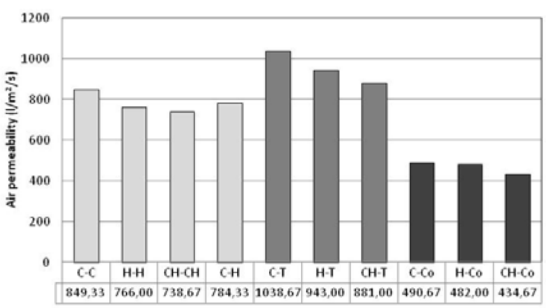


FIGURE 2. Air permeability test results.

Air permeability test results and the statistical analysis of the samples are given in *Figure 2* and *Table II*, respectively. It was observed that there is not any significant difference between the air permeability values of fabrics knitted by engineered polyester yarns. This categorically pointed out that fabric structure is the decisive parameter, whereas surface structure of the fibers didn't result in any significant effect on air permeability of the fabrics. On the other hand, the use of lyocell and cotton yarns in the fabric structures exhibit a significant difference in air permeability values, although there is not a great difference between the yarn counts of selected yarns. This is thought to be due to the difference in the packing density of the yarns. Thus, the addition of lyocell yarn into the structure led to an increase in air permeability, due to the finer characteristic of this yarn. Conversely, the addition of cotton yarns to the knitted structure decreased the air permeability.

Thermal Properties

Humans strive to keep their body core temperature at a constant level of approximately 37 ^{o}C. Since maintaining of thermal equilibrium of the body is of importance, heat transfer from/to the body is the most important parameter for thermal comfort. Thermal resistance is a measure of the clothing's ability to resist heat flow through itself. Under a certain condition of climate, if the thermal resistance of clothing is small, the heat loss will gradually increase with a sense of coolness [15]. Thermal absorptivity, which is the objective measurement of the warm-cool feeling of fabrics, is another important thermal property. Thermal absorbtivity of fabrics was introduced by Hes [16] to characterize thermal feeling during short contact of human skin with the fabric surface. A warm-cool feeling is the first sensation. When a human touches a garment that has a different temperature than the skin, heat exchange occurs between the hand and the fabric. If the thermal absorptivity of clothing is high, it gives a cooler feeling at first contact [17].

TABLE II. Statistical analysis of air permeability results.

Material	N	Subset for alpha = 0.05					
		1	2	3	4	5	6
CH-Co	3	434.67					
H-Co	3	482.00					
C-Co	3	490.67					
CH-CH	3		738.67				
H-H	3		766.00	766.00			
C-H	3		784.33	784.33	784.33		
C-C	3			849.33	849.33	849.33	
CH-T	3				881.00	881.00	
H-T	3					943.00	943.00
C-T	3						1038.67
Sig.		.288	.385	.119	.073	.082	.063

Duncan-Means for groups in homogeneous subsets are displayed

Thermal resistance and thermal absorptivity values of the samples are given in *Figures 3 and 4*, respectively. The results indicat that the engineered polyester yarns (Channeled PES, hollow PES and channeled/hollow blended PES yarns) provide higher thermal resistance and lower thermal absorptivity properties that are similar to each other. In fact, it was expected that the hollow PES yarns would provide higher thermal resistance due to entrapped air within the fiber structure. However no difference in the thermal properties of the polyester fabrics depending on the physical structure of fibers was addressed. This explains that the effects of air gaps within the fabric structure (especially inter yarn pores) are more pronounced than inner hollow of the fibers in terms of thermal properties. The use of lyocell or cotton yarns in the fabric structure decreased thermal resistance values and increased thermal absorpitivity; however there is not any significant difference between the thermal values of the fabrics produced by lyocell-PES or cotton-PES plied yarns (*Tables III and IV*).

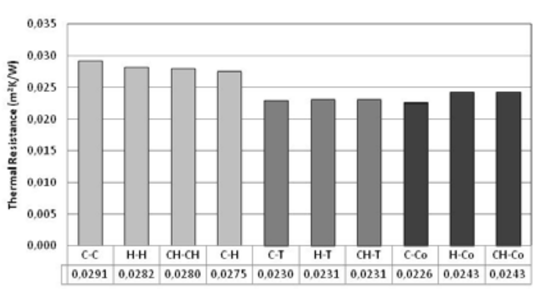


FIGURE 3. Thermal resistance test results.

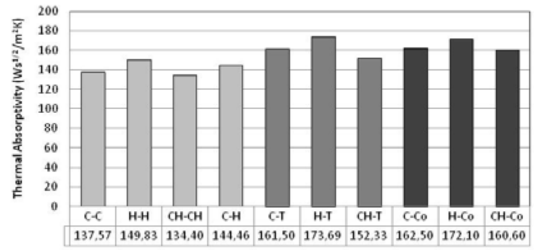


FIGURE 4. Thermal absorptivity test results.

TABLE III. Statistical analysis of thermal resistance results.

Material	N	Subset for alpha = 0.05	
		1	2
C-Co	3	.02260	
C-T	3	.02300	
CH-T	3	.02313	
H-T	3	.02313	
CH-Co	3	.02433	
H-Co	3	.02433	
C-H	3		.02750
CH-CH	3		.02803
H-H	3		.02820
C-C	3		.02913
Sig.		.154	.165

Duncan-Means for groups in homogeneous subsets are displayed.

TABLE IV. Statistical analysis of thermal absorptivity results.

Material	N	Subset for alpha = 0.05				
		1	2	3	4	5
CH-CH	3	134.40				
C-C	3	137.57	137.57			
C-H	3	144.46	144.46	144.46		
H-H	3	149.83	149.83	149.83	149.83	
CH-T	3		152.33	152.33	152.33	
CH-Co	3			160.60	160.60	160.60
C-T	3				161.50	161.50
C-Co	3				162.50	162.50
H-Co	3					172.10
H-T	3					173.69
Sig.		.062	.074	.052	.130	.118

Duncan-Means for groups in homogeneous subsets are displayed.

In accordance with the findings above, it can be noted that the fabrics knitted by engineered polyester yarns provide higher thermal insulation and give a warmer feeling when compared with the samples including cellulosic yarns. It was also proved that neither fiber blend nor yarn blend (plied) of channeled and hollow polyesters exhibit any significant difference on thermal characteristics.

TABLE V. Statistical analysis of water vapor permeability results.

	N	Subset for alpha = 0.05										
		1	2	3	4	5	6	7	8	9	10	11
H-H	3	30.67										
H-Co	3	31.43	31.43									
C-Co	3		33.00	33.00								
CH-Co	3			33.73								
C-H	3			34.33	34.33							
CH-CH	3			35.13	35.13	35.13						
H-T	3				36.43	36.43	36.43					
C-C	3					36.87	36.87					
C-T	3					37.27	37.27					
CH-T	3						37.53					
H-T*	3						38.10					
H-H*	3							40.25				
H-Co*	3								42.52			
C-H*	3								42.52			
CH-Co*	3								42.63			
C-Co*	3								44.24			
CH-CH*	3									47.03		
C-T*	3									48.18	48.18	
CH-T*	3										49.20	
C-C*	3											52.16
Sig.		.447	.124	.056	.052	.056	.144	1.000	.123	.256	.313	1.000

Duncan - Means for groups in homogeneous subsets are displayed.
* Samples treated with moisture management finishing

Water Vapor Permeability

Water vapor permeability is the ability to transmit vapor from the body. Ambient temperature and humidity, and the moisture resistance of clothing are the main parameters that assign the rate of sweat evaporation from body surface. If the moisture resistance is too high, due to the lower rate of evaporation, the stored heat in the body cannot be dissipated which causes an uncomfortable sensation [15].

Figure 5 illustrates the relative water vapor permeability values of the samples, before and after moisture management finishing. The results indicate that the water vapor permeability characteristics of the samples improved to a great extent by the application of moisture management treatment. This increment is more pronounced for the samples produced by channeled PES yarns. The statistical results reveal that the channeled PES yarns provided the highest water vapor permeability properties (*Table V*). This situation can be explained by the principle of applied water vapor permeability test which is matched with the convection mass transfer law. In convection mass flow, mass flow rate is directly proportional to the surface area along the direction of the flow. Thus, higher fiber surface area of channeled structure leads to higher water vapor permeability characteristics. Besides, the plying of lyocell yarn with channeled PES yarn did not create a negative effect on water vapor permeability, whereas the use of cotton yarn caused a decrease as well as air permeability results.

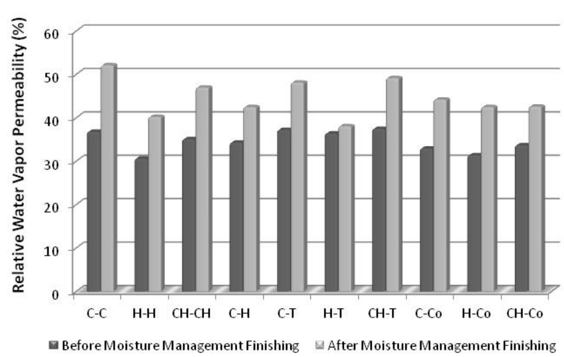
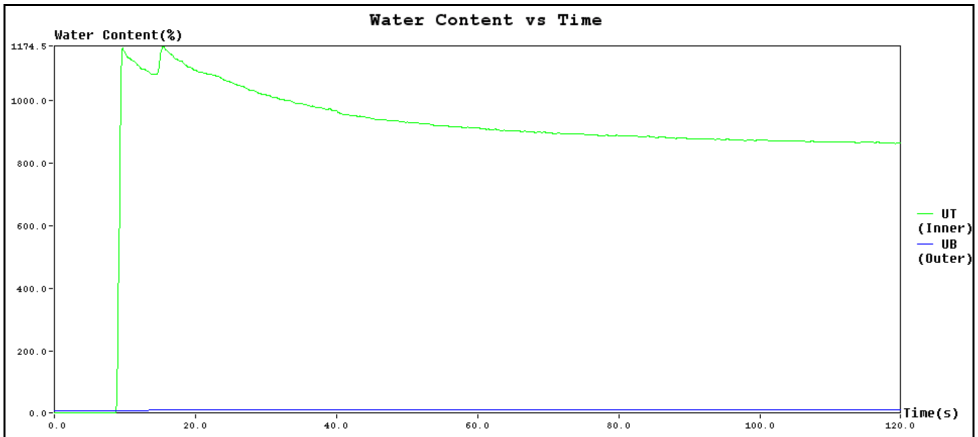
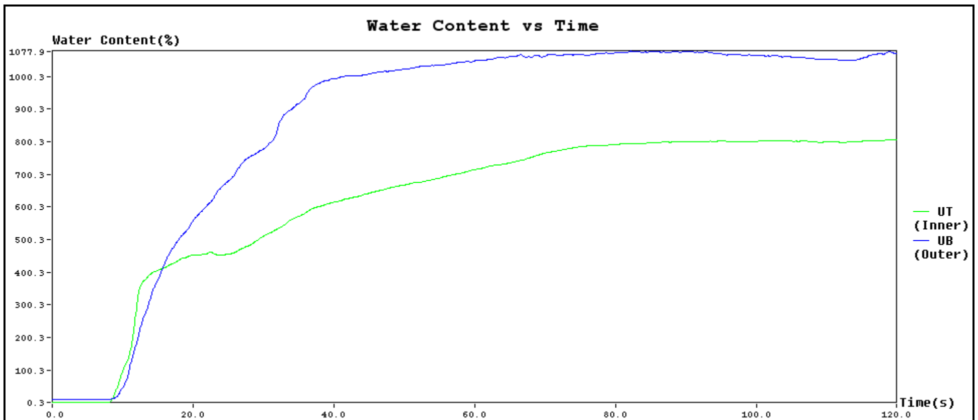


FIGURE 5. Relative water vapor permeability results.



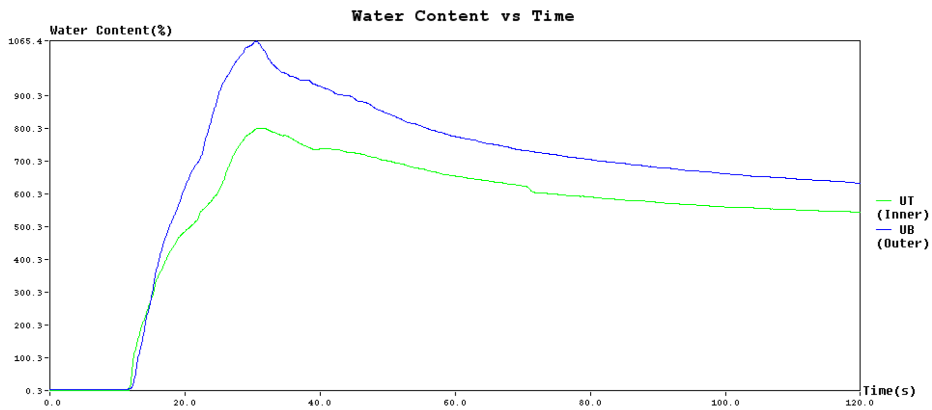
	Top Surface	Bottom Surface
Wetting time(sec)	8.031	119.953
Absorption rate(%/sec)	459.5267	0.0
Max wetted radius(mm)	5.0	0.0
Spreading Speed(mm/sec)	0.6095	0.0
One way transport capability	-858.3306	
Description	MMT-	

FIGURE 6. MMT results for the fabrics produced by channeled PES yarns before moisture management finishing.



	Top Surface	Bottom Surface
Wetting time(sec)	7.718	8.359
Absorption rate(%/sec)	11.61	29.5779
Max wetted radius(mm)	10.0	10.0
Spreading Speed(mm/sec)	0.9878	0.8778
One way transport capability	243.4633	
Description	MMT-	

FIGURE 7. MMT results for the fabrics produced by channeled PES yarns after moisture management finishing.



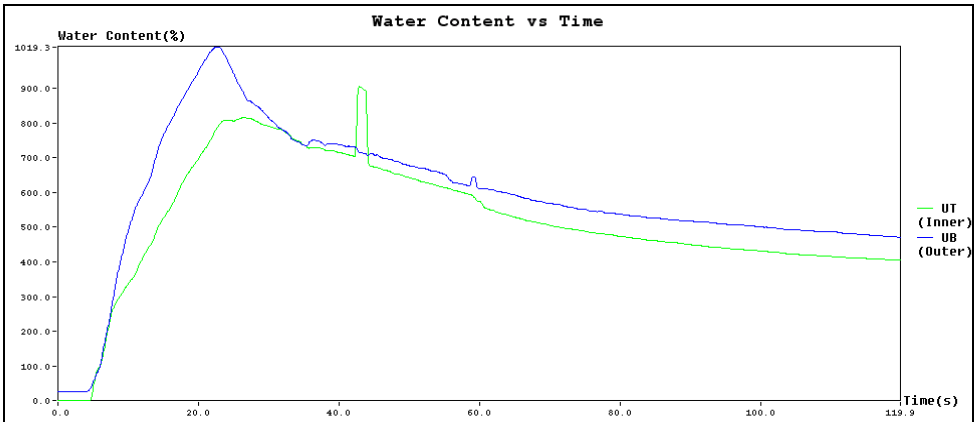
	Top Surface	Bottom Surface
Wetting time(sec)	11.156	11.313
Absorption rate(%/sec)	40.0029	54.5906
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	1.3181	1.2817
One way transport capability	117.1277	
Description	MMT-	

FIGURE 8. MMT results for the fabrics produced by hollow PES yarns after moisture management finishing.

Moisture Management Properties

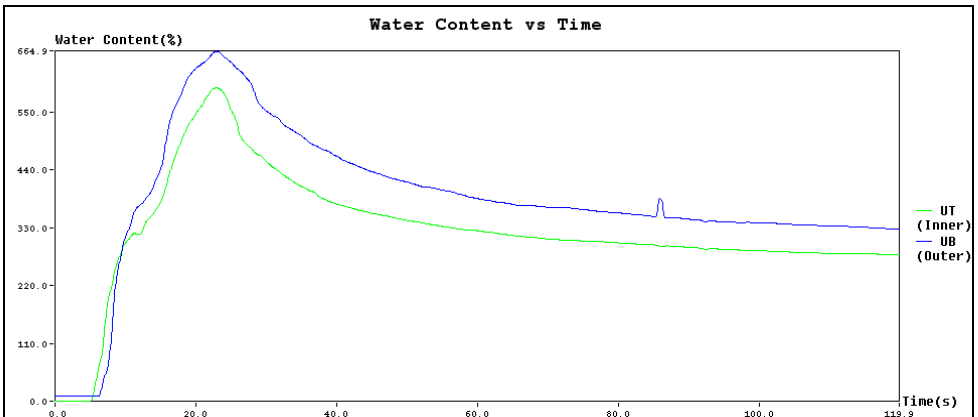
The moisture transport properties of the garments have great influence on thermal comfort of the body [18, 19]. The moisture management test results of the samples point out that the fabrics produced by engineered polyester yarns exhibit very low one way transport capability, even for channeled polyesters. Synthetic fibers can absorb only a comparatively small amount of moisture because of their hydrophobic character, and this causes poor wettability [19]. An illustrative example is given in *Figure 6*. In order to improve this characteristic the samples were treated with moisture management finishing (MMF) and an excessive increase occurred after MMF, especially for channeled polyesters (*Figure 7*).

As already known, the moisture transfer properties of active wear are of importance to a great extent in terms of quick drying and dry feeling. Channeled PES fabrics were found to be advantageous with regards to moisture transfer, as shown in *Figure 7*. For synthetic fibers, liquid moisture transport mainly depends on the capillarity of the structure. Also it is known that the decrease in the capillary radius generates higher pressure which provides faster flow through the capillary [18]. Owing to the higher capillarity of channeled polyesters, water can be easily transferred through the surface by capillary forces. This result concluded that these fabrics can easily transfer sweat generated after any activity, while keeping a dry feeling. Besides, hollow PES fabrics have also represented adequate transport properties (*Figure 8*), whereas because of the hydrophilic character of lyocell and cotton, the fabrics including cellulosic fibers were observed to have lower moisture management capability due to the higher moisture absorption capacity of these fibers (*Figures 9 and 10*).



	Top Surface	Bottom Surface
Wetting time(sec)	4.125	3.953
Absorption rate(%/sec)	40.1036	52.4396
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	2.3641	2.1427
One way transport capability	69.7972	
Description	MMT-	

FIGURE 9. MMT results for the fabrics produced by channeled PES-lyocell yarns after moisture management finishing.



	Top Surface	Bottom Surface
Wetting time(sec)	4.672	5.875
Absorption rate(%/sec)	32.3033	37.973
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	2.3588	2.1167
One way transport capability	59.5194	
Description	MMT-	

FIGURE 10. MMT results for the fabrics produced by channeled PES-cotton yarns after moisture management finishing.

Drying Properties

The non-evaporated sweat leads to a wet feeling which generally results in discomfort, due to the adhering of fabric onto the skin and unpleasant cool feeling [20, 21]. Additionally, the warm-cool feeling is also changed after sweating [20]. Therefore, drying properties of garments are as important as moisture management properties, especially after any activity resulting in sweating. *Figure 11* indicates the drying times of the fabrics. As seen, engineered polyester yarns provide faster drying. In synthetic fabrics, moisture is transferred through and also along the fabric by the capillary forces, so the wetted area is very large because of high capillarity and poor absorption. On the other hand, as expected, the fabrics including cellulosic fibers have longer drying periods due to higher absorption rate of lyocell and cotton thanks to their hydrophilic character.

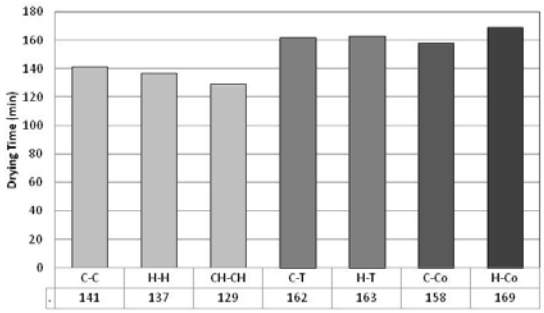


FIGURE 11. Drying times.

CONCLUSION

In this study, fabrics knitted by different blends of polyester, lyocell and cotton yarns were analyzed in terms of thermal comfort. Air permeability, thermal resistance, thermal absorptivity, water vapor permeability, moisture management and drying properties were tested and evaluated statistically. The results indicate that:

- Engineered polyester fabrics have high air permeability values that are similar to each other, and the addition of lyocell yarn into the structure led to an increase in air permeability.
- The fabrics knitted by engineered polyester yarns provide higher thermal insulation and give warmer feeling compared with the samples including cellulosic yarns. The use of lyocell or cotton yarns in the fabric structure decreased thermal resistance and increased thermal absorptivity values.
- The water vapor characteristics of the samples improved to a great extent by the application of moisture management treatment. The channeled PES yarns provided the highest water vapor permeability and the addition of lyocell yarn did not create a negative effect.
- It was proved that neither fiber blend nor yarn blend (plied) of channeled and hollow polyesters exhibit significant difference on thermal properties as well as air and water vapor permeability.
- In order to maintain the moisture management property, the samples needed to be treated with moisture management finishing (MMF) and an excessive increase occurred after MMF, especially for channeled polyesters. The channeled PES fabrics were found to be advantageous with regards to moisture transfer, whereas the cellulosic fibers were observed to have lower moisture management capability.
- Engineered polyester yarns provide fast drying due to their capillary effect and hydrophobic characteristics.

As a conclusion, when all comfort parameters are considered, channeled polyester yarns provided higher levels of thermal comfort properties for hot climates and/or high physical activities. Nevertheless, it should be noted that moisture management finishing is required to achieve these superior thermophysiological comfort properties.

Engineered polyester yarns are relatively expensive. Thus, in order to reduce production costs, the blends of channeled PES and lyocell yarns can be recommended (especially for the conditions free from liquid sweating) since the addition of lyocell yarn into the structure did not cause a negative effect on water vapor permeability. Furthermore, lyocell yarns led to an increase in air permeability and thermal properties

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