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Alkaline Hydrolysis of Polyester Woven Fabrics and its Influence on Thermal Comfort Properties

Alsaid Ahmed Almetwally*

Textile Research and Technology Institute, National Research Centre, Dokki, Cairo, Egypt

Abstract

The aqueous alkaline reaction using sodium hydroxide on polyester fibers is a well-known process to give a silk-like fabric. In this process, hydrolytic scission of ester linkages of polyester chains occurs on the fiber surface. The key parameters of this process are NaOH concentration, temperature, treatment time, and pressure of squeezing rollers. The main goal of this study was to examine the thermal comfort features of polyester woven fabrics treated with an aqueous solution of caustic soda. The findings of this study revealed that the treated and untreated woven fabrics differ significantly in terms of their vertical wicking height. The vertical wicking height of all treated samples is superior to that of the untreated one. NaOH concentration and treatment temperature were found to have a significant and negative impact on the thermal resistance of the treated fabrics. On other hand, machine speed and pressure have a positive effect on the treated fabrics. It was also found that NaOH concentration, treatment temperature, machine speed, and pressure have all a significant influence on the air permeability of treated fabrics

***Keywords*:** Polyester fibre, weight reduction, alkaline treatment, thermal comfort, air permeability, thermal resistance, thermal conductivity

1. Introduction

Polyester fibers have conquered the first rank among all synthetic fibers because of their outstanding mechanical characteristics such as high tenacity, easy wash, considerable durability, and wear and wrinkle-free characteristics. However, apparel made from polyester fibers or filaments have some disadvantages such as waxy and clammy feel, high static charge, hydrophobicity, oleophobicity, low moisture regain, and tendency to pill in particular with blends [1-3]. Several attempts have been carried out to overcome these deficiencies. One of such methods is the weight reduction (de-weighing) or more specifically, the hydrolysis of polyethylene terephthalate by alkaline sodium hydroxide solution. This process has been used in the textile industry for a long time, in which some of the ester bonds in the polymer chains are split at ester linkages, resulting in the formation of carboxyl and hydroxyl polar groups, which improve polarity and hydrogen bonding capacity with water molecules, and thus better wettability [4-6].

Generally, the reaction of polyester fibers with an aqueous solution of sodium hydroxide is called topochemical, meaning that it is confined to the fiber surface, which in turn the reaction doesn't affect the polyester fiber core [7]. Weight reduction of the polyester fibers gives many advantageous characteristics such as increasing the absorbency, hydrophilicity, moisture regain and dye uptake while decreasing the tendency to pill and generation of static charge. Additionally, this process improves fabric handle resulting in a soft silk-like texture. Also, a reduction of fiber diameter, breaking strength, and elongation properties are associated with alkaline hydrolysis [5,8]. Sodium hydroxide concentration, temperature, treatment time, specific area of polyester fibers, previous history of the fibers, presence of accelerator, pre-setting effect, and polyester fabric construction are the key factors influencing the weight loss of polyester textile materials due to alkaline hydrolysis [9,10].

In the last two decades, numerous research works have operated on cotton and polyester yarn woven

*Corresponding author e-mail: saaa2510@gmail.com
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fabrics and their blends [11-26], fewer of them have been conducted on polyester fabrics, particularly their thermal comfort properties.

Thermal comfort refers to sensations of hot, cold, dry, or dampness in clothes and is usually associated with environmental factors, such as heat, moisture, and air velocity [11]. The Thermal comfort of textile products can be evaluated using an assortment of thermal and moisture management properties such as fabric weight, thickness, thermal resistance, thermal conductivity, wickability, air permeability, and water vapor permeability [12-14].

Małgorzata and Krzysztof [15] examined the structural parameters of woven fabrics on their thermal resistance. A significant correlation between integrated fabric structure, weft liner density, and thermal insulation properties was found. The thermal properties of textured knitted fabrics were investigated by Özçelik et al. [16]. They found that the thermal resistance of textured filament fabrics was higher than those woven from non-textured filament yarns. Because of decreasing contact area between human skin and textured yarns, thermal absorptivity values will be decreased. Due to the increased cover factor and thickness of textured yarn fabrics, they will be less permeable to air than those woven from non-textured yarns. Also, thermo-physiological properties of polyester fabrics knitted from false-twist textured, air-jet textured, and flat monofilament polyester yarns were studied [16,17]. The findings revealed that the thermal resistance of flat textured polyester fabrics was lower than textured fabrics.

In his study of thermal comfort properties of cotton polyester woven fabrics with different weave structures, Hakan Özdemir [18] found that weave structure and constituent fiber properties significantly affect thermal comfort properties of cotton polyester blended fabrics. It was also observed that sateen derivative weaves have the highest thermal resistance values making them suitable for winter clothes. On the other hand, twill weaves were appropriate for the hot climatic conditions because of their lower thermal resistance.

Moisture management is one of the key parameters of thermal comfort. It deals with the transportation of the perspiration away from the human skin to the surrounding environment. In order to keep the skin dry and hence the cloth wearer feels comfortable, the perspiration should evaporate quickly. Therefore, the structural design and quality of fibers that constitute the fabric should be modified to have a good performance in absorbing, transporting, and dissipating moisture. Such fabrics that have these characteristics are called moisture management fabrics. In the last few years there were a few research works concerning such types of fabrics [19,20].

This paper sheds light upon the thermal comfort properties of microfiber polyester-woven fabrics treated with an aqueous solution of sodium hydroxide. The key factors of this treatment were NaOH concentration, machine speed, temperature, and pressure of squeezing rollers. The influence of these parameters on the weight reduction of polyester fabrics and their effects on thermal comfort properties were investigated.

2. Experimental work

2.1. *Materials*

In this study, bleached plain 100% polyester woven fabric with warp and weft density of 30 ends/cm and 25 picks/cm respectively, and 198 g/m^2 was used. This type of fabric was woven from warp and weft staple PET fibers with linear densities of 135d/108f for warp yarns and 150d/48f for weft yarns.

The fabric samples have been subjected to weight reduction treatment with caustic soda with different parameters. The main factors of the weight reduction process, viz, sodium hydroxide concentration (%), the temperature of the steamer (treatment temperature) (^{o}C), treatment time (min), and the pressure of squeezing rollers (bar) were examined. Three levels of each independent variable of the weight reduction process were varied and used. The levels of each independent variable were listed in table 1.

Independent factors	Levels		
	-1	0	1
Caustic soda concentration (X_1), %	19	23	27
Temperature (X_2), ^{o}C	90	110	125
Machine speed (X_3), m/min	20	30	40
Pressure of squeezing rollers (X_4), bar	1	2	3

Table 1: Factors of weight reduction process and their levels and codes.

According to the independent factors and their levels that have been chosen above, a 3^4 full factorial design should be performed. Thus, eighty-one fabric samples, each with different treated conditions will be produced. Besides, one fabric sample has not been treated with caustic soda (blank sample), therefore the total number of fabric samples produced in this study should be eighty-two samples. Instead, and in order to reduce the number of treatments, the Taguchi L_9 orthogonal array (OA) was used. Using the Taguchi technique, the total number of experiments was reduced to one-ninth. That is, using the Taguchi technique, the total experimental treatments were 9 beside the blank simple. The experimental design using L_9 Taguchi Orthogonal Array (OA) which layouts the production procedure of the treated fabric samples in this study was listed in table 2.

Table 2: Layout of the experimental treatments using L_9 orthogonal array to treat drawn textured polyester

Sample No.	NaOH (%)	Temperature (°C)	Speed (m/min)	Pressure (bar)
1	**19**	**90**	**20**	**1**
2	**19**	**110**	**30**	**2**
3	**19**	**125**	**40**	**3**
4	**23**	**90**	**30**	**3**
5	**23**	**110**	**40**	**1**
6	**23**	**125**	**20**	**2**
7	**27**	**90**	**40**	**2**
8	**27**	**110**	**20**	**3**
9	**27**	**125**	**30**	**1**
10	**Untreated fabric sample (blank sample)**			

2.2. Weight reduction process

The process, largely known as a weight reduction technique, to which its patent was registered in 1958, is a prevalent finishing operation. In this process, the leaching of PET fabric's surface is widely adopted to realize a smooth surface and increased hydrophilicity in conjunction with a reduction in fabric weight and filament diameter [10].

Throughout this study, weight reduction operation of polyester woven fabric using an aqueous solution of caustic soda is accomplished in Misr Spinning and Weaving Company, Al-Mahala El-Kobra, Egypt, on continuous weight reduction machine, model ISSR-AW/2W.

The weight reduction process consists of four different stages, namely treatment with NaOH, steaming, washing, and drying respectively. Drawn textured polyester woven fabrics were treated with an aqueous solution of sodium hydroxide at room temperature (25-30 ^{0}C) with three different concentrations of NaOH, i.e .19%, 23% and 27%. A Soda bath is followed by two squeezing rollers through which the alkaline polyester fabrics pass to remove the excess of soda in the treated fabrics. The pressure exerted on squeezing rollers is varied to be 1 bar, 2 bar, and 3 bar respectively. After that, the woven fabrics were transferred into the steaming chamber in which the main reaction between NaOH and polyester filaments takes place. In this study, the temperature of the steamer (treatment temperature) ranged between 90 ^{0}C, and 125 ^{0}C. Following that the treated woven polyester fabrics pass through two washing stages, in which treated woven polyester fabrics are rinsed with running water at room temperature. Finally, the fabric samples pass through twelve drying cylinders, which are heated with superheated steam to dry the alkali-treated polyester fabrics. It should be noted that all cylinders on this machine have a width of 180 cm, but the operating width is approximately 160 cm.

The alkaline hydrolysis of polyester filaments is mainly occurred in the steamer and in the presence of high temperatures. During the hydrolysis reaction between sodium hydroxide and polyester filament, PET will be split into its monomers, i.e. Terephthalic Acid (TA) and Ethylene Glycol (EG) as shown in figure 1. It was believed that the alkaline hydrolysis mainly acts on the filament surface and doesn't affect the filament core significantly.

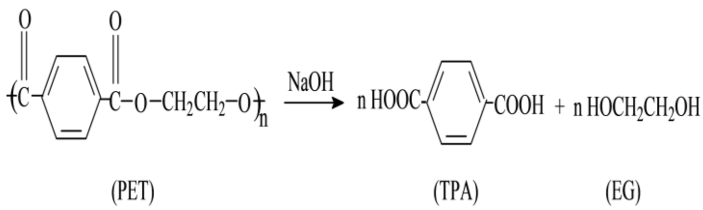


Figure 1: Alkaline hydrolysis of polyester

2.3. Laboratory testing.

Before testing, all fabric samples (whether untreated (blank) or treated samples) were left in a standard atmosphere for 24 hours to be dried and to be ready for measurements. All fabric tests were performed in the warp direction, and each fabric property was tested ten times and the average value was calculated.

The percentage of weight reduction of all treated fabric samples was calculated according to the following equation:

$$\text{Weight reduction (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$

Where, W_1 and W_2 are the weights per unit area of untreated and treated fabric samples respectively.

Fabric thickness of untreated and treated samples was measured using a fabric thickness tester according to ASTM D 1777- 97. The overall fabric porosity was calculated by the following formula [27]:

$$Porosity(\phi) = 1 - \frac{\rho_a}{\rho_b}$$

Where ρ_a is the fabric density (g/cm^3) and ρ_b is the average fiber density (g/cm^3). Fabric density depends on the weight and thickness of fabric, as shown in the following equation:

$$Fabricdensity(g/cm^3) = \frac{Fabric\_weight(g/cm^2)}{Fabric\_thickness(cm)}$$

Thermal comfort properties of treated and untreated polyester woven fabrics were measured in terms of air permeability, thermal conductivity, thermal resistance of fabrics, and relative water vapor permeability. Measurement of the thermal characteristics of polyester woven fabrics was done by means of an Alambeta instrument according to ISO 11092-2014.

Thermal conductivity is defined as the quantity of heat transmitted through the thickness of a surface area of fabric because of the temperature difference between its both sides. Thermal conductivity can be calculated using the following equation:

$$\lambda = \frac{\phi \times L}{A \times \Delta T}$$

λ = Thermal conductivity (W m^{-1} K^{-1})

ϕ = Amount of conducted heat (W)

A = area through which heat is conducted (m^2)

ΔT = drop temperature (K)
L= fabric thickness (m)

The higher thermal conductivity values associated with a particular cloth indicate that it gives a cooler feeling in comparison with other fabrics with lower conductivity values.

Thermal resistance is defined as the ability of a material to resist heat transmission through it. As the thermal resistance increases, the heat loss through the fabric decreases. Heat resistance is attributable to the air trapped within the individual fibers and between fibers and each other. Thermal resistance is a reciprocal of thermal conductivity multiplied by the fabric thickness. Thermal resistance can be calculated from the following equation:

$$R = \frac{t}{\lambda}$$

Where, R is the thermal resistance (W^{-1}m^{2}K), t is the fabric thickness in centimeter and λ is the thermal conductivity.

Relative water vapor permeability was also measured using the Permetest instrument according to ISO 11092-2014. Because the water is flown into the measuring head of this instrument, it loses some amount of heat. The lost heat from the measuring head in the case of being bare and covered with fabric was measured respectively. The relative water vapor permeability is expressed by the following formula:

$$RWV = \frac{Q_f\,(Wm^{-2})}{Q_b\,(Wm^{-2})} \times 100$$

Where, Q_f and Q_b are the lost heat from the covered and bare measuring heads respectively.

Vertical wicking height was measured in the warp direction for all treated and untreated polyester woven fabrics according to the method proposed by Fangueiro et al [28]. In this method, fabric samples were cut with dimensions 200 mm× 25 mm in warp and weft directions respectively. The specimens were hung vertically in the warp direction, and a clamp of weight 1.2 grams is fixed at the end of the fabric samples which is dipped in the water at 3 cm from its end. The wicking height is measured every 0.5

minutes and for 10 minutes for all samples as a direct evaluation of the fabric wicking performance.

Table 3: Physical properties of untreated and treaded woven polyester fabrics

Sample No.	Physical properties				
	weight (g/cm^2)	Thickness (mm)	Weight reduction (%)	Density (g/cm^3)	Fabric porosity
1	184.333	0.365	7.1	0.505023	0.734199
2	179	0.362	9.7	0.494475	0.73975
3	174.6677	0.348	11.9	0.501916	0.735834
4	185.667	0.368	6.4	0.504529	0.734458
5	177	0.359	10.8	0.493036	0.740507
6	151	0.322	23.9	0.468944	0.753187
7	186.667	0.374	5.9	0.499109	0.737311
8	145.333	0.314	26.7	0.462845	0.756397
9	143	0.311	27.9	0.459807	0.757996
10 (blank)	198.333	0.4	……	0.495833	0.739035

In order to explain and discuss the experimental results related to thermal comfort characteristics of untreated and treated polyester woven fabrics, their physical properties such as fabric weight, thickness, density, and porosity were measured. The values of these physical characteristics under different conditions of the weight reduction process for all ten fabric samples were tabulated in table 3. Also, the thermal comfort characteristics and vertical wicking at different times of untreated fabrics (Blank sample) are presented in table 4 and table 5 respectively

Table 4: Thermal Comfort characteristics of untreated polyester woven fabrics (Blank sample)

Air permeability ($cm^3/cm^2.sec$)	**Relative water permeability (%)**	**Thermal resistance (m^2KW^{-1})**	**Thermal conductivity Wm-1K-1 × 10^{-6}**
6.796	64.38	5.42	73.82

Table 5: Vertical wicking of untreated polyester woven fabrics at different times

Time (sec)	**Vertical wicking (cm)**	**Time (sec)**	**Vertical wicking (cm)**
0	**0**	**3.5**	**7.5**
0.5	**2**	**4**	**7.8**
1	**3.5**	**4.5**	**8.1**
1.5	**4.5**	**5**	**8.5**
2	**5.7**	**5.5**	**8.8**
2.5	**6.2**	**6**	**9.2**
3	**6.7**	**6.5**	**9.5**

2.4. Statistical analysis

On the basis of the selected independent variables and the adopted experimental design represented in tables 1, and 2, Analysis of Variance (ANOVA) was used to reveals which of the above variables significantly affect the thermal characteristics of the alkaline treated polyester woven fabrics. The significance level in this statistical analysis is $\alpha \leq 0.05$. A regression analysis was also used to derive the regression models which correlate the independent variables of the weight reduction process parameters to the treated fabric thermal properties. The multiple linear regression models have the following linear form:

$Z= a + b X_1 + c X_2 + d X_3 + e X_4$

Where,

Z = dependent variables (thermal comfort properties of the treated fabric samples)

X_1, X_2, X_3 and X_4= independent variables (shown in table 1)

a = constant, and b, c, d, and e = regression coefficients.

The coefficient of determination (R^2 value) was used to assess the prediction power of these regression models. The value of R^2 ranges between zero and one. As this value approaches one, this means that the regression models fit the data very well and they can be used reliably to predict the characteristics of treated fabrics at the different levels of weight reduction parameters.

3. Results and discussion

Before explaining and discussing the experimental results regarding thermal comfort properties, the SEM and FTIR results will be displayed first because they are closely related to the efficiency of the weight reduction process and treated fabric characteristics and secondly they will help us in understanding the influence of the aqueous treatment with caustic soda on thermal comfort properties.

3.1. *Scanning Electron Microscopy (SEM)*

In order to ascertain the alkali hydrolysis of drawn textured polyester filament 's surface, treated and untreated polyester woven fabrics were viewed under Scanning Electron Microscope (SEM) and their results were depicted in figure 2. From this figure, it can be noticed that, the untreated polyester filament appears with a smooth, flat, and thicker surface without any cavities.

In the case of alkali-treated polyester filaments, the alkali attacks nearly the entire filament's surface and resulting in its erosion. With the advances of alkaline hydrolysis, the erosion that extends inside the filament causes the formation of cavities or pits on the filament's surface. The pits on the treated filament's surface seem to be elliptical and elongated in the direction of the filament axis. This result is in agreement with what was observed for drawn textured polyester filaments (DTY) with Latta [29]. The elongated pits in the direction of the drawn textured filament axis may be ascribed to increased crystalline and amorphous orientation of the accessible regions. It can also be observed that at a high concentration of sodium hydroxide solution, the pits appear deeper, wider, and more in size, and the filament diameter becomes thinner. Also, with alkaline treatment, the surface of polyester filament becomes rougher.

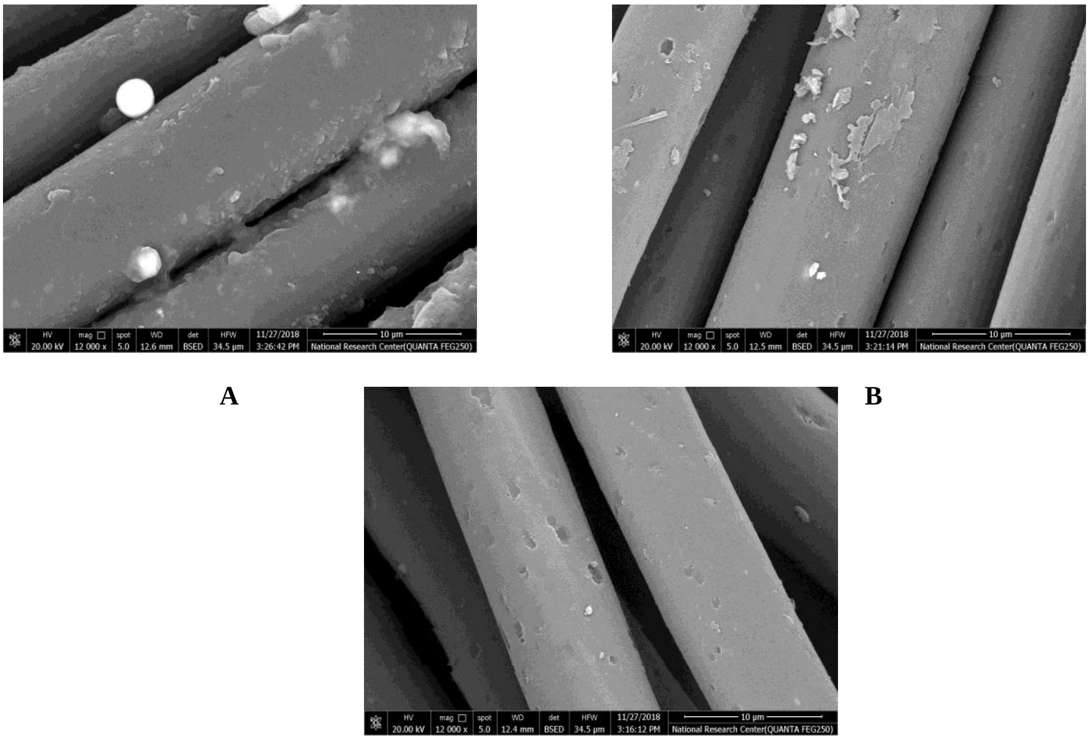
3.2. *FTIR results*

The results of FTIR spectra of untreated and alkali-treated drawn textured polyester filaments were depicted in figure 3. From this figure, it can be seen that there is a slight difference between the hydrolyzed and un-hydrolyzed samples. The high peaks appear in the wavelength ranging from 700 cm^{-1} to 1700 cm^{-1} points out to the original signal, like the prominent spectra of stretching vibration domain of C=O at 1709 cm^{-1} and C-O-C stretching vibration band at 1101cm^{-1} and 1252 cm^{-1}. All these peaks assure the presence of the ester linkage. The polyester-treated filaments show an additional peak at 2200 cm^{-1} due to the presence of carboxylic group (-COOH) on the surface of treated filaments because of the hydrolyses of the ester linkage. Finally, FTIR results are agreeing with those obtained by [14, 33].

3.3. *Vertical wicking*

Vertical wicking which is the spontaneous travel of a liquid through a porous material by a capillary force is an effective index of fabric thermo-physiological comfort, especially for underwear. Throughout this study, the wicking behavior of the treated and untreated polyester woven fabrics was investigated in terms of vertical wicking height in centimeters in the warp direction. The experimental results of the vertical wicking height were presented in figures 4 through 6.

The statistical analysis proved that there is a significant difference between the treated samples and each other, and between them and the untreated sample in terms of their vertical wicking height. In general, the vertical wicking height of all treated samples is superior to that of the untreated ones.



A B

C

Figure 2: Scanning electron micrographs of micro polyester filaments: A – untreated filament, B- treated filament with 19% sodium hydroxide concentration and C- treated filament with 27% sodium hydroxide concentration.

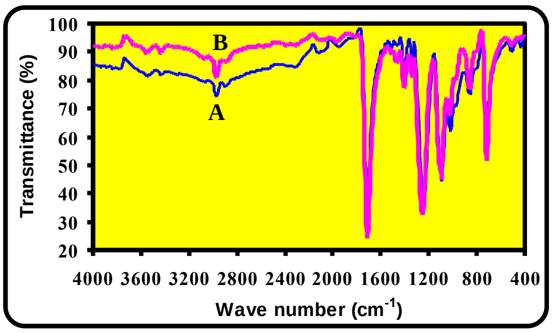


Figure 3: FTIR spectra of (A) untreated and (B) alkali treated drawn textured polyester woven fabrics.

In other words, vertical wicking of all treated fabric samples tended to be higher than that of the untreated fabric. For all fabric samples, it can be seen that the wicking height increases with time and with a decreasing slope. This decreasing slop may be attributed to the liquid moves at first in the smaller pores of the fabrics, in which the height rate will be faster because of the effect of the capillary action and its high pressure [30]. With time, the liquid continues to fill in the larger pores at a decreasing rate. When the mass of water absorbed in the fabric specimen is balanced with the hydrostatic head of water, the values of the vertical wicking become stabilized; as a result, the quasi-equilibrium state is reached [31]. From these figures, it can also be seen that the capillary rise of water into the treated fabric samples is stabilized after about 8-8.5 minutes, whereas for untreated fabric samples, it is stabilized after approximately 7-7.5 minutes.

The maximum vertical wicking values can be sequenced in descending order as follows: sample No.9 > sample No. 8> sample No. 6> sample No. 3> sample No. 5> sample No. 2> sample No.1> sample No.4> sample No.7> blank. This sequence indicates and confirms that fabric samples treated with higher NaOH concentration, higher temperature, and lower machine speed showed pronounced vertical wicking values. The statistical analysis also proved that the temperature and NaOH concentration were the most influential factors on the maximum values of vertical wicking followed by the machine speed; while the pressure was found to have no significant influence on the maximum values of the vertical wicking. Increasing NaOH from 19% to 27% leads to increasing the vertical wicking by about 15.6%, while increasing the temperature led to increasing the vertical wicking by approximately22.3%, and increasing the machine speed reduced the vertical wicking by 8.5%. Compared to the blank sample, the alkaline treatment of polyester woven fabrics increased their vertical wicking behavior by about 56%. The above results assured that alkaline treatment of woven fabrics reduced their mass per unit area, fiber, yarn, and fabric thickness, which in turn increases the fabric porosity. Finally, aqueous treatment with caustic soda of micro polyester woven fabrics enhanced significantly the thermal comfort of the treated fabric samples under study in terms of their vertical wicking behavior.

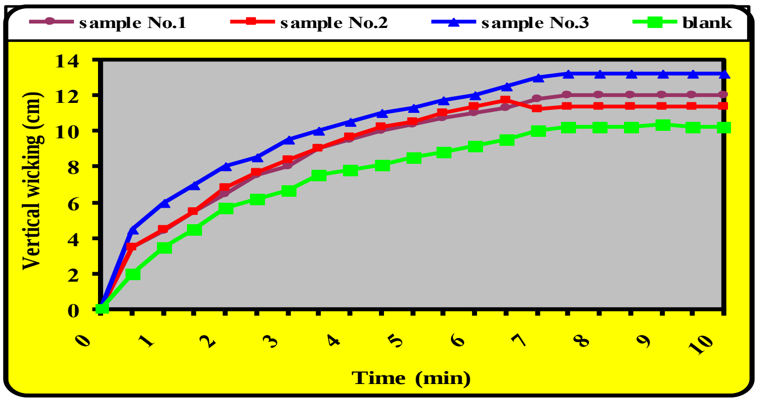


Figure 4: Vertical wicking behavior of treated and untreated polyester woven fabrics at 19% NoaH concentration

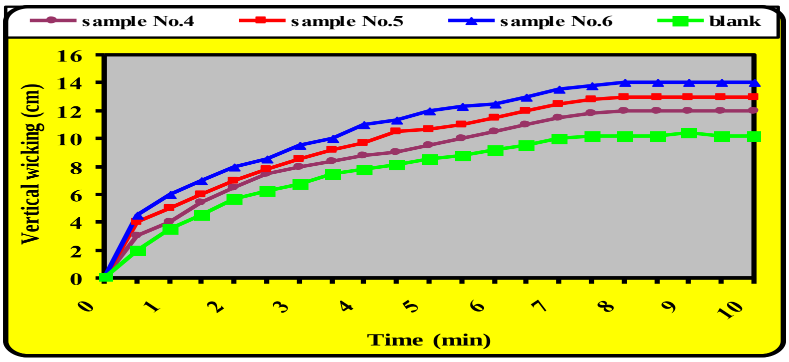


Figure 5: Vertical wicking behavior of treated and untreated polyester woven fabrics at 23% NoaH concentration.

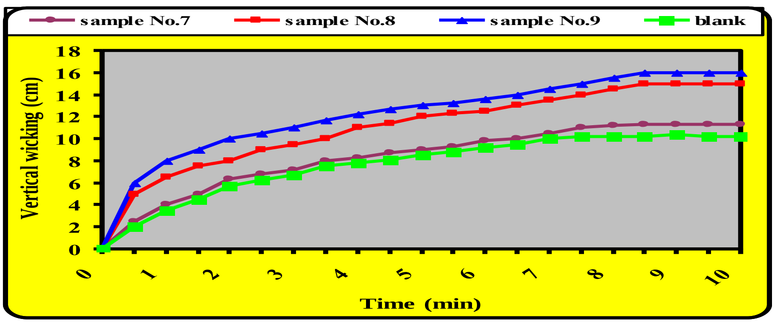


Figure 6: Vertical wicking behavior of treated and untreated polyester woven fabrics at 27% NoaH concentration.

3.4. *Thermal resistance*

Experimental Values of thermal resistance of alkaline treated polyester woven fabrics were illustrated in figures 7 and 8. The statistical analysis showed that all the weight reduction parameters significantly influence the thermal resistance values. It was observed that temperature and machine speed were the most influential factors on thermal resistance. It was also estimated that NaOH concentration, temperature, machine speed, and pressure accounted for 13%, 38.7%, 15%, and 24.8% of the effects on the thermal resistance of alkaline treated fabrics.

Figure 7 depicted the response surface of the influence of NaOH concentration and temperature on the thermal resistance of treated polyester woven fabrics. It can be seen that both variables have a negative influence on the thermal resistance values. That is as the level values of both factors increases, the thermal resistance of treated fabric decreases. Increasing aqueous caustic soda concentration from 19% to 23% leads to a decrease in the thermal resistance by about 11.6%. While increasing the temperature from 90°C to 125 °C leads to decreasing the thermal resistance values by approximately 22.5%. The negative effect of caustic soda concentration and its temperature on the thermal resistance may be ascribed to accelerating the erosion of the treated fabric surface with both, which in turn reduces fabrics' thickness and increases their porosity.

Figure 8 illustrated the response surface of the machine speed and the pressure on the thermal resistance of the alkaline treated polyester woven fabrics. It is shown that as both variables increase the thermal resistance reacts in the same trend. Increasing machine speed from 20 to 40 m/min leads to an increase of the thermal resistance of alkaline treated polyester woven fabrics by about 20%; while increasing pressure led to increase the thermal resistance value by 18%. The positive influence of machine speed on thermal resistance may be attributed to decreasing the reaction time of caustic soda with polyester woven fabrics which slows down the hydrolysis of the fabric surface, which in turn increases the fabric thickness and reduces its porosity.

Compared to untreated fabric samples, the alkaline treatment with NaOH at the defined machine parameters enhanced significantly the thermal resistance of the treated fabric samples. In other words, aqueous treatment of polyester woven fabrics with caustic soda reduced their thermal resistance by about 50%. This is because of the lower thickness and higher porosity associated with treated fabrics with caustic soda.

The multiple regression model which correlates the thermal resistance of the polyester fabrics with the weight reduction process parameters has the following linear form:

$$Y= 8.3 - 0.7 X_1 - 0.03 X_2 + 0.02 X_3 + 0.4 X_4$$

Where, the dependent variable, Y, represents the thermal resistance of alkaline treated woven polyester fabrics The statistical analysis proved that the coefficient of determination for this model is about 0.66 which means that this model explained 66% of the variation in the thermal resistance. This implies that, to some extent, this model fits data very well.

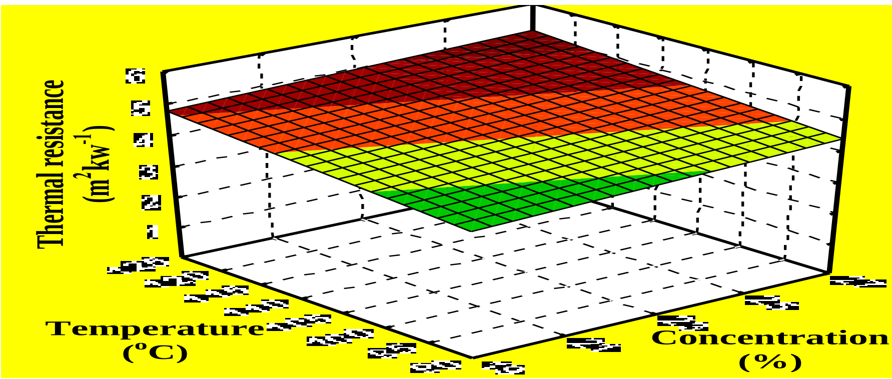


Figure 7: Response surface of the effect of NaoH concentration and temperature on thermal resistance of polyester woven fabric.

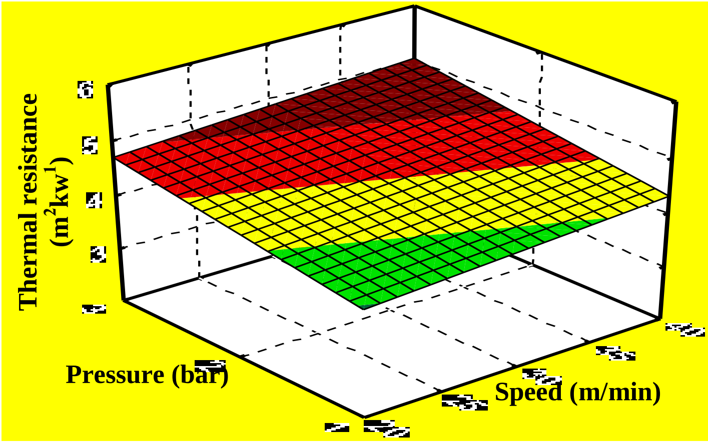


Figure 8: Response surface of the effect of machine speed and pressure on thermal resistance of polyester woven fabric

3.5. *Air permeability*

Air permeability is one of the most important parameters which defines and quantifies the physiological thermal comfort of woven fabrics. This property of woven fabrics is greatly influenced by fabric structure, fabric thickness, and porosity. The experimental values of air permeability of drawn textured polyester woven fabrics subjected to weight reduction with different conditions were depicted in figures 9 and 10. The statistical analysis proved that the variation in weight reduction process parameters such as NaOH concentration, treatment temperature, machine speed, and pressure have all a significant influence on the air permeability of treated fabrics at a 0.01 significance level.

Figure 9 shows the influence of both caustic soda concentration and treatment temperature on the air permeability of polyester woven fabrics. From this figure, it can be seen that as the levels of both variables increase, the air permeability has the same trend. Increasing the concentration of the caustic soda solution leads to increasing polyester fabrics' air permeability by about 49%. It was also found that the air permeability of hydrolyzed woven polyester fabrics was increased by approximately 86% with the increase in the treatment temperature. This result confirms that treatment temperature is one of the most influential parameters in the hydrolysis of polyester fabrics with caustic soda. The positive influence of hydrolysis process parameters on air permeability can be attributed to reduced fabric thickness and increased fabric porosity as shown in table 3.

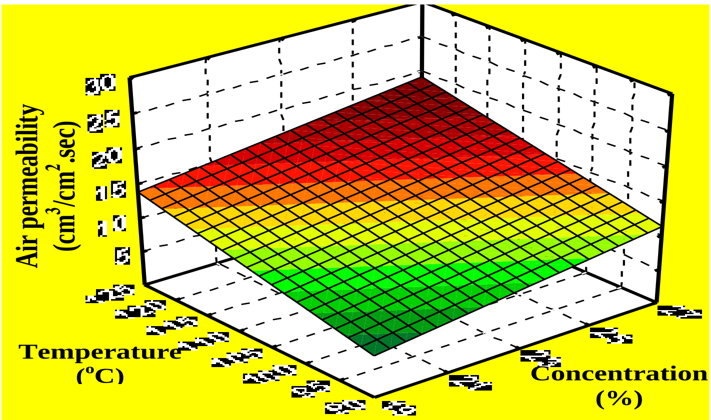


Figure 9: Response surface of the effect of NaoH concentration and temperature on air permeability of polyester woven fabrics.

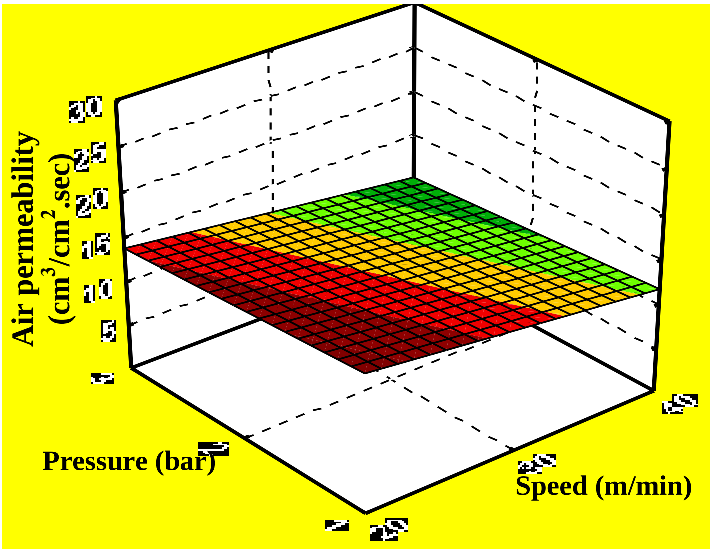


Figure 10: Response surface of the effect of machine speed and pressure on air permeability of polyester woven fabrics.

The influence of machine speed and pressure of the squeezing rollers on the air permeability of woven polyester fabric was plotted in figure 10. This figure shows the negative effect of both variables on the air permeability of hydrolyzed polyester fabrics. As the levels of both variables increase, air permeability decreases. The air permeability of hydrolyzed woven polyester fabrics reduced by 27% and 11% with the increases in machine speed and pressure of squeezing rollers respectively. The negative influence of machine speed on fabric's air permeability is the result of lower treatment time.

It can also be observed that the air permeability of woven polyester fabrics has increased from 6.8 $cm^3/cm^2.sec$ in the case of untreated fabrics to 16.6 $cm^3/cm^2.sec$ for alkaline treated fabrics. This means that the thermal comfort of woven polyester fabrics has improved significantly by the treatment with caustic soda solution.

The air permeability of hydrolyzed polyester woven fabric was found to be linearly correlated with hydrolysis process parameters with the following model:

$$Y = -20.8 + 0.7 X_1 + 0.2 X_2 - 0.2 X_3 - 0.8 X_4$$

Where, the dependent variable, Y, represents the air permeability of alkaline treated woven polyester fabrics. While independent variables, X_1 through X_4, were listed in table 1. The statistical analysis proved that the coefficient of determination of this model is 0.89; this means that this model explains the experimental results very well.

3.6. *Relative water vapor permeability*

Compared to air permeability, water vapor permeability differs in relation to the factors that force it to pass through the fabric structure. The mechanism of water vapor permeability through any textile material consists of diffusion, sorption, and transmission of water vapor through the fabric structure by forced convection. With respect to woven polyester fabric, diffusion through fabric structure is the dominant factor in this mechanism. Water vapor can mainly diffuse through the spaces and pores between yarns, filaments, and through filaments themselves. In general, diffusion is probably to take place in fabrics that have more open spaces and thinner thickness [32].

The values of relative water vapor permeability of alkaline treated polyester filament fabrics are seen in figures 11 and 12. The statistical analysis proved that alkaline treatment parameters have a significant influence on water vapor permeability of treated polyester fabrics except for the effect of squeezing rollers' pressure. Figure 11 shows the response surface of the effect of both NaOH concentration and treatment temperature on relative water vapor permeability of alkaline treated polyester fabrics. As seen from this figure, increasing the levels of both variables causes an increase in water vapor permeability of alkaline treated polyester fabrics. This result may be due to the low thickness and high porosity of alkaline treated polyester woven fabrics. It was proved that water vapor permeability through treated polyester fabrics increased by about 4% and 8% with increasing concentrations of caustic soda and treatment temperature respectively. By contrast, and as seen in figure 12, machine speed and squeezing rollers' pressure have negative effects on the relative water vapor permeability of the treated polyester fabrics. Increasing the machine speed signifies that treatment time is reduced. Therefore, the loss in fabric weight is small enough to not allow the passage of a large amount of water vapor. The pressure of the squeezing rollers was found to have no significant influence on the water vapor permeability for the treated polyester woven fabrics. Generally, as the pressure of squeezing rollers increases, the relative water vapor permeability of the alkaline treated polyester fabrics slightly decreased from 70% to 67.7%. Whereas, water vapor permeability decreased by around 1% with increasing the pressure of the squeezing rollers.

Compared to untreated polyester fabrics, it was found that the alkaline treatment of the polyester woven fabrics improved the thermal comfort significantly regarding their relative water vapor permeability. In general, the relative water permeability of alkaline treated fabric was about 70.5% against 64.38% for untreated samples. This is attributable to the lower thickness and higher porosity of alkaline treated fabrics.

The relative water vapor permeability of alkaline treated woven polyester fabrics is linearly related to the alkaline treatment parameters in the following model:

$$Y = 48.4 + 0.33\ X_1 + 0.16\ X_2 - 0.13\ X_3 - 0.01\ X_4$$

Where, the dependent variable, Y, represents the relative water vapor permeability of alkaline treated woven polyester fabrics. The coefficient of determination of this model is approximately 0.96 which signifies that the model fits the data very well.

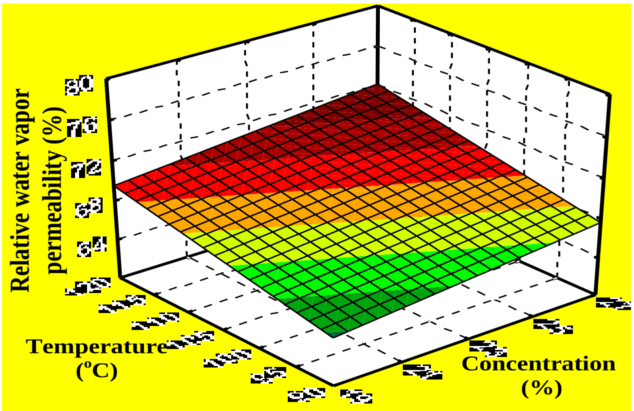


Figure 11: Response surface of the effect of NaoH concentration and temperature on relative water vapor permeability of polyester woven fabrics.

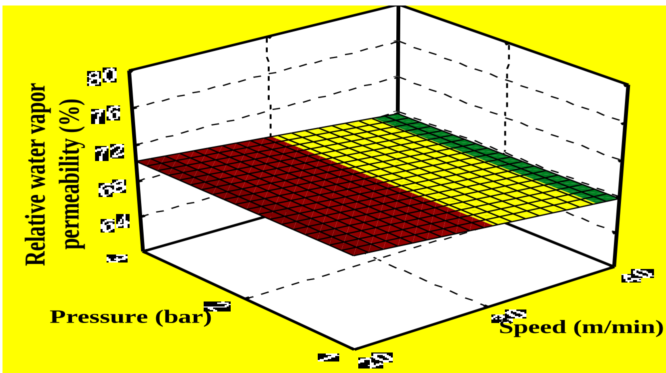


Figure 12: Response surface of the effect of machine speed and pressure on relative water vapor permeability of polyester woven fabrics.

3.7. *Thermal conductivity*

Values of thermal conductivity of alkaline treated woven polyester fabrics versus different parameters of weight reduction process were depicted in figure 13 and 14. The statistical analysis proved that all weight reduction parameters except for machine speed have a significant influence on alkaline woven polyester fabrics' thermal conductivity. Figure 13 depicts the response surface of the effects of caustic soda concentrations and treatment temperature on the thermal conductivity of alkaline treated polyester woven fabrics. As seen from this figure, a positive trend was detected for both independent variables confirming that as both variables increase, the thermal conductivity of the treated polyester fabrics reacts in the same manner. The statistical analysis proved that NaOH concentration and treatment temperature accounted for 13% and 20% respectively of the effects on thermal conductivity of drawn textured polyester fabrics. With increasing the concentration of caustic soda and the treatment temperature, the thermal conductivity values were increased by 12% and 21% respectively. The positive influence of both variables on the thermal conductivity values may be ascribed to the high weight loss and porosity of the treated fabric samples associated with hydrolysis treatment. On the contrary, as seen in figure 14, the speed of weight reduction machine and squeezing rollers' pressure have a negative influence on the thermal conductibility of the alkaline treated fabrics. As both independent variables increase, the thermal conductivity value decreases. Thermal conductivity values of the alkaline polyester treated fabrics are reduced by approximately 2% and 19.8% with increasing machine speed and squeezing rollers' pressure respectively. This is a natural result because of lower porosity and increased fabric thickness associated with the higher levels of machine speed and squeezing pressure.

Compared to blank (untreated) fabric samples, the high thermal conductivity of drawn textured polyester fabrics was associated with alkaline treated samples because of high weight loss, high porosity, and low thickness as a result of alkaline hydrolysis. It was estimated that the thermal conductivity of alkaline treated polyester fabrics improved by about 61% due to the alkaline process.

The thermal conductivity of alkaline treated woven polyester fabrics is linearly related to the alkaline treatment parameters in the following model:

$$Y = 22.8 + 1.2\,X_1 + 0.41\,X_2 + 0.3\,X_3 - 9\,X_4$$

Where, the dependent variable, Y, represents the thermal conductivity of alkaline treated woven polyester fabrics. The coefficient of determination of this model is approximately 0.84 which means that the model fits the data very well.

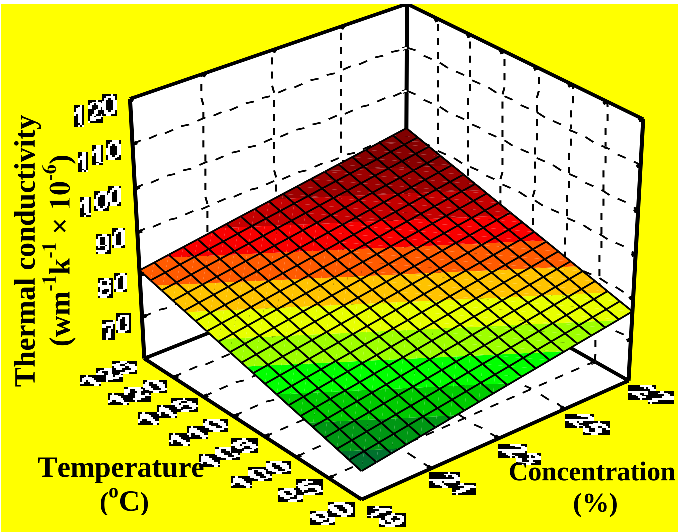


Figure 13: Response surface of the effect of NaoH concentration and temperature on thermal conductivity of polyester woven fabrics.

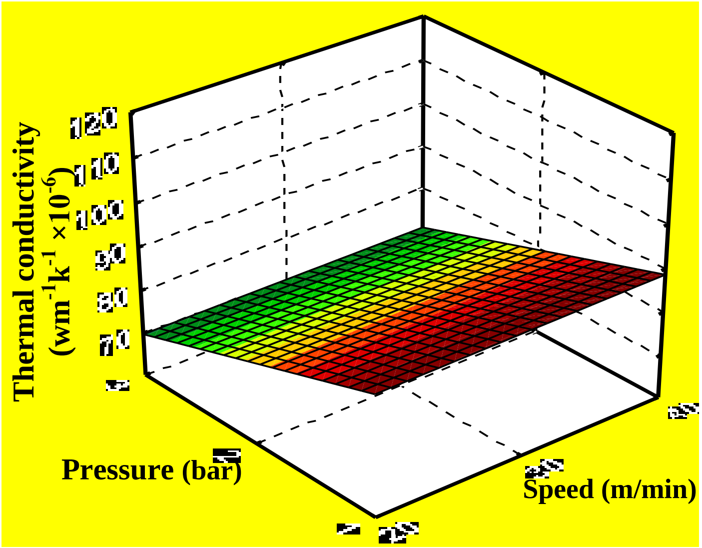


Figure 14: Response surface of the effect of machine speed and pressure on thermal conductivity of polyester woven fabrics.

Conclusion

In order to give a soft and silk-like handle for drawn textured polyester fabrics, the polyester filament diameter should be decreased significantly. This is done by the weight reduction process, in which the polyester fabrics are treated with aqueous caustic soda. In this process, hydrolytic scission of ester linkages of polyester chains takes place on the fiber surface. There are no changes in the orientation and/or crystallinity of the polyester filaments. The key parameters of this process were caustic soda concentration, treatment temperature, the pressure of the squeezing rollers, and machine speed (treatment time). All these independent variables were investigated for their effects on the thermal comfort of drawn textured polyester fabrics. The findings of this study can be summed up as follows:

- Vertical wicking of hydrolyzed samples, which is an effective index of fabric thermo-physiological comfort, was found to be superior to that of untreated ones.

- Treatment time and temperature were found to be the most negatively influential factors on fabric thermal resistance. As the levels of both variables increase, the thermal resistance of polyester fabrics decreases.

- Air permeability defines and quantifies substantially the physiological thermal comfort of woven fabrics. The variation of weight reduction parameters have a significant effect on this fabric property.

- Due to the low thickness and high porosity of alkaline treated polyester woven fabrics, they are superior to un-hydrolyzed fabrics regarding their relative water vapor permeability.

- Because of the high weight loss and porosity of the treated fabric samples, they have much thermal conductivity values compared to untreated fabrics.

The prediction models derived in this study can be effectively and reliably used to predict the thermal comfort characteristics of the alkali-treated polyester woven fabrics at different conditions of the weight reduction process.

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