Frictional Behavior of Plain Woven Fabrics Constructed from Polyester and Cotton Yarns in Different Environmental Conditions

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ABSTRACT
Frictional characteristics of woven fabrics can determine smoothness and softness values of the fabric. Moreover different environmental conditions can leads to change the properties of the weaves.

In this paper, we studied the effect of temperature and relative humidity variations on the frictional properties of cotton and polyester fabrics. Plain woven fabrics were produced with polyester warp yarn and two different weft yarns (cotton and polyester). Each fabric was examined in various temperatures and relative humilities; then the frictional forces measurement was carried out on the fabrics in warp over warp direction. The results show that there is a statistically significant difference between the frictional parameters. This difference relates to the type of fiber material (weft yarns), temperature, and relative humidity.

In addition, the data reveal that cotton fabrics have more static and kinetic forces than polyester fabrics in all environmental conditions. Moreover, polyester fabrics exposed to a temperature of nearly 45°C and 100% RH, have the maximum smoothness. The highest roughness values for cotton fabrics were under conditions of 45°C and 20% RH.

Keywords: Plain woven fabrics, Relative humidity, Temperature, Cotton and polyester yarns, Adhesion, Roughness, Frictional resistance.

INTRODUCTION
Frictional properties of sliding surfaces are often characterized by the coefficient of friction defined when one fabric is rubbed mechanically against itself or tactually between finger and thumb. [1, 2]

These properties of fabrics are important in the determination of degree of roughness, smoothness and other surface characteristics. [3] Several theories of friction have been proposed or developed but generally fall into two main divisions: the coulomb or surface roughness theory and the surface interaction theory. [4] Howell [5] and Makinson [6] proposed a simple relationship for fibers which later was accepted in textile materials as follows:

$$F = aN^n + a_0 \tag{1}$$

where, a = constant of friction, n = friction index,
N = normal load, and a_0 = adhesion between the surfaces. The value of n has been found to lie between 0.67 and 1.0, being the limits of elastic and plastic deformations respectively. Next, it is suggested that adhesion term (a_0) giving a finite friction even at zero loads and from this (adhesion) term are extremely small[7].

In another consideration, total frictional force is defined as follows [8]:

$$F_{friction} = F_{adh} + F_{deform} + F_{cohesion} + F_{viscous} \tag{2}$$

where, F_{adh} is the joining together of two dissimilar materials, F_{deform} is a bulk phenomenon (due to a delayed recovery of the elastomer after indentation by a particular asperity), $F_{cohesion}$ is the joining together of different portions of the same material, and $F_{viscous}$ is the viscous drag under wetted conditions.

Indeed, the effective surface force is now the sum of F_{adh} and $F_{viscous}$. Also the effective bulk force is now the sum of F_{deform} and $F_{cohesion}$.

In accordance with the adhesion theory, the overall frictional resistance between two bodies, such as fabric against fabric, is composed of two terms, namely [9]:

(a) The ploughing term, that is related to the relative height of surface asperities.

(b) The adhesion term, that is related to the true area of contact between the fabrics.

A few papers have been published about the effects of temperature on fabric frictional properties; and most studies have been performed under conditions of room temperature. [3] Results show that by heating, the moisture content of cotton decreases and hence the friction between the fibers also decreases. [7]

Gwodsow *et al* [10] studied skin friction and sensations in neutral and warm environments and determined that the maximum skin wittedness of (43%) corresponds to a skin relative humidity of about 80%. Also they reported that fabric pleasantness decreased as air temperature and humidity increased. Markee *et al* [11] considered the water absorbed into the cotton and polyester fabrics. They were unable to find a perceived difference between wearing cotton and polyester in a warm humid environment, even at the early stages of their experiment.

Kenins [12] studied the influence of fiber type and moisture on measured fabric-to-skin friction. His results showed that fiber type has a small effect on fabric-to-skin-friction compared to the effect evoked by wetting the skin, but moisture has large effect on friction. Also he showed that wetting the skin, approximately doubled the frictional force. In fact changing humidity from 10% to 90% resulted in a change in forearm skin friction of about 20% to 50%, but with changing humidity to 100%, skin friction is double that of dry skin friction. A general experience reported was that a material in lower humidity, felt “rougher” than at high humidity. [12]

Other results indicated that although fiber type may contribute to the effects of changing humidity, its effect is a minor one. [12] The effect of sliding velocity of fabric was studied on frictional properties. [13]

Several theories have been proposed to understand the fundamental basis of adhesion, often with the aim to offer a universal solution. In every theory, different mechanisms, such as mechanical interlocking, interdiffusion, electrostatic attraction and chemical interaction forces are related adhesion properties. [14] Ramazani [15] considered the effect of moisture on mechanical properties and adhesion strength of nylon 6 and 66 cords. He concluded that the changes in mechanical characteristics and adhesion strength reflected in lower adhesion strength were due to moisture absorption and higher elongation-at-break, and that these changes were attributed to the plasticizer effect of moisture on the molecular chains of nylon 6 and 66 and degrading the isocyanate groups of RFL.

The present paper reports an investigation of the effect of temperature, relative humidity and material variables on the frictional properties of plain woven fabric using a special cabinet to generate different environmental conditions.

MATERIALS AND METHODS

Two different series of plain woven fabrics were produced from 153 denier (17 Tex)-40 filament polyester warp yarns and 306 denier (34 Tex)-68 filaments intermingle polyester (p) and 16.88 Ne (34.98 Tex)-580 T.P.M ring spun cotton weft yarns (c), as indicated in *Table I.*

TABLE I. Details of fabric physical parameters.

Sample No.	Fabric type		Ends per cm	Picks per cm	Warp count (den)	Weft count (den)	Fabric Wt. (g/m^2)	Thickness (mm)
	warp	weft						
1	100% polyester filament	100% cotton spun	41.0	20.8	153	314	151	0.32
2	100% polyester filament	100% polyester Intermingle	41.4	20.6	153	306	148	0.26

DESIGN OF CABINET

This conditioning cabinet was made from Perspex in small dimensions (100 × 60 × 70 cm). In order to isolate the cabinet, its inner in wall was covered by foam material. A schematic diagram of the cabinet is shown in *Figure 1*.

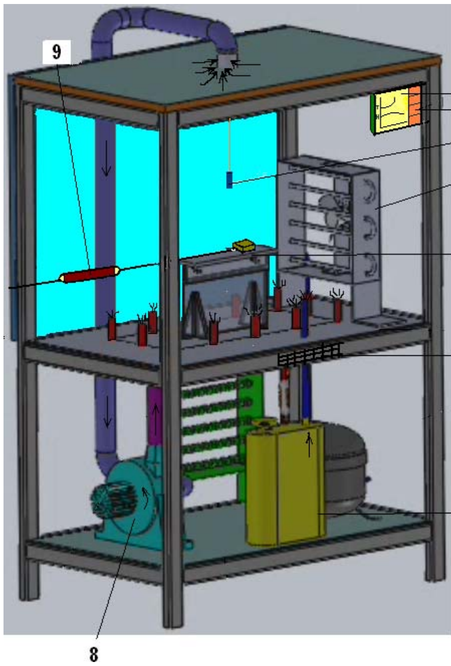


FIGURE 1. A schematic diagram of cabinet.

The cabinet consists of the following components:

1. L.C.D; to draw Temp-Time and Humid-Time diagrams by linking to sensor.
2. Touch key board; to enter temperature and relative humidity.
3. Temperature and Relative humidity sensor; to measure both temperature (-40°C ~123.8°C) and relative humidity (0% ~100%) value together.
4. Cooling unit; to bring down temperature near to -25°C.
5. Adjustable Jaw; to maintain and fixed Perspex platform horizontally.
6. Heating unit; to increase temperature up to 100°C.
7. Humidifier; to increase humidity values above to 100.
8. Central fan; to circularize air flows.
9. Small slider and guide; to pull sled by the instron cross head with negligible friction motion.

DATA EXPRESSION

Four temperature from 0°C to 45°C with 15°C intervals (0°C, 15°C, 30°C, 45°C) and five relative humidity from 20% to 100% intervals (20%, 40%, 60%, 80%,100%) were selected. Therefore twenty various environments were made to perform friction tests on the fabrics. Before starting the experiment, the samples were exposed to the above mentioned conditions for 60 minute. Specimens in each of conditions was tested in warp over warp direction of motion.

Both static and dynamic frictional resistance was determined by trace analysis in accordance with a procedure used by several other investigators. [16, 17, 18, 19] Frequency of data collection was 20 data points per second. Static and kinetic frictional forces were measured using a 20kgf load cell, with 0.49 cN sensitivity. The highest peak at the beginning of motion corresponds to the force required to initiate movement of sled was interpreted as the force needed to overcome static friction. The mean of peaks and troughs (equivalent to drawing a straight line through the middle the stick slip pulses) was taken as the kinetic frictional resistance and the different between the static and dynamic frictional force was taken as the F_S-F_K. These parameters describe the complete surface topography and are well correlated with tactile sensations of smoothness, scroopiness, softness, roughness and rigidness normally felt on fabric surfaces. Previous studies reported that the smaller the difference between static and the kinetic frictional forces (values of F_S-F_K), the smoother the fabric surface felt. [20]

RESULTS AND DISCUSSION

The experimental results of frictional parameters for all environments are given in *Table II*, and shown in *Figure 3*. A typical stick-slip chart, of plain1/1 cotton and polyester fabrics in warp over warp direction is shown in *Figure 2*.

The results were analyzed at 95% level significant by using ANOVA and Tukey tests using SPSS software (version 15). The final brief results from the statistical analysis are tabulated in *Table III*. It should be noticed the unit of frictional force is cN. It is evident from these results that there is a statistically significant difference between the frictional parameters owing to differences in environments in warp over warp direction of motion. Therefore, it can be concluded that the type of fiber material, relative humidity, and temperature, have important influence on surface adhesion. The Tukey tests to categorize the groups in homogeneous subsets for cotton and polyester fabrics in different relative humidity and temperature are shown in *Table IV-VII*.

TABLE II. Frictional parameters of fabrics in various environments.

Temp / Hum	T=0°C				T=15°C				T=30°C				T=45°C			
	Code	F_S(cN)	F_K(cN)	F_S-F_K (cN)	Code	F_S(cN)	F_K(cN)	F_S-F_K (cN)	Code	F_S(cN)	F_K(cN)	F_S-F_K (cN)	Code	F_S(cN)	F_K(cN)	F_S-F_K (cN)
RH=20%	F11c	85.5	66.5	19.0	F12c	89.5	68.4	21.0	F13c	90.6	69.3	21.3	F14c	101.4	75.0	26.4
	F11p	33.4	30.1	9.3	F12p	40.1	30.1	10.1	F13p	41.1	30.4	10.7	F14p	44.1	30.3	13.7
RH=40%	F21c	88.6	68.3	20.3	F22c	91.8	69.2	22.5	F23c	92.8	71.3	21.5	F24c	97.6	73.6	24.0
	F21p	40.3	30.8	9.5	F22p	41.0	29.9	11.1	F23p	42.1	30.6	11.5	F24p	44.1	29.9	14.2
RH=60%	F31c	90.5	68.2	22.3	F32c	94.2	69.7	24.4	F33c	95.7	72.5	23.2	F34c	96.5	73.1	23.4
	F31p	42.7	31.1	11.6	F32p	42.1	30.0	12.1	F33p	42.3	30.1	12.2	F34p	42.4	29.8	12.6
RH=80%	F41c	92.7	69.0	23.6	F42c	91.1	68.4	22.8	F43c	88.6	67.4	21.2	F44c	84.0	64.4	19.6
	F41p	44.5	31.0	13.5	F42p	40.2	29.0	11.2	F43p	39.5	28.5	11.1	F44p	39.2	28.2	11.0
RH=100%	F51c	96.2	70.5	25.7	F52c	87.5	67.9	19.6	F53c	83.6	66.2	17.4	F54c	77.4	62.7	14.7
	F51p	46.6	31.1	15.5	F52p	38.1	29.1	9.0	F53p	37.5	29.1	8.4	F54p	37.0	29.0	8.0

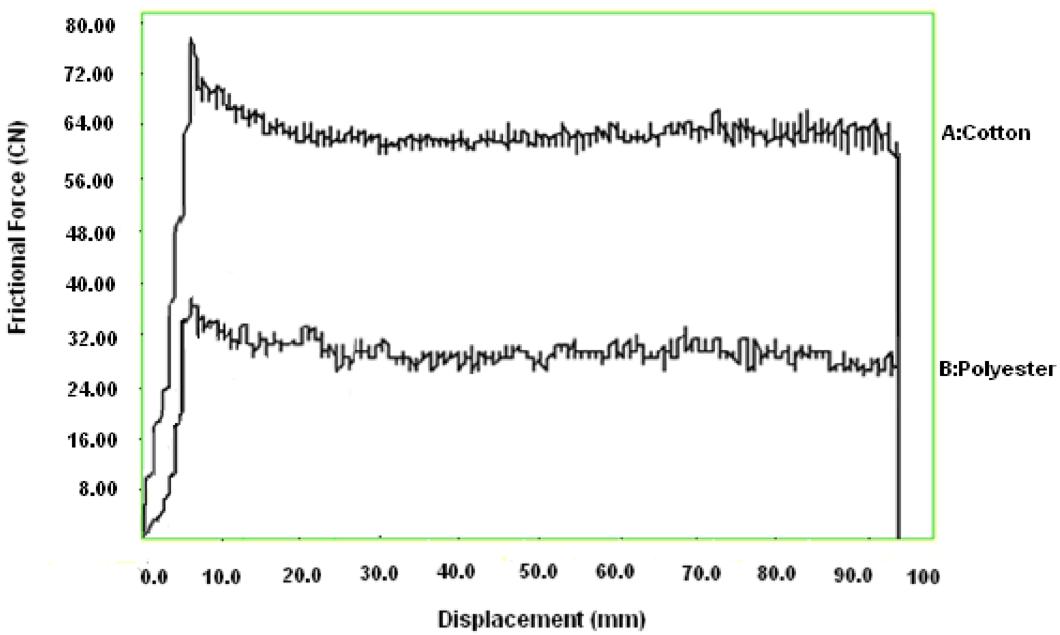
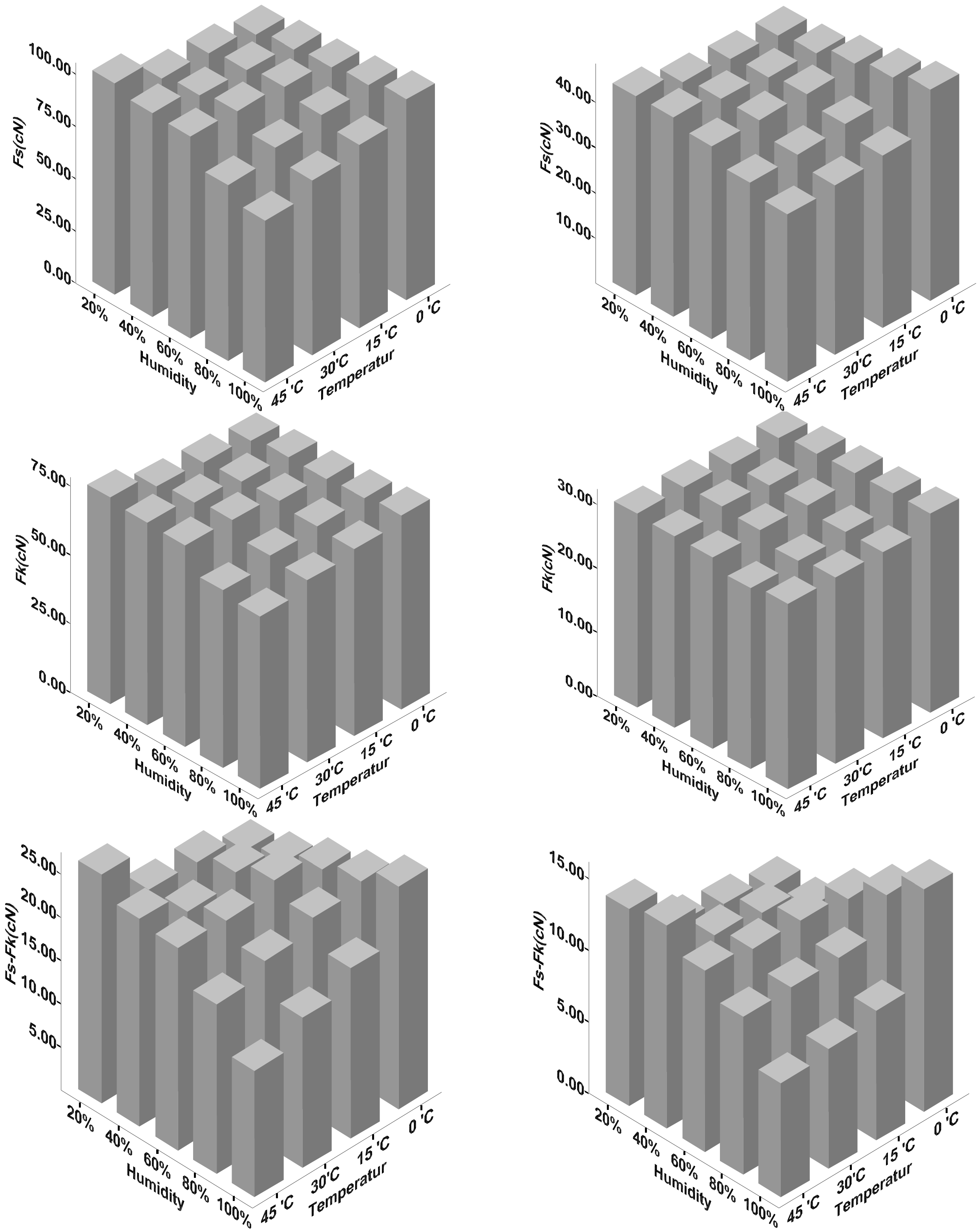


FIGURE 2. Stick-slip diagrams of plain1/1 (A: cotton and B: polyester) fabrics under 45°C and 100% RH.

TABLE III. A brief results of ANOVA test on cotton (C) and polyester (P) fabrics.

Frictional parameter / Variables	F_S(cN)		F_K(cN)		F_S-F_K(cN)	
	C	P	C	P	C	P
T= 0°C	*	*	*	*	*	*
T= 15°C	*	*	*	*	*	*
T= 30°C	*	*	*	*	*	*
T= 45°C	*	*	*	*	*	*
RH= 20%	*	*	*	*	*	*
RH= 40%	*	*	*	*	*	*
RH= 60%	*	-	*	*	*	*
RH= 80%	*	*	*	*	*	*
RH= 100%	*	*	*	*	*	*

***** Significant
- Non significant



A: Cotton Fabric

B: Polyester Fabric

FIGURE 3. Effects of temperature and relative humidity changes on frictional parameters (F_S, F_K and F_S-F_K) of fabrics (A: cotton, B: polyester).

EFFECT OF RELATIVE HUMIDITY VALUE ON THE FRITIONAL PARAMETERS

The results of ANOVA and Tukey tests in *Tables IV* and *V*, indicate that there is a statistically difference from the interaction relative humidity with temperature on F_S-F_K values. This means that relative humidity values causes decreasing of surface properties (surface asperity) in some temperatures, and increasing in other temperature values.

With reference to results in *Tables IV* and *V*, it is obvious, that at temperature of 0°C, with rising relative humidity values (within the range of 20% to 100% RH), there is an increase in the F_S-F_K parameter. In fact, due to increasing moisture regain in fabrics, many layers of water molecules may be bound and water may condense on the pores and cracks of the fiber surface. When exposed to cool environmental conditions, this causes frozen hydrogen bonds to be formed between water molecules and yield surfaces which lead to the strong adhesion forces.

It is evident from the experimental results (*Tables IV* and *V*), that at temperatures 15°C and 30°C, with increasing relative humidity, from 20% to 60% RH, an increase in adhesion forces between surfaces occur as well as the F_S-F_K parameter.. But within the range of 60% to 100% RH, the F_S-F_K parameter decrease. These results imply that at standard conditions (65% relative humidity and 15°C-30°C); the amount of chemical water absorption is reached to the highest value (*Figure 4*), indicating strong adhesion between water molecules and cellulose. However at 80% and 100% RH, the surface of cellulose reaches to the saturation level for the absorption of water. Therefore, the absorbed water layer behaves as a lubricant for further absorption of H_2O molecules. This leads to the decline of surface adhesion and hence frictional surface. It is similar to the previous studies [21, 22] that resulted under relative higher humidity, the behavior appears equivalent to that given by hydrodynamic lubrication conditions, and it is possible that the smooth surface and absorbed layers of water cause such behavior. As shown in *Table V*, frictional behavior of polyester fabrics at 15°C is as equal that at 30°C. This indicates that temperature within this range has the same effect on adhesion force as between surfaces of polyester fabrics

It should be noted that at 45°C, increasing of relative humidity causes the breakage of intermolecular bonds. Hence the decreasing attraction forces between surfaces and decline frictional properties in cotton and polyester fabrics (*Tables IV* and *V)*. This agrees with the previous results [7] which expressed that on heating, the moisture content of cotton decreases and the friction between fibers also decreases.

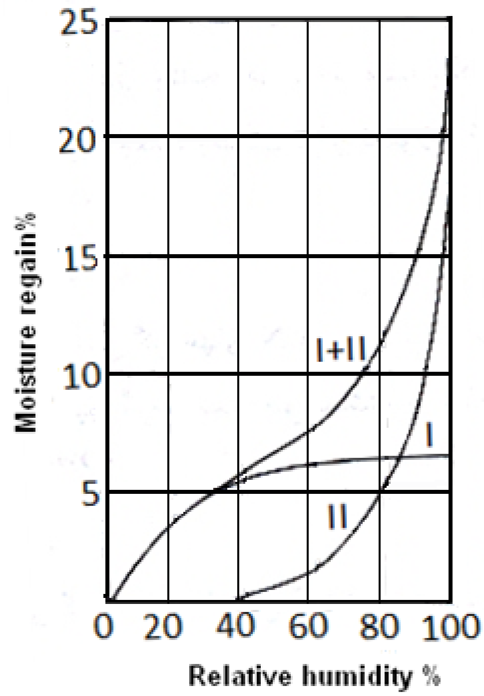


FIGURE 4. Effects of moisture regain and relative humidity changes on chemical (I) and physical (II) water absorption. [7]

EFFECT OF TEMPERATURE VALUE ON THE FRITIONAL PARAMETERS

Experimental results in *Tables VI* and *VII*, show that changing temperature value has a significant influence on frictional parameters of cotton and polyester fabrics. Extent of adhesion between two polymeric layers composed of different polymer phases is controlled by the degree of atomic and molecular interactions between the segments of the two polymers as well as the possibility for interdiffusion of the segments of one phase on to the other phase. However both degree of interactions and interdiffusion are governed by the ease of segmental motions of the two polymers phases. Therefore, temperature can play a significant role.

As shown in *Tables VI* and *VII*, it is evident that at 20% RH, with rising temperature, is increased degrees of roughness both (cotton and polyester) fabrics are increased. The amount of water absorbed is usually given by the parameter moisture regain, which is the mass absorbed per unit dry mass of fiber and expressed as percentage. In a low relative humidity condition (20% RH), cotton fibers inside the fabric are only able to absorb water chemically, (limited to 3.75% regain) and don not have water absorption physically (*Figure 4*). Fibers moisture regains at 0°C are at the highest values. Heat, decreases moisture content of cotton yarns. It causes increasing projection of yarn knuckles (crown height). [3]

TABLE IV. Tukey test for relative humidity to display F_S-F_K (cN) values in fabrics with cotton weft yarn.

Temp / RH	0°C					15°C				30°C			45°C			
Code	1	2	3	4	5	1	2	3		1	2	3	1	2	3	4
20%	19.0						21.1				21.3					26.4
40%		20.3						22.6			21.5				24.0	
60%			22.3						24.4			23.2			23.4	
80%				23.6				22.8			21.2			19.6		
100%					25.7	19.6				17.4			14.7			

TABLE V. Tukey test for relative humidity to display F_S-F_K (cN) values in fabrics with polyester weft yarn.

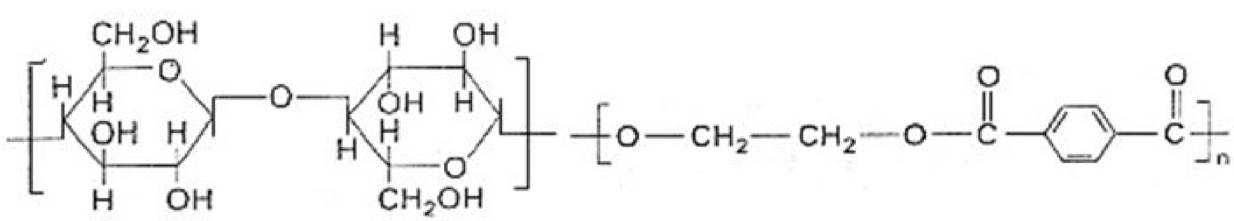
Temp / RH	0°C				15°C				30°C				45°C			
Code	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
20%	9.3					10.0				10.7						13.7
40%	9.5						11.1				11.5	11.5				14.2
60%		11.6						12.1				12.2			12.6	
80%			13.5				11.2			11.1	11.1			11.0		
100%				15.5	9.0				8.4				8.0			

TABLE VI. Tukey test for temperature to display F_S-F_K (cN) values in fabrics with cotton weft yarn.

RH / Temp	20%			40%				60%			80%			100%			
Code	1	2	3	1	2	3	4	1	2	3	1	2	3	1	2	3	4
0°C	19.0			20.3				22.3					23.6				25.7
15°C		21.0				22.5				24.4			22.8			19.6	
30°C		21.3			21.5			23.2	23.2			21.2			17.4		
45°C			26.4				24.0		23.4		19.6			14.7			

TABLE VII. Tukey test for relative humidity to display F_S-F_K (cN) values in fabrics with polyester weft yarn.

RH / Temp	20%			40%			60%		80%		100%		
Code	1	2	3	1	2	3	1	2	1	2	1	2	3
0°C	9.3			9.5			11.6			13.5			15.5
15°C		10.1			11.1		12.1	12.1	11.2			9.0	
30°C		10.7			11.5		12.2	12.2	11.1		8.4	8.4	
45°C			13.7			14.2		12.6	11.0		8.0		



A: Cotton B: Polyester

FIGURE 5. Chemical constitutions of the primary repeat unit of fabrics (A: cotton, B: polyester). [3]

Also at 20% RH, increasing temperature to 45°C, in fabrics with polyester weft yarn, can produce electrostatic attraction that increases static friction and roughness of fabrics. Other results (*Tables VI* and *VII)* determine that in both of cotton and polyester fabrics, between 15°C to 30°C, rough surface were constant. Because of this limitation, temperature is not able to create difference on adhesion force between the surfaces

As shown in *Figure 5*, cotton fibers in the fabric have hydrophilic groups (OH); and, therefore, at 40% RH can form hydrogen bonds with water molecules, directly. The amount of water absorbed is 5.1% water absorption chemically and 0.63% water absorption physically (*Figure 4*). [7] Therefore, chemical interaction due to attraction can increase adhesion forces and frictional parameters in cotton fabrics, as well(*Table VI*). Obviously, how much is absorbed per unit mass (of fibers) at 40% RH with different temperatures is lower than at standard conditions (65% RH and 20°C). It is evident with rising temperature, moisture regain in fibers decrease intensively. So similar to 20% RH, it leads to surface protrusions and increasing in frictional parameters (*Table VI*).

As shown in *Table VII* for polyester fabric, observed that within the range of 0°C to 30°C, moisture slightly, effected frictional parameters. The chemical water absorption of polyester fabric at 40% RH, is very little, (0.1-0.2% almost). [7] Therefore, frictional parameters of them, between 0°C and 45°C, are equal.

Experimental results from the F_S-F_K parameter in both fabrics (*Tables VI* and *VII*) show that at 60% RH and with different temperatures, the rates of change in frictional behavior of fabrics, are near to each other. Fibers absorb moisture to varying degrees depending on their chemical and physical structures. Moisture regain from ambient air at standard conditions (65% RH and 20°C) for cotton and polyester fabrics are 7.5% and 0.4% regain respectively (*Figure 4*). [7]

Because cotton fibers in the fabric have hydrophilic groups (OH), at 60% RH condition, the most chemical water absorption (hydrogen bonds) occurs between cellulose and water molecules. [12] The amount of water absorbed is 6.2% water absorption chemically and 1.87% water absorption physically. At 60% RH, the increase in friction with humidity can be largely attributed to the swelling of hydrophilic fibers as a result of moisture absorption. This will result in an increase in the true area of contact and a corresponding increase in fabric friction (*Table VI*). Also with increasing temperature (in the range of 0°C to 30°C), it is determined that temperature does not change smoothness values and static frictional resistance of polyester fabrics. In fact, due to lack of polar groups, polyester fiber has a very small attraction for water, which makes the material hydrophobic (*Figure 5*).

As shown in *Table VI* and *VII*, under relatively higher humidity, the behavior appears equivalent to that given by hydrodynamic lubrication conditions. It is possible that the smooth surface and absorbed layers of water led to such behavior. [23] Moisture regain of cotton fibers at 80% RH is 11.23%. [7] The amount of water absorbed, chemically does not change at 60% RH, and remains at 6.23% water absorption. But physical water absorption increased to 5% intensively. It should be noticed that the hydrogen bonds due to physical attraction are very weak particular when exposure to warm conditions. These properties cause addition force between fabric surfaces. Hence with rising temperature, smoothness of surfaces increases in cotton and polyester fabrics (*Table VI and VII*).

Saturation is reached at 100%. Up to this point, there is little water on the surface of the fibers. The amount of water taken up by these processes is called regain, and is highest in natural cotton fibers. These fabrics also take up water by wicking (capillarity along surface irregularities) and along the spaces between fibers. In this situation, water may be released by pressure applied to the fabric-to-fabric surfaces. With absorption, dimensions change. [22] With saturation, fibers may increase in cross-section area volume by 25-75%. Fiber length also increases, but by small amount (~1%).

In 100%, moisture regains of cotton and polyester fibers are equal to 24.75% and 2.5%, respectively. Data in *Table VI*, indicate that in cotton fabrics, the amount of water absorbed chemically is similar to that at 60% and 80% RH. (6.25% water absorption) and physical water absorption increases to 18.5%. This agrees with the results of previous researchers. [7] This behavior appears equivalent to that given by hydrodynamic lubrication conditions. [23] It is possible that smooth surfaces and absorbed layers of water (due to physical water absorption) led to such behavior. Therefore, at 100% RH, particular with rising temperature values, a decrease frictional parameters in cotton and polyester fabrics can be expected (*Table VI and VII*).

EFFECT OF THE TYPES FIBER MATERIAL ON THE FRITIONAL PARAMETERS

As shown in *Table II*, it is obvious that static and kinetic resistance of cotton fabrics is twice that of polyester fabrics in all of environments. This is because of polyester yarn is less populated with surface hairs than cotton yarn.

This is in agreement with previous results that report that fiber type has an important influence on fabric frictional parameters. [24, 25] When a fabric is in contact with another fabric, the surface fibers penetrate into the domain of the fibers in the contacting fabric. On the other hand, cotton and polyester fibers differ from each other in chemical and physical structures, and, as a consequence, in their surface and bulk properties. The surface morphology and the surface and bulk physical properties, including mechanical properties, play an important role in influencing fiber frictional properties; and, through it, the latter's performance in processing, handling, and end use application.

CONCLUSION

The relative humidity date show that the temperature factor within the range of 15°C to 30°C does not have a significant effect on the frictional parameters of polyester fabrics. Considering temperatures under the same relative humidity conditions, it was found that at 0°C temperature, frictional parameters in fabrics are at the highest values. This is attributed to the frozen hydrogen bonds between water molecules which adhere to surfaces and lead to the strong adhesion forces

Also polyester fabrics under nearly 45°C and 100% RH, were found to have maximum smoothness, but the most roughness values were for cotton fabrics at 45°C and 20% RH.

Relative humidity, type of fiber material, and temperature were found have an important influence on surface adhesion and fabric frictional properties related to mechanical interlocking, electrical, and chemical interactions.

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