IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 06, Issue 04 (April. 2016), ||V3|| PP 20-26

Experimental study and mathematical model to follow the hydrophilic property changes as result of stone wash treatment

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Abstract: - the technique based on contact angle measurements has been used to study, evaluate and follow the wetting property of denim fabric surface before and after stone washing treatment. Then, a mathematical model is proposed that describes the hydrophilicity of treated denim fabric as function of time. This mathematical equation is used to interpret the experimental data in terms of kinetic parameters of the water drop spreading. Results show that the theoretical model predictions are in reasonable agreement with experimental data with higher average determination coefficients. It's also observed that the drop spreading process of water could be divided into two steps, viz rapid and slow processes.

Keywords: - *Denim fabric; stone washing treatment, mathematical model, wetting property.*

I. INTRODUCTION

Denim is the most amazing fabric and it is the huge component in the wonderful world of fashion. It's the staple garment that everyone owns. It's versatile, it's tough, it's durable, it's easy to work with, it's warm … Denim clothing are the most preferred and popular of today's youth, especially the washed-out jeans or the Denim jeans with old look. So, the increasing demands for aesthetic textile products cause the development of new treatments and techniques for processing and designing textiles [1-3]. That's why, manufacturers looking to develop, optimize and evaluate these new processes.

Control, optimize and implementation of these production processes in company require understanding of the physic-chemical properties of cotton which is the main component of jeans. The cotton is known as the "king" of textile fibers because most of the world's fabric is made of cotton. It is characterized by a good strength and it is considered to provide comfort due to its good moisture adsorption and wicking properties [4]. The dyed cotton can be considered as a hydrophilic fiber. After dyeing and elimination of all natural impurity, this fiber can interact with water molecules. Indeed, cotton, a cellulose-based material, is a natural material. It has strong polar groups (-OH) that readily interact with water, giving a good hydrophilicity property. So, cotton fabrics have surfaces that are easy to be wet, with water contact angle of < 90°.

Treatments of finishing garments during washing are the important parameters influencing mechanical properties. The application of these treatments causes aged look for garment [5] and reduce greatly the mechanical properties [6]. Also, it is well known that the wettability, the hydrophilicity and the absorption ability of the cotton fiber change with application of these treatments of finishing on the fabric [7-9]. The spreading and impregnation of liquid on treated and untreated textile fabrics is the subject of numerous studies which interested on the hydrophilic property of the material. The capillary rise phenomena in fibrous porous media are of great importance in wetting and wicking in textile structure and extensive publications are available [10-14]. The surface tension, the gravitational forces, the viscous forces and the contact angle have been considered and studied and investigated to characterize the wettability of textile and porous materials [15-17].

In this article, we are interested in the changes of hydrophilic property of jeans dyed fabrics as a result of stone washing treatment. The wettability of the untreated and treated jeans fabrics is evaluated by measuring the contact angle using the GBX Digidrop apparel. Also, a mathematical model has been developed using MatLab to predict the complete profile of the horizontal wicking of water drop through the woven fabrics considering different influencing parameters, i.e. amount of pumice stone used for washing and the duration of the treatment. The developed model allows the possibility to determine the diffusion kinetic parameters of the water in the textile.

II. MATERIAL AND METHOD

2.1. Material and treatments

Indigo dyed denim garments are used for this experiment. The fabric is commercially available 100% cotton with 3/1 twill weave construction, 30 warp yarns per cm and 20 weft yarns per cm. The linear density of warp and weft are 96 and 100 Tex, respectively. The surface density of the fabric is about 430 g/m².

Before stone treatment, the desizing was conducted in liquor containing soda ash (1,5 g/L), detergent (0,5 g/L), desizing agent (0,5 g/L) and garments to liquid ratio of 1:40 in industrial machine at 55°C for 20 minutes. After that garments were washed with hot water (80°C) followed by cold washing (30°C).

Then, the garments dyed by indigo are washed in industrial washers with stones. Fresh pumice stone are added to the garments during wash. We are used two amounts of pumice stone for two duration times. The experimental designs of treatments are as follow:

Table 1 Level of different variables for experimental design

Treatments	Variables	Symbols	Levels	
stone washing	Amount of pumice (Kg/Kg)	[C]	1,5	3
	Duration	D	25	50

2.3. Measurements

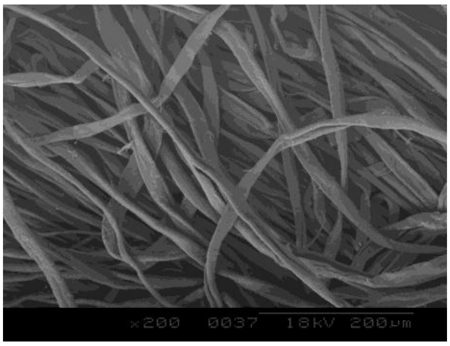
In order to study the influence of the washing treatment on the hydrophilicity of the denim fabrics and to evaluate the wetting property of the textile surface, method of contact angle measurements were investigated. “Water-textile surface” contact angle were measured using the drop shape analyzer (Digidrop GBX Contact angle Meter - France) equipped by video-camera system and computer software. The contact angle of the liquid was measured using 5µL droplet which was gently deposited on the surface using the syringe.

III. RESULTS AND DISCUSSIONS

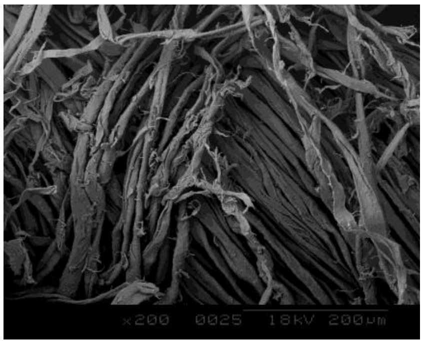
3.1. Visualization of the surface of the treated fabric

Before studying the influence of washing treatments on wettability of the textile, we are analyzed the treated textile surface via the Scanning Electron Microscopy (SEM). This technique allows visualization of the surface of the textile and then detects the changes in roughness degree. Samples (stone washed and unwashed) were cut at 4 cm² pieces. Specimens were examined at 200 X magnification.

Figure 1 displays the SEM images of the original fabric (the unwashed fabric) vs. the treated one (stone washed fabric) at 200X magnification. It is clear and easy to distinguish the difference on the topographical properties of the surface between the three substrate samples.



(a)



(b)

FIG. 1 SEM micrographs at magnification of 200x. (a) Micrograph of the original jean fabric, (b) Micrograph of the fabric treated by 3Kg/Kg of Pumices for 50 minutes

From the figure 1, it is observed that the surface of sample washed with 3kg/kg of pumices C for 50 minutes is somehow worn and frayed at the surface. Moreover, it is noticed some sign of fiber fracture, and roughness. The mechanism of wear with stone wash is characterized by signs of fiber fracture, debris and roughness formation.

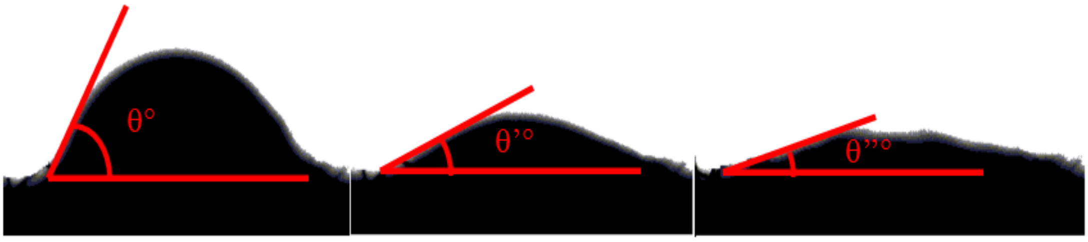
3.2. Hydrophilic study of the treated fabric

Wetting of water on the textile surface depends not only on the chemical nature but also on the morphological structure and topographical properties of the surface. For this reason, we are study the wettability of the original jean fabric and the washed one by measuring the contact angle of the substrate with the water. The volume of water used for the contact angle measurements was 5µL. The well-known young equation describes the balance at the three-phase contact angle of the textile, water and vapor.

$$\gamma_{tex,v} = \gamma_{tex,w} + \gamma_{w,v} \cos \theta_y$$

Where:

$\gamma_{tex,v}$, $\gamma_{tex,w}$ and $\gamma_{w,v}$ are the surface tension of the textile/vapor interface, of the textile/water interface and of the water/vapor interface respectively.



t=0s, θ=68° t=0.20s, θ=17.3° t=0.36s, θ=9°

FIG. 2- Evolution of the water – stone treated fabric (W=3Kg/Kg, D=50min) contact angle vs. time

Considering results given in figure 2 which illustrates the evolution of water contact-angle on the textile substrate, we can observe that the contact angle on the sample washed by pumices stone changes as a function of time from 68°, at the first contact, until 9° after 0.36s due to its good moisture adsorption and hydrophilic properties.

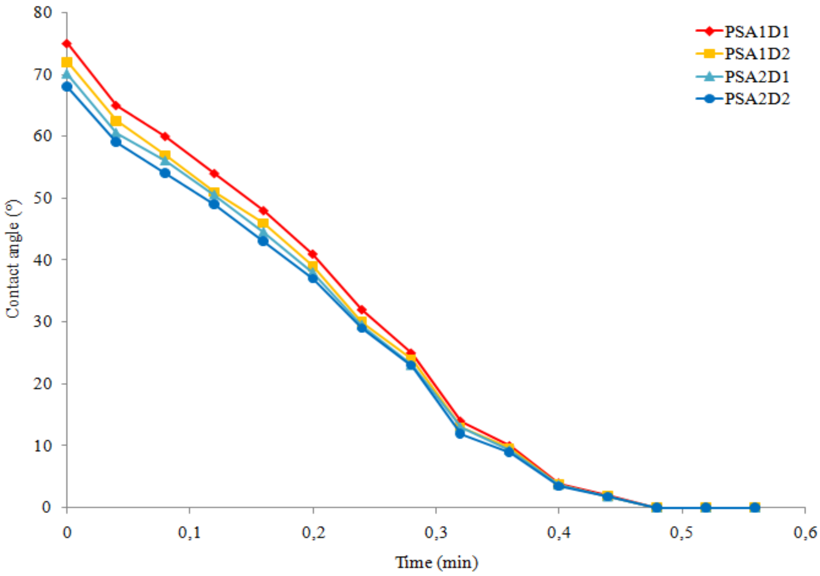


FIG. 3 Evolution of the water – denim fabrics contact angles vs. time

In figure 3, we have reported experimental data of the evolution of the water contact-angle on all samples used in this study as a function of time when water drop deposited on the surface. From curves, it was noted that at the same time the water-denim fabric contact angle is significantly influenced by the washed treatment. The lowest contact angle value was noted for the fabric washed by 3 kg/kg of pumices stone for 50 minutes and the highest one was noted for the untreated fabric.

Factors that influence the "water - stone washed denim fabric" contact angle were evaluated by using factorial plots; main effects and interactions. Main effects of each parameter (Amount of pumices stone and treatment duration) on contact angle after wash treatment are displayed in figure 4.

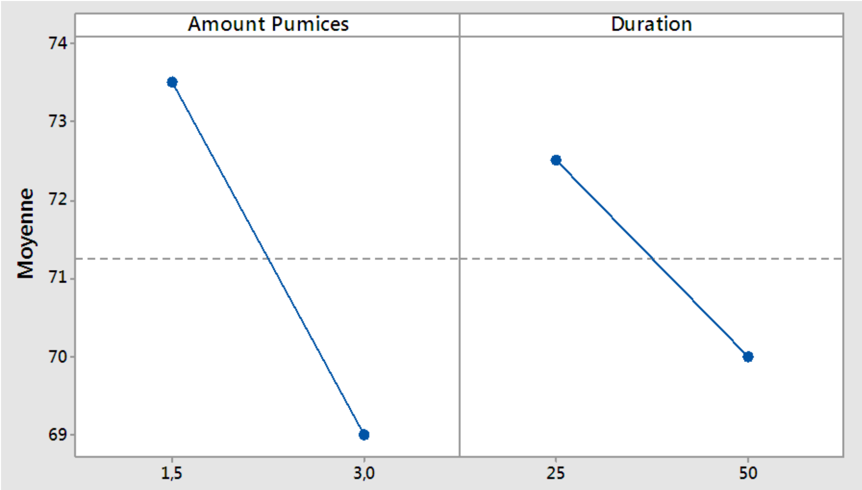


FIG. 4 Maineffects diagram for water-textile contact angle at stone washing treatment

From figure 4, the effect of Amount pumices stone and treatment duration on the water-textile contact angle is clearly identified. The Amount of pumices stone parameter shows a more significant influence as compared to duration of treatment process.

The interaction plot shown in Figure 5 is a plot of means of water-textile contact angle for each level of one factor with the level of the second factor held constant. Interactions plots are useful for judging the presence of interactions, which means that the difference in the response at two levels of one factor depends upon the level of another factor. Parallel lines in an interactions plot indicate no interaction.

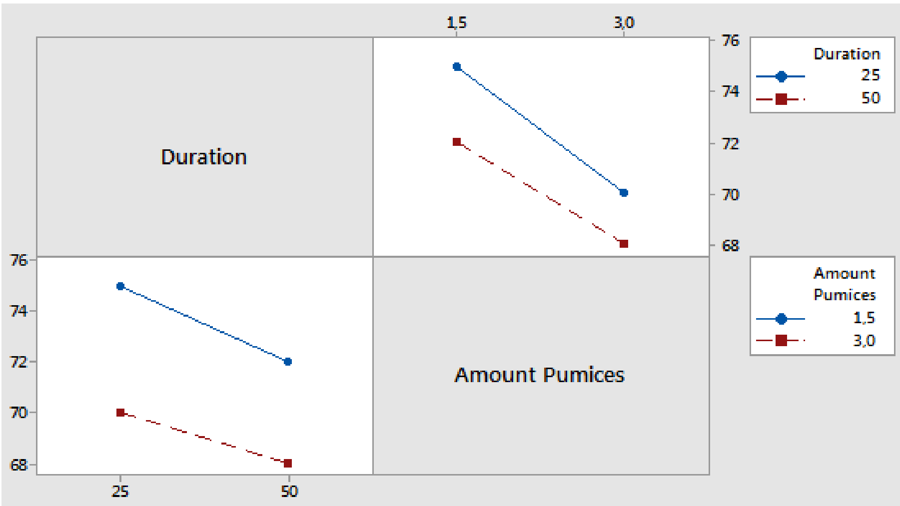


FIG. 5 Interaction diagram for water-textile contact angle at stone washing treatment

As it is clear from figure 5, interaction diagram shows a negligible interaction between the duration and the amount of pumices stone because the lines have the same tendency.

Figure 6 illustrate the contour plots which show contour lines of Amount of pumices stone and D factors. The contour plots were helpful to see the shape of the response surface and to understand how the response changes in a given direction by adjusting the design variables and, so, to find the optimum response.

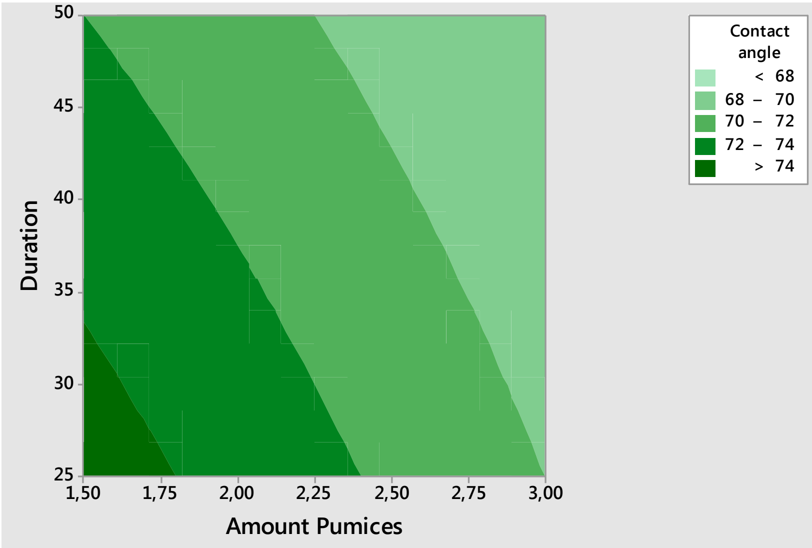


FIG. 6 Contour plots of Water – textile contact angle versus D and Amount of pumices stone

3.2. Spreading kinetics of the water drop deposited on denim fabric

In order to better understand the influence of stone wash treatment on hydrophilic properties of textile and to interpret the spreading kinetics of water drop deposited on textile surface, the experimental "water-fabric" contact angles at each time were curve fitted using MatLab to the exponential kinetics model (Figure 7). This model has a double exponential form as given by the following equation [18]:

$$\theta = \theta_{\infty} exp(-K_1 t)$$

Where θ is the water-fabric contact angle at time "t" and the terms θ_{∞} are the water-fabric contact angles at first contact (time=0s). K_1 is the spreading kinetic of water drop.

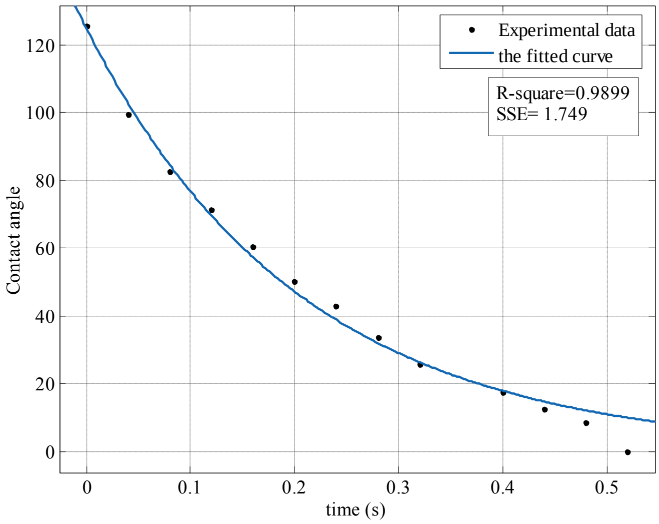


FIG. 7 Fitted curve of the water – untreated denim fabrics contact angles vs. time

In figure 7 the lines were the best fit of the mathematical model to the kinetics experimental data. The validity of the exponential model in the three fabric cases in describing the kinetic data is checked by the correlation coefficient (R-square) and the sum of square due to error (SSE). R-square and SSE were defined as:

- Sum of Squares Due to Error (SSE) which measures the total deviation of the response values from the fit to the response values. A value closer to 0 indicates that the model has a smaller random error component;
- R-square is the square of the correlation between the response values and the predicted response values. It can take on any value between 0 and 1, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model.

Table 2 summarizes the exponential model fitting parameters, the R² and the SSE coefficients for samples used in this study.

Table 2: Goodness-of-fit statistics parameters in different cases of treatment

Sample	θ_∞	K_1	SSE	R-square
Untreated	124.70	4.867	1.748	0.9899
PSA1D1	74.86	6.101	0.634	0.9849
PSA1D2	72.34	6.355	0.998	0.9852
PSA2D1	70.55	6.581	1.292	0.9871
PSA2D2	68.41	6.788	1.008	0.9829

Where:

- (PSA1D1): Pumice Stone – Amount = 1,5 kg /kg – D= 25 min;
- (PSA1D2): Pumice Stone – Amount = 1,5 kg /kg – D= 50 min;
- (PSA2D1): Pumice Stone – Amount = 3 kg /kg – D= 25 min;
- (PSA2D2): Pumice Stone – Amount = 3 kg /kg – D= 50 min.

The exponential model proposed to describe the evolution of water contact angle with time is tested by comparing the theoretical curve with the experimental one. As shown in table 2, for all samples, the high R² values (>0.98) and the law SSE values (<1.8) indicate that the experimental data are well correlated to the exponential model.

From the exponential model, it could be found that the initial water-fabric contact angles for the untreated and the stone washed fabrics were varied from 124.7° to 68.41°. The kinetic parameter for the untreated and the stone washed fabrics ("K_1 (s^{-1})") were varied from 4.867 s^{-1} to 6.788 s^{-1}. These results indicate that the hydrophilic property of the denim fabric is influenced by the washing treatment. Indeed, using values of measurement of contact angles as the primary data, we can study the degree of wetting when the denim fabric and the water interact and then the hydrophilic property of the textile. For example, a large angle (124.7°>> 90°) as observed in the case of the untreated fabric correspond to low wettability and therefore the fiber can be considered as hydrophobic. However, a small contact angles (68.41°<<90°) as observed in the case of the PSA2D2 washed fabric correspond to high wettability and then the denim fabric can be considered as hyrdrophilic.

IV. CONCLUSION

In this work, after visualization of the surface of the stone washed and unwashed denim fabric via SEM technique at 200 X magnification, we have investigated the experimental study of the dynamic spreading of water drop on stone washed cotton denim fabrics using an exponential model. The simulation curves by MatLab showed good fits with the experimental data of the water – textile surface contact angles. The validity of the mathematical model in describing the kinetic data is checked by the correlation coefficient (R-square) and the sum of square due to error (SSE). Finally, we noted that the stone washing treatment of the denim fabric have a significant influence on the kinetic rate of spreading of water drop. Indeed, results show that the spreading kinetic rate was increased when the textile was washed. It was very important in the case of stone washing treatment using 3 kg/kg for 50 minutes.

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