Study of physical, moisture-management and stretch properties of underwear fabrics

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ABSTRACT – REZUMAT

Study of physical, moisture-management and stretch properties of underwear fabrics

This study investigated and characterized the physical properties and their influence on moisture management and stretch properties of underwear fabric made of different compositions of fibres. It is found that fabric made of finer filament yarn, having an open and porous structure, smaller stich length, and smaller thickness has higher air permeability, water vapour permeability, better moisture transport and overall moisture management capacity. It is also found that elastic recovery is higher in the wale direction in the case of weft-knitted fabrics. Furthermore, a fabric with longer stich length has higher stretch in both directions and more recovery in the wale direction. In addition, it is found that warp-knitted fabric has better moisture transport.

Keywords: *fabric composition, humid, water vapour transmission, elastic recovery, weft knitted fabrics, warp knitted fabrics*

Studiul proprietăților fizice, de gestionare a umidității și de întindere ale materialelor pentru lenjeria de corp

Acest studiu a investigat și caracterizat proprietățile fizice și influența lor asupra gestionării umidității și proprietăților de întindere ale materialelor pentru lenjeria de corp din diferite compoziții de fibre. Se constată că materialul textil din fire filamentare mai fine, având structură deschisă și poroasă, lungime mai mică a ochiurilor și grosime mai mică are permeabilitate mai mare la aer, permeabilitate la vapori de apă, transport mai bun al umidității și capacitate generală de gestionare a umidității. De asemenea, se constată că revenirea din întindere este mai mare în direcția şirului de ochiuri de tricot în cazul tricoturilor din bătătură. În plus, un tricot cu o lungime mai mare a ochiurilor are o întindere mai mare în ambele direcții și o capacitate de revenire mai mare în direcția şirului de ochiuri de tricot. În plus, s-a constatat că tricotul din urzeală are un transport mai bun al umidității.

Cuvinte-cheie*: compoziția tricotului, umed, transmisia vaporilor de apă, revenire din întindere, tricoturi din bătătură, tricoturi din urzeală*

INTRODUCTION

Comfort is a vital consideration in selecting underwear as it has direct contact with human skin and sensitive body parts [1]. Thermal comfort is related to moisture management (MMT) and thermal regulation properties of a fabric. MMT is the ability of a fabric to wick or diffuse the moisture from perspiration through the fabric as quickly and efficiently as possible. It is reported that the fibre type of the underwear affects MMT properties [2] and hydrophobic fibres provide higher breathability to the fabrics [3]. Heat transfer through fabric layers by conduction also influences the comfort of underwear [4]. In addition, stretch and recovery properties are critical for the ergonomic comfort of underwear [5]. Most recently, it is reported that fabric with good air permeability (AP) (485 mm/s), overall moisture management capacity (OMMC) of (0.61), and short drying time (16 min) is more suitable for summer sportswear [6].

To date, several materials have been investigated to study the influence of material on the thermos-physiological response of fabric and clothing-skin microclimate. For example, it is reported that polypropylene underwear gives a higher degree of skin and clothing dampness sensation [7]. It has also been reported that fabric made of 56% polyamide, 39% polypropylene, and 5% elastane gives the best performance in terms of wet comfort index (WCI) [8]. Another study revealed that fabric made of 98% modal and 2% elastane, and another made of 47% cotton, 47% modal and 6% elastane give better performance. Because of the balance of the content between modal and elastane, softness and stiffness can be retained with additional breathability, moisture absorption and extensibility characteristics [9]. Prakash et al. reported that fabric made of Bamboo possesses high AP with relative water vapour permeability (Wvp) of 40–50% and absorbs more water compared to cotton and polyester [10]. Likewise, in a study of sweat accumulation by the underwear fabric, it is reported that wool has slightly more sweat accumulation than polypropylene because of its non-absorbent and high-wicking properties [11]. Recently, Phase Changing Materials (PCM) that can liberate latent heat from transformation between liquid-solid, has been utilized in underwear for improving thermo-regulating effects to the underwear. It is revealed that because cotton has large porosity, therefore PCM can be integrated through encapsulation to increase latent heat-storing capacity. Furthermore, shape-stabilized PCM can prevent polyester from reaching above the melting point and act as a supporting material to give a cooling effect [12]. The relationship between fabric structures and MMT properties has also been investigated. It is reported that the fabric structure and stitch density (SD) influence the fabric's physical characteristics like thickness and porosity, which ultimately influence the fabric comfort or MMT properties [13]. It is also found that the interlock knitting of fabric at a lower gauge and higher stitch length (SL) results in a loose structure with larger air gaps as compared to the tighter fabric structure [14]. Oğlakcioğlu and Marmarali reported that single jersey fabrics have higher Wvp [15]. In another study, single pique and honeycomb fabrics made of silk yarns have been investigated. Another study reported that the OMMC capacity of the fabric is 'very good' to 'excellent'. They concluded that the vertical wicking ability of single pique silk fabrics is influenced by tuck stitches and slick structures to increase moisture absorption rates [16]. It has also been reported that double face polypropylene-cotton blended knitted fabric has better MMT because the hydrophobic polypropylene in the base layer creates a capillary effect to transfer sweat to the hydrophilic, absorbent cotton surface layer. Therefore, moisture is wicked by the base layer followed by absorbency and quick drying by the surface layer [17]. It is concluded that warp-knit Raschel fabric has better AP, MMT, and low thermal and water vapour resistance. It is reported that fabrics with a fleecy structure have a higher initial water absorption rate and one-way transport capacity [18].

The studies mentioned, provided an understanding of the physio-thermal and MMT properties of materials including bamboo, cotton, polyester, modal, and polypropylene with spandex. However, very few studies focused on the relationship between material combination, structure, and physical and mechanical properties of the fabric. The structural properties of fabric including SD, SL, areal density (AD), thickness, fabric structure, and fibre combination are parameters that affect the MMT properties of underwear fabric and their comfort characteristics in real-life applications. Therefore, this study aims to investigate and compare MMT, and mechanical properties of underwear fabric having different structural parameters and fibre combinations. Underwear fabrics made of cotton, polyester cotton blend, nylon, viscose, bamboo, and modal are tested to obtain their real characteristics including tensile properties, MMT properties, breathability, absorbency, and wicking. This study, it is aimed to find a certain structure, fibre or combination of fibres that gives better performance in terms of MMT and mechanical properties. These findings will also help to explore further the factors that will affect the performance of underwear.

MATERIAL AND METHOD

Fabric compositions, types, structures, physical properties, water vapour permeability (Wvp) and air permeability (AP) of underwear fabrics used in this study are given in table 1. Fabric structure and physical properties were evaluated in standard atmospheric conditions (65±5 % RH and 20±5 °C). The areal densities (AD) of fabrics were calculated according to ASTM D3776. The thicknesses of the fabrics were measured according to ASTM D1777 using a digital fabric thickness tester by AMES. Course/cm (CPc) and wale/cm (WPc) were measured according to standards ASTM D8007. The yarn linear density was measured according to the standard ASTM D1059. SD of the fabrics was calculated as the product of CPc and WPc. The SL is measured according to the standard EN 14970. The structure of each fabric is photographed by Leica Microsystems GmbH. The AP of fabrics was measured according to the standard ASTMD737 at a pressure drop of 100 Pa using an SDL Atlas AP tester. The Wvp was tested according to standard BS 7209. The MMT properties of fabrics were evaluated by using the SDL Atlas MMT tester, according to the standard AATCC 195-2009. The stretch-recovery and growth properties of fabrics in both course direction (CD) and wale direction (WD) were measured on an electronically controlled INSTRON tensile testing machine according to standard ASTMD 6614. Three replicates of each fabric were tested, and the results were averaged. In addition, to study the association between all indicators obtained from the MMT test, correlation analysis was performed using Minitab® [19] and correlation coefficients were calculated [20]. Moreover, the *p* value less than 0.05 shows a significant correlation.

RESULTS AND DISCUSSIONS

Physical properties and breathability of underwear fabrics

Table 1 just shows the physical properties of studied underwear fabrics. It can be seen that fabrics K1A K1B and K3 with higher thickness or SD have lower AP. This is because higher thickness or SD resulted in compact fabric structure, higher fibre content and decreased fabric porosity. On the other hand, fabric K2 and K4 has higher AP because they have lower thickness even with higher SD. It was also reported that the AP of bi-stretch woven fabric decreases by using a higher elastane yarn ratio [21].

However, this might not apply to all kinds of knitted fabrics. It can also be seen from table 1 that fabrics K4, K5 and fabric K6 have higher elastane ratios. In the case of fabric K5, a higher elastane ratio along with higher SD and smaller SL make the fabric structure more compact which resulted in lower AP. However, in the case of fabrics K4 and K6, a higher elastane ratio did not decrease the AP. In the case of fabric K4 the least thickness and use of ultra-thin

Table 1

PHYSICAL PROPERTIES, COMPOSITION, WVP AND AP OF UNDERWEAR FABRICS AND STANDARD TEST METHODS USED										
Fabric	**Yarn (Tex)**	**Course/cm (CPC) & Wales/cm (WPC)**	**Stitch density (SD) /cm²**	**Stitch length (mm)**	**Fabric areal density (g/m²)**	**Fabric thickness (mm)**	**Fabric structure/ Composition**	**Water vapour permeability (g/m²/24h)**	**Air permeability (ml/s/cm²) at 100Pa**
K1A	28	29±01.00 18±02.00	522±69.00	1.4±0.2	203±2.00	00.90±0.02	SJ 97%C:3%S	625.00±4.00	33.00±3.50
K1B	29	25±01.00 16±00.00	400±07.00	1.6±0.1	173±10.50	00.78±0.02	SJ 97%C:3%S	632.00±2.18	54.50±3.50
K2	24.5	28±00.00 20±00.00	560±00.00	1.4±0.1	206±02.00	00.33±0.02	SJ 94%V:4%S	654.00±8.00	54.00±4 .00
K3	24.5	29±01.00 21±01.00	609±29.00	1.3±0.2	194±01.50	00.54±0.02	SJ 95%M:3%S	657.00±2.00	57.00±4.50
K4	16.5	30±02.00 20±00.00	600±33.00	1.1±0.2	104±00.50	00.31±0.01	SJ 89%P:11%S	660.00±0.50	77.00±3.60
K5	16.5	44±02.00 25±01.00	1100±77.00	1.00±0.2	192±02.00	00.40±0.03	I 89%N:11%S	636.00±1.50	34.00±2.90
K6	16.5	36±02.00 21±01.00	756±64.00	0.92± 0.6	178±01.00	00.60±0.02	WK 88%P:12%S	714.00±5.50	72.00±3.50

Note: * Fabric structure/Composition: SJ = Single Jersey, I = Interlock, WK = Warp Knitted, W = Woven, C = Cotton, V = Viscose, M = Modal, N = Nylon, P = Polyester, S = Spandex.

yarn (AIRism) [22], resulted in higher AP. Therefore, thickness, SD, or both and elastane ratio are not the only parameters which influence AP. For example, in the case of fabric K6, both SD and thickness are higher, but this fabric has a higher AP. The reason for this is its porous structure with many capillaries. Therefore, more air can pass through this fabric resulting in higher AP.

Figure 1 presents the results of AP and Wvp or breathability of fabrics. Fabric K4 and K6 have higher Wvp and those fabrics with lower AP like fabrics K1A, K1B, K2, K3 and K5 have lower Wvp. Moreover, the most breathable fabric is K6. Because of the open structure of this fabric and higher AP, more water is evaporated through this fabric resulting in higher Wvp.

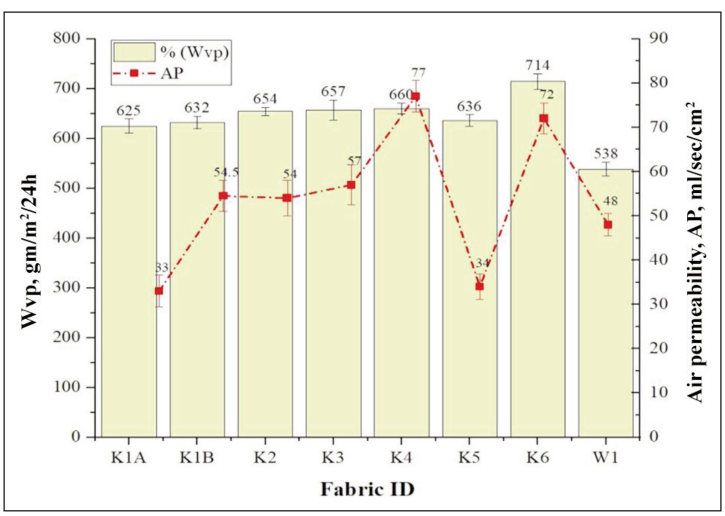

Fig. 1. Comparison of air permeability (AP) and breathability (Wvp) of underwear fabrics

MMT properties of underwear fabrics

The results of MMT indices obtained by the moisture management test are given in table 2. The wetting time at the top (WTt) and bottom surface (WTb) demonstrates the phenomenon during the initial contact with water. Generally, WTt is shorter. However, it can be seen that fabrics K1B, K2 and K4 have shorter WTb. This is because the thickness (as listed in table 1) of these fabrics is smaller. Therefore, the water passed through the fabric layer in a shorter time to the sensors at the bottom. Conversely, fabrics K1A, K1B, K3 and K5 have higher thickness and more fibre mass is required to be wetted resulting in higher wetting time. Additionally, fabrics K4 and K6 have shorter wetting times, because of their structure. Both of these fabrics have more capillaries as compared to other fabrics which is why water can pass through these fabrics more quickly resulting in shorter wetting time. Likewise, comparing the results of water absorption rate at the top (ARt) and bottom surface (Arb), it can be seen that fabric K6 has higher water absorption rates because the structure of fabric K6 is open and porous and has many capillaries like pores therefore, this fabric absorbed more water in less time. Furthermore, comparing the results of maximum wetted radius at the top (MWRt), at the bottom (MWRb), water spreading speed at the top (SSt) and bottom surfaces (SSb), the indices show how quickly fabric can spread moisture to a larger area.

It can be seen from table 2 that fabrics K1B, K2, K4 and K5 have larger MWRt. All fabrics have similar MWRb (10 mm) except fabric

Table 2

INDICES OF MMT PROPERTIES OF UNDERWEAR FABRICS										
MMT indices	Wetting time (s) Mean±SD		Absorption rate (%) Mean±SD		Max. Wetted Radius (mm) Mean±SD		Spreading speed (mm/s) Mean±SD		AOTI (R%) Mean±SD	OMMC Mean±SD
	WTt	**WTt**	**ARt**	**ARb**	**MWRt**	**MWRb**	**SSt**	**SSb**		
K1A	13.05±2.76	57.55±3.82	75.31±46.24	3.58±0.42	5.00±0.00	10.00±0.00	0.40±0.09	0.31±0.09	1304±67.96	0.50±0.01
K1B	12.14±9.05	5.87±1.56	35.29±19.54	49.04±39.68	13.33±6.24	10.00±0.00	1.73±1.40	2.23±1.11	1452±78.00	0.72±0.02
K2	6.4±0.2	5.8±1.2	35.49±1.42	8.3±4.52	15.00±0.00	10.00±0.00	2.43±0.09	2.61±0.08	1306±27.30	0.64±0.03
K3	12.06±2.95	25.94±6.9	69.71±32.63	37.02±26.00	7.50±2.50	10.00±0.00	0.63±0.13	1.37±0.85	1594±103.00	0.61±0.05
K4	3.40±0.23	2.64±0.52	46.89±15.47	12.32±8.16	27.5±2.5	12.5±2.50	6.61±1.02	3.6±0.08	1780±157.00	0.73±0.02
K5	11.92±3.55	26.07±9.6	59.07±13.48	5.07±0.63	15.00±0.00	10.00±0.00	0.503±0.08	0.702±0.26	1733±132.00	0.50±0.02
K6	6.62±1.26	9.94±1.05	168.79±10.57	18.00±1.41	5.00±0.00	10.00±0.00	0.79±0.17	2.96±0.69	2156±47.95	0.64±0.01

K4. This is because the MMT tester cannot accurately show MWRb. This problem has also been reported previously [23]. A larger wetted radius means that the fabric is a quick dry fabric with a higher drying rate. It can also be seen that fabric K4 has the largest value of MWRt and SSt. This is because of smaller fabric thickness, smaller AD, and the use of ultra-thin polyester fibres (AIRism) [22]. This fabric has higher permeability and prevents the build-up of moisture, making it more breathable and water can spread quickly to a larger area. On the other hand, fabrics K1A, K1B and K3 have higher thickness and fibre mass per unit area and more water can be absorbed in a smaller area resulting in smaller MWRt. Likewise, because of their open and more breathable structure as explained earlier (higher Wvp), fabric K4 and K6 showed higher accumulated one-way transport index (AOTI) values. Considering the results of OMMC of fabrics, it can be seen that most of the fabrics have very good OMMC except fabrics K1A and K5. It can also be seen that OMMC is inversely related to wetting time while directly related to the maximum wetted radius and spreading speed. From the above discussion, it is also evident that AOTI and OMMC have no relationship with other indices within tested samples.

The correlation coefficient between indexes of the MMT test and physical properties is given in table 3. AOTI has a strong positive correlation with Wvp confirming that fabrics with higher Wvp have good moisture transport ability. This is also evident from the results of AOTI (table 2) and Wvp (table 1).

Besides, AOTI and Wvp have a strong negative correlation with SL. Because a fabric with longer SL has a loose fabric structure with a larger exposed surface area of yarn and moisture takes longer to be

Table 3

CORRELATION COEFFICIENT BETWEEN INDEXES OF MMT, STRETCH AND PHYSICAL PROPERTIES									
Indices		**N**	**Correlation**	**P-value**	**Indices**		**N**	**Correlation**	**P-value**
Wvp	AOTI	7	0.875	0.004**	WTb	SSb	7	–0.705	0.051**
SL	AOTI	7	–0.921	0.003**	AP	SSb	7	0.913	0.002**
SSt	OMMC	7	0.702	0.050**	MWRb	MWRt	7	0.820	0.013**
SSb	OMMC	7	0.893	0.003**	ARt	MWRt	7	–0.640	0.044*
AP	OMMC	7	0.824	0.012**	WTt	MWRb	7	–0.677	0.032*
SSb	SSt	7	0.746	0.034**	WTb	WTt	7	0.820	0.013**
MWRt	SSt	7	0.894	0.003**	AP	WTt	7	–0.779	0.023**
MWRb	SSt	7	0.942	0.000**	T	WTt	7	0.638	0.045*
WTt	SSt	7	–0.754	0.031**	AP	WTb	7	–0.677	0.033*
AP	SSt	7	0.651	0.040*	T	WTb	7	0.820	0.013**
WTt	SSb	7	–0.818	0.013**	SL	Wvp	7	–0.672	0.034*
Indices		**N**	**Correlation (CD)**		**P-value**		**Correlation (WD)**		**P-value**
Stretch%	SL	7	0.823		0.011*		0.515		0.119
Recovery%	AD	7	0.247		0.297		**0.891**		**0.004***
Recovery%	Growth%	7	**–0.910**		0.002*		**–0.766**		**0.022***
SD	SL	7	**–0.816, 0.013***						

Note: ** Correlation is significant at 0.05 level (2-tailed), * Correlation is significant at 0.05 level (1-tailed).

transported resulting in smaller Wvp and AOTI. Likewise, OMMC has a strong positive correlation with SSb, SSt and AP. In addition, AP also has a strong positive correlation with SSt and SSb and a negative correlation with WTt and WTb. This shows that a fabric with higher AP has a faster spreading speed and at the same time can be wetted quickly. Because of higher AP, water spreads quickly on top, leading to quick transport of water to the bottom surface, resulting in shorter wetting time and higher OMMC. Moreover, SSt also showed a significant positive correlation with SSb, MWRt and MWRb. The correlation with MWRb was found to be very strong. The correlation analysis also showed that MWRt and MWRb have a positive correlation. MWRt has a negative correlation with ARt while MWRb has a negative correlation with WTt. These correlations indicate that a fabric with smaller ARt, faster SSt and shorter WTt has faster SSb, and larger MWRt and MWRb. This is also evident from MMT test results (table 2). Fabric K4 has the highest SSt, SSb and correspondingly larger MWRt and MWRb. On the other hand, SSt has a significant negative correlation with WTt, while SSb has a significant negative correlation with WTt and WTb. Furthermore, thickness (T) has a positive correlation with WTt and WTb. These correlations indicate that a fabric with a smaller thickness has shorter WTt, and WTb has a larger SSb. This is also evident from MMT test results (table 2). Fabric K4 has the least thickness, smallest WTt and WTb and fastest SSt and SSb. Additionally, WTt and WTb have a strong positive correlation with each other indicating that a fabric that can be wetted faster on the top surface can also be wetted quickly on the bottom surface.

Stretch properties of underwear fabrics

To identify physical parameters that influence the stretch and recovery properties of underwear fabrics, Pearson's correlation analysis was performed and the parameters with strong and significant correlation with stretch properties in CD and WD were plotted for comparison as shown in table 3 and figures 2 and 3. It is evident from the results that the direction with elastane induction (CD in case of weft knitted fabrics and WD in case of warp knitted fabric) has higher stretch. Stretch % has a significant positive correlation with Stich Length (SL) in CD indicating that a fabric with longer SL has higher stretch. This is also supported by the results in figure 2, Fabric K1A and K1B with longer SL showed the highest stretch% in CD. This is because SL is the length of yarn along CD and longer SL makes the fabric structure looser and easier to stretch. Furthermore, SL and SD have a significant negative correlation with each other confirming that a fabric with a smaller SL has a higher SD. This is because smaller SL makes fabric structure compact and tight resulting in increased SD and difficulty to stretch. In addition, it is evident from figures 2 and 3 that the fabrics with smaller SD and longer SL have higher stretch% and lower recovery%. Additionally, the recovery % is even higher in WD for these fabrics. One possible reason for this might be the fact that yarns run in CD in weft-knitted fabrics, therefore stretching in this direction stretches the yarns in their longitudinal direction that is parallel to the yarn axis and upon higher stretching there is a permanent deformation set in within the yarn structure because of fibre-to-fibre displacement as well as due to the extension of polymer chains in elastane filament. Therefore, the fabric cannot recover fully from stretch resulting in increased growth and smaller recovery. However, in WD there is no elastane filament, and elasticity comes from the interlooping of yarns in the fabric structure. Hence, upon stretching not only the stretch% is smaller but also the yarns are not stretched along their axis resulting in higher recovery% as shown in figure 3.

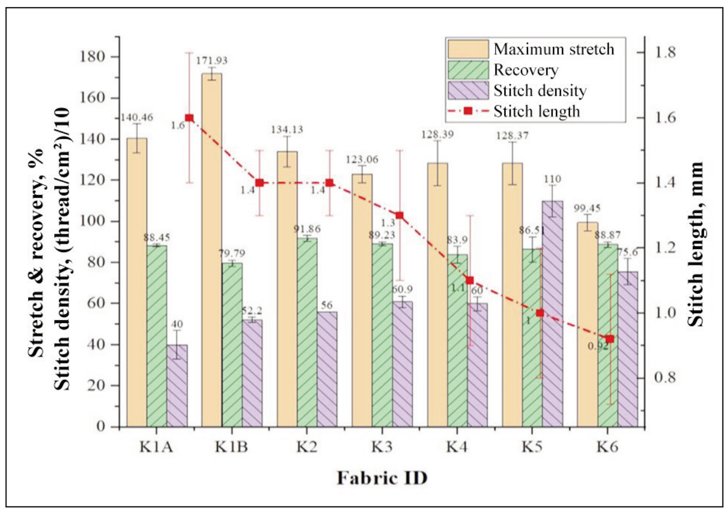

Fig. 2. Comparison of stretch and physical properties of different fabrics in course direction

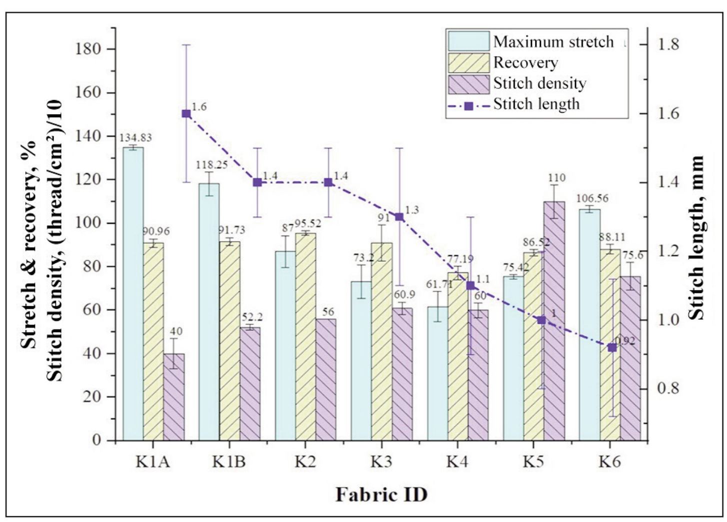

Fig. 3. Comparison of stretch and physical properties of different fabrics in the wale direction

Furthermore, the recovery% is also influenced by SD. Because of higher SD, the fabric becomes tight and difficult to deform resulting in lower stretch% and higher recovery%. The warp knitted fabric K6 also showed higher stretch% along the direction with elastane filament that is WD. Because of higher SD and tight warp knitted structure, this fabric has similar recovery% in both directions.

Additionally, the recovery% in WD has a strong positive correlation with AD. This is because fabric with higher AD has longer SL and upon stretching in WD, the yarns are stretched in a direction that is at 90° to their axis because of longer SL, the loops do just slide over each other and the yarns are not stretched up to the point of permanent deformation build up. This resulted in a higher recovery % in this direction. This is also evident from figure 2, Fabrics K1A, K1B, K2 and K3 have higher AD and showed higher recovery% in WD.

CONCLUSIONS

In this study physical, moisture management and stretch properties of underwear fabrics made of cotton, polyester cotton blend, nylon, viscose, bamboo, and modal are tested and characterized. Following conclusions can be drawn from this study.

- A fabric made of finer filament yarn, having a smaller thickness and higher AP has shorter WTt, WTb, faster SSt, SSb, larger MWR and better OMMC.
- A fabric with a smaller thickness shorter WTt and WTb has higher SSb.
- A fabric with higher WVp and smaller SL has higher AOTI.
- A fabric with Smaller ARt, faster SSt and shorter WTt has faster SSb and larger MWR.
- A fabric with shorter WTt also has shorter WTb.
- Stretch is higher in the direction of elastane filament induction while recovery is higher in WD in the case of weft-knitted fabrics but in the case of warp-knitted fabrics recovery is the same in both directions.
- A fabric with longer SL has higher stretch% in both directions and more recovery % in WD.
- A fabric made of finer filament yarn with a more porous and tighter structure, smaller thickness and AD, higher SD, and smaller SL has better OMMC and recovery%.
- A fabric with longer SL has better stretch%.

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