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Assessing friction in silk-like finished polyester fabrics

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Abstract

The influence of the silk-like finishing process on the frictional properties of polyester fabrics was examined by assessing fibre-to-metal friction through parameter R in a 100% polyester woven fabric processed under variable conditions of NaOH concentration and vaporization time. The alkali concentration influenced static and dynamic friction in the fabric, whereas the vaporization time only affected static friction. Process variables can be used to predict the frictional performance of silk-like finished fabrics via parameter R for dynamic friction. Fabric weight loss by effect of the silk-like finishing treatment influences the coefficient of fibre-to-metal friction. Industrially, the silk-line finishing process is typically monitored through weight loss in the finished fabric. As shown here, however, it can also be monitored by assessing changes in fabric surface via the dynamic friction parameter R.

Keywords: Friction properties, silk-like, polyester fabrics

Introduction

Silk-like finishing, which is used to obtain 100% PES fabrics mimicking natural silk in drape and hand, has been a widespread industrial treatment for a long time (Dave, Kumar & Srivastava, 1987). Essentially, the process involves treating polyester fabric with an aqueous solution of caustic soda under variable conditions of concentration, temperature and exposure time. As a result, polyester fibres undergo nucleophilic substitution and hydrolysis by reaction with alkali metal hydroxides, hydroxyl ions in the hydroxides attacking the electron-deficient carbon atoms of carbonyl groups in the polyester to form an intermediate anion. This is followed by chain scission and leads to the formation of terminal hydroxyl and carboxyl groups (Zeronian & Collins, 1989).

Hot soda solutions hydrolyse polyester fibre surfaces, thereby gradually reducing their thickness and weight. The hydrolysis rate depends on the alkali concentration and temperature used. Some studies have exposed a linear relationship between treatment time and the square root of residual fibre weight (Zeronian & Collins, 1989), (Gacén, 1991); others, have found a non-linear relationship of fibre weight loss to alkali concentration and temperature at each treatment time (Dave, Kumar & Srivastava, 1987). Industrial and research evidence suggest that temperature has an even stronger effect on the reaction rate than has alkali concentration, which in turn is more influential than treatment time (Zeronian & Collins, 1989).

The fabric weight loss resulting from the silk-like finishing process has been the subject of several studies since the 1980s. Such studies have revealed that treating fabric with soda has no effect on fibre cross-section (Soon & Seon,1995) (Zeronian & Collins, 1998), but alters fibre and yarn thickness (Sanders & Zeronian, 1982), Haghighat & Nouri, 1999). The process has also been studied in relation to the mechanical properties of fabric yarns (Sanders & Zeronian, 1982) (Zeronian & Collins, 1998); loss of tensile strength (Shet, Zeronian & Needles, 1982); specific structure energy (Sanders & Zeronian, 1982); bending rigidity, stiffness and shear modulus, (Needles, Brook & Keighley, 1985), (Davis & Amirbayat, 1994) (Haghighat & Nouri, 1999); drop properties (Davis & Amirbayat, 1994); air permeability (Sanders & Zeronian, 1982); water vapour and liquid water transfer (Needles, Brook & Keighley, 1985); contact angle and wicking (Sanders & Zeronian, 1982) (Needles, Brook & Keighley, 1985); hand properties (Soon & Seon,1995) and the effects of weight loss in polyester microfiber-based fabrics on their physical and mechanical properties (Mousazadegan, Saharkhiz & Maroufi, 2010) . Other authors have examined the influence of silk-like finishing variables on fabric properties (Carrera-Gallissà, 2014) or their effects on polymer surfaces (Zeronian & Collins, 1989).

The earliest mathematical law for fabric friction was proposed in 1699 by Amontons as the following linear relationship:

$$F = \mu N \qquad (1)$$

where *F* is the friction force, in Newton, *N* the normal force or load on the contact surface and *μ* a proportionality constant known as the “coefficient of friction”. However, the frictional behaviour of easily deformed materials such as fabrics, which are essentially viscoelastic, is better expressed by the following non-linear relation (Bowden & Tabor, 1954):

$$F = C \cdot N^n \qquad (2)$$

where *C* is the coefficient of contact and *n* the friction index. Obviously, if *n* = 1, then *C* = *μ.* Equation 3 can be rewritten as follows:

$$F/A = C \cdot (N/A)^n \qquad (3)$$

where *A* is the apparent contact area, in m^2. This relation can be made linear by logarithmic transformation:

$$\lg(F/A) = \lg C + n \lg(N/A) \qquad (4)$$

And eq. 4 can be simplified to

$$\lg f = \lg C + n \lg P \qquad (5)$$

The coefficient of contact (*C*) and the friction index (*n*) are typically used to determine the friction parameter *R*, which is a quantitative factor for characterizing friction properties in fabrics (Hermann, Ramkumar, Seshaiyer & Parameswaran, 2004).

$$R = \frac{C}{n}\,(Pa)^{1-n} \qquad (6) \quad (Pa)^{1-n}$$

The frictional properties of textile fabrics have been the subject of much study as regards the influence of structure, yarn type, regain and acidity on the coefficient of static friction. The studies revealed that the condition and chemical history of a fabric have a slight but definite effect on its coefficient of static friction, but also that fabric structure has a greater effect, and the nature of fibres seemingly an even greater one (Thorndike & Varley, 1961).

A subsequent study of the kinetic coefficient of friction for plain, twill and satin weaves revealed that the apparent contact area influences the frictional properties of fabric and that Amonton's second law fails in most fabrics. Similar studies examined the influence of fabric structure on surface frictional resistance (Zurek, Jankowiak & Frydrych, 1985), (Carr, Posey & Tincher, 1988), (Ajayi, 1992a) and found that Amonton's law does not hold in most of the textile materials examined, whereas Wilson's model relating frictional force to normal force and apparent contact area led to close correlation among data (Wilson, 1963).

Other studies have examined the influence of fibre composition (Ajayi, 1992b) and finishing treatment (Ajayi, Elder, Kolawole, Bello & Darma,1995). Also, a study on the potential relationship between fabric compression and friction revealed that the greater compression was, the softer was the fabric and the greater the difference between static and dynamic kinetic forces (Ajayi & Elder, 1997)

Two studies on the influence of fabric structure on stick–slip motion (Ajayi, 1992b), (Ajayi & Elder, 1997) found this phenomenon to be periodic and strongly influenced by fabric structure, side (warp or weft), reed space and the presence of protruding yarns; also, the number of stick–slip peaks was well correlated with yarn sett in woven fabrics and, especially, with the number of ribs in knitted fabrics.

The fabric-to-metal surface and fabric-to-fabric frictional characteristics of various textile materials revealed that the normal load and frictional force were logarithmically related in all types of fabric, and also that fabric-to-metal friction was less sensitive to fabric morphology and rubbing direction than was fabric-to-fabric friction.

Fabric friction is affected by many factors including fibre and blend type, blend proportion, yarn structure, fabric structure, crimp, crimp height and compressibility (Ratina Moorthy & Kandhavadivu, 2015).

Aim

The only study among the previous ones dealing with friction in silk-like finished fabrics was based on microroughnes and friction coefficient measurements made with Kawabata KES4 equipment on both sides of a finished polyester fabric (Mousazadegan, Saharkhiz & Maroufi, 2010). Based on the results, weight reduction had little effect on roughness or the coefficient of friction. Although KES equipment provides interesting information, friction can be examined in broader, more accurate terms by using the sliding plate method. The primary aim of this work was to elucidate the influence of process variables in the silk-like finishing of fabric with NaOH on frictional properties as determined with the plate method in silk-finished polyester fabric specimens.

Materials and Methods

Preparation of silk-like fabrics

The present study was conducted on a 100% PES fabric (figure 1) the characteristics of which are summarized in Table 1. The fabric was subjected to a silk-like finishing treatment at a Pad-Steam pilot plant comprising an impregnation vat, a vaporization zone, a washing train and a drying zone (Fig. 2).

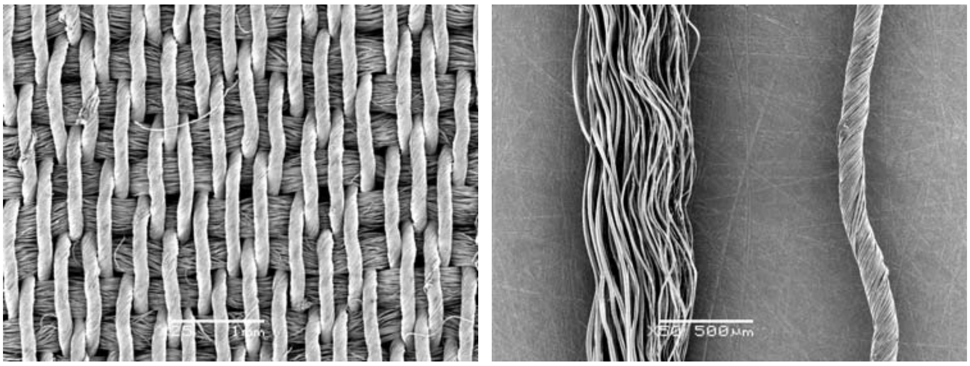

Figure 1. Left: Woven fabric consisting of twisted continuous polyester filaments (warp) and untwisted continuous polyester filaments (weft). Right: Magnified view of a weft filament (left) and a warp filament (right).

Property	**Crude, washing and stabilization at 120 ºC**
Composition	100% PES
Weave	Satin (3e^2, b. 2,2,1) (figure 1)
Warp titre (Tex)	Twisted continuous filament, 19 400 Tex
Weft titre (Tex)	Untwisted continuous filament, 43 800 Tex
Yarn density/cm	70
Pass density/cm	26
Aerial weight (g/m^2)	260.540
Thickness at 2 g/cm^2 (mm)	0.497

Table 1. Properties of the woven fabric studied.

Table 2 summarizes the characteristics of the experimental set-up. The study was conducted in accordance with an experimental plan involving two factors (soda concentration and vaporization time) at three levels each (figure 3). The nine experiments needed defined an experimental region consistent with the usual industrial conditions for fabric weight and aerial weight. Using a 3^2 factorial design allowed not only linear effects and interactions, but also curvature effects, to be examined. Because the design comprised only 8 degrees of freedom, it precluded assessing experimental error. The principal effects possessed 2 degrees of freedom each and interactions 4. With two replications, the total number of degrees of freedom would have been $(2 \cdot 3^2) - 1 = 17$ and that for experimental error 9.

Pilot plant width	33 cm
Foulard pressure	10 kg
NaOH concentration	300, 325 and 350 g/l + 2 g/l Sandopan DTC
Vaporization temperature	105 ºC, saturated vapour
Vaporization time	8, 10 and 12 min
Washing	2 washing vats containing water at 60 ºC and 1 at room temperature
Neutralization	2 vats containing a 2 g/l concentration of 80% acetic acid
Rame temperature	90 ºC
Rame drying time	1 min

Table 2. Specifications of the Pad-Steam system used.

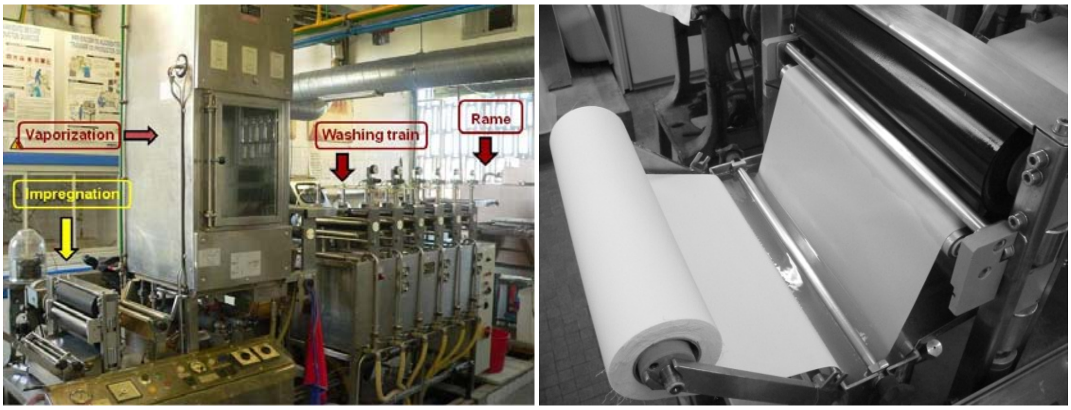

Figure 2. Pad-Steam pilot plant used in the fabric finishing treatment.

The 3^2 plan used is depicted schematically in figure 3. The null hypothesis (H_0) was that the properties of the target fabric would be insensitive to differences in the process variables and hence that the factors examined would have no effect. The alternative hypothesis (H_1) was that the fabric properties would be influenced by changes in the process variables.

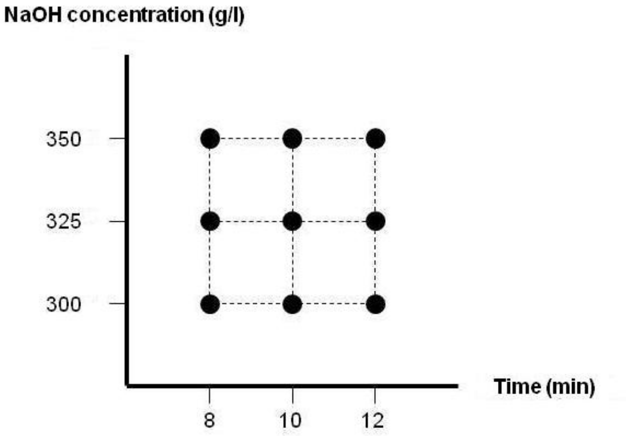

Figure 3. Experimental design. Each dot represents a measured response.

The finished fabric specimens obtained under the different conditions used were subjected to various analyses in order to determine their coefficients of friction as described below.

Friction measurement equipment

The frictional force of the finished fabric was measured with a modified version of the Instron Tensile Tester (23,24) (Ajayi, 1992a),(Ajavi, 1992b) (see figure 4) under the experimental conditions summarized in table 3.

Plate weight	100, 200, 300, 400 and 500 g
Plate material	Polished brass
Contact area	20 cm^2
Plate travel speed	300 mm/min
Atmospheric conditions	20 ºC and 65 % RH

Table 3. Experimental conditions for the friction tests.

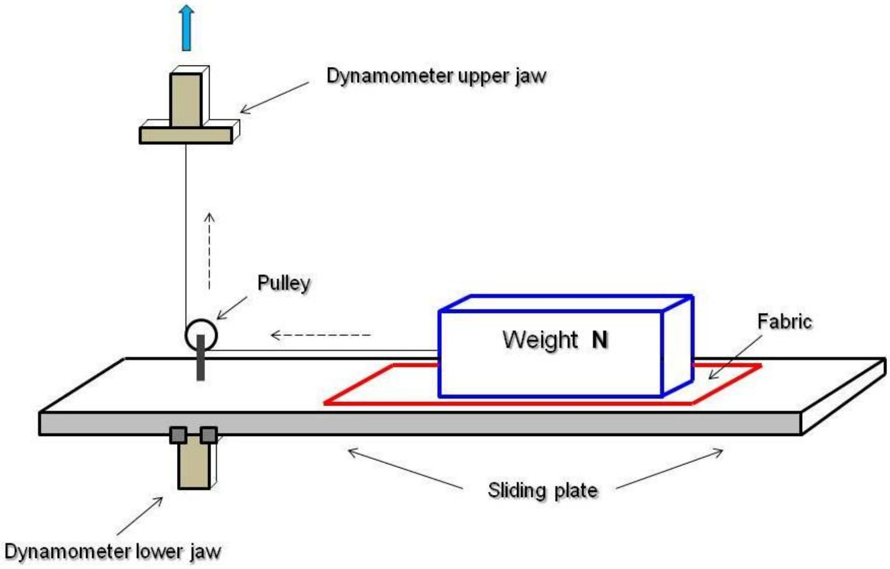

Figure 4. Friction measurement equipment.

Results and discussion

Fabric-to-fabric friction was examined in preliminary tests; the results, however, did not allow frictional changes to be elucidated because fabric structure was much more influential than were surface changes resulting from the finishing process. Also, as expected, rubbing two identical surfaces (fabric over fabric) was more difficult than rubbing two of different nature (fabric over metal). We thus focused on fabric-to-metal friction in order to minimize the effects of fabric characteristics on frictional properties. The results of the frictional tests are shown in tables 4 and 5.

Block	**Concentration (g/l)**	**Time (min)**	$F/A = C\ (N/A)^n$		**Static friction parameter**
			***P*-value**	R^2_{adj} **(%)**	$R(\mathrm{Pa})^{1-n}$
1	300	8	0.0163	85.15	77.47
1	300	10	0.0066	91.77	75.59
1	300	12	0.0043	93.79	61.73
1	325	8	0.0075	91.04	54.13
1	325	10	0.0032	94.96	58.33
1	325	12	0.0076	91.02	47.85
1	350	8	0.0172	84.63	47.72
1	350	10	0.0301	77.95	47.34
1	350	12	0.0147	86.11	48.79
2	300	8	0.0193	83.43	71.67
2	300	10	0.0179	84.22	60.14
2	300	12	0.0008	97.92	55.56
2	325	8	0.0105	88.87	47.09
2	325	10	0.0012	97.27	53.49
2	325	12	0.0036	94.47	56.80
2	350	8	0.0246	80.62	55.29
2	350	10	0.0077	90.94	54.36
2	350	12	0.0176	84.42	52.26

Table 4. Static friction parameter.

Block	**Concentration (g/l)**	**Time (min)**	$F/A = C\ (N/A)^n$		**Dynamic friction parameter**
			***P*-value**	R^2_{adj}**(%)**	***R* (Pa)**$^{1-n}$
1	300	8	0.0134	86.97	36.75
1	300	10	0.0056	92.67	47.52
1	300	12	0.0034	94.70	46.49
1	325	8	0.0272	79.34	30.84
1	325	10	0.0026	95.61	42.27
1	325	12	0.0123	87.63	35.78
1	350	8	0.0348	75.81	28.63
1	350	10	0.0402	73.48	30.13
1	350	12	0.0296	78.19	30.11
2	300	8	0.0161	85.28	41.15
2	300	10	0.0144	86.28	37.75
2	300	12	0.0013	97.24	44.29
2	325	8	0.0321	77.03	25.45
2	325	10	0.0008	98.13	36.32
2	325	12	0.0100	89.23	32.33
2	350	8	0.0338	76.35	25.19
2	350	10	0.0287	78.63	25.89
2	350	12	0.0293	78.61	25.92

Table 5. Dynamic friction parameter.

The data of table 4 were subjected to analysis of variance. The figures of merit of the analysis are shown in table 6.

Source	**Sum of squares**	**Degrees of freedom**	**Mean square**	***F*-ratio**	***P*-value**
C (Concentration)	823.486	1	823.486	27.88	0.0003
T (Time)	62.434	1	62.434	2.11	0.1739
CC	141.999	1	141.999	4.81	0.0507
CT	135.134	1	135.134	4.58	0.0557
TT	14.871	1	14.871	0.50	0.4927
Blocks	11,350	1	11.350	0.38	0.5479
Total error	324,912	11	29.537		
Total	1514,190	17			

Table 6. Analysis of variance of *R* for static friction.

The linear component of the concentration factor had a significant influence (*P* = 0.0003) and was thus an effective contributor to changes in friction parameter, R; by contrast, the significance of its quadratic component (*P* = 0.0505) and its interaction with concentration (*P* = 0.0557) both exceeded 5%. Figure 5 shows the variation of *R* with process variables and figure 6 that with their interactions. As can be seen from figure 5, *R* increased in a non-linear manner with increasing concentration. Also, as can be seen from figure 6, *R* decreased markedly with increasing concentration at short times but changed little with this variable at long times. Because its coefficient of determination was 69.60%, the linear model cannot be used for predictive purposes (see the estimated response surface in figure 7).

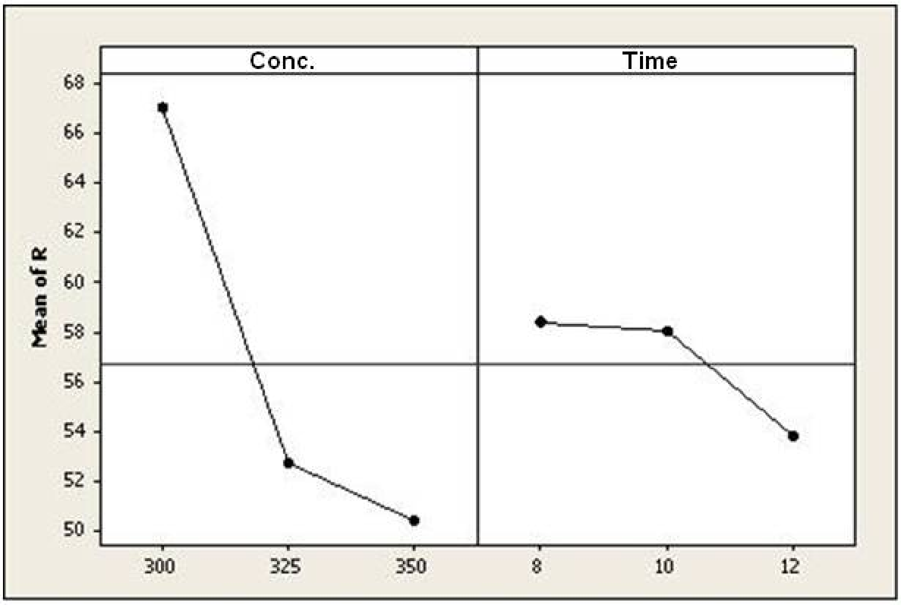

Figure 5. Main effects plot for *R* (static friction).

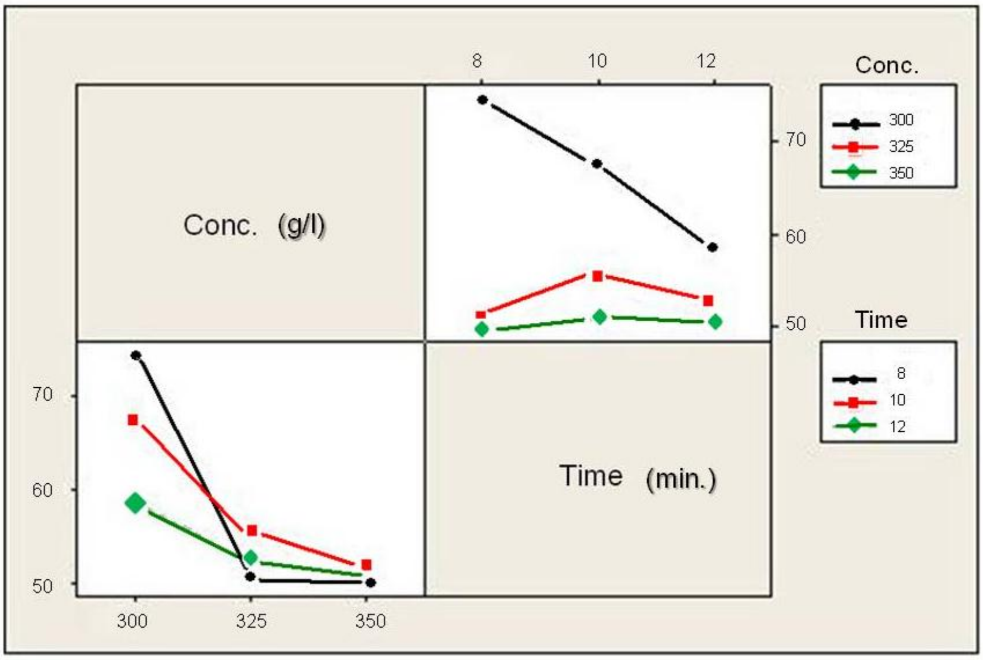

Figure 6. Interaction effects plot for *R* (static friction).

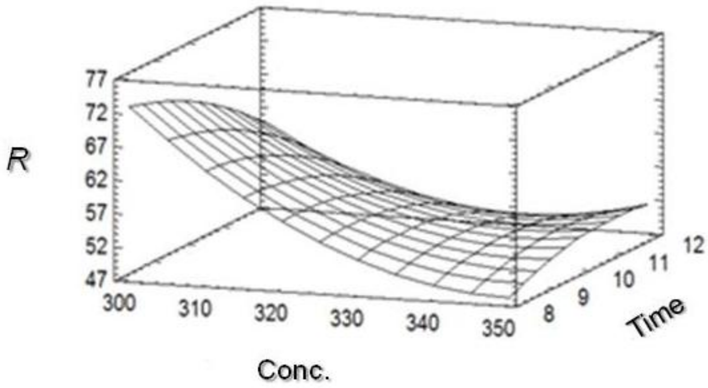

Figure 7. Estimated response surface.

Table 7 shows the figures of merit of the ANOVA of the results in table 5.

Source	**Sum of squares**	**Degrees of freedom**	**Mean square**	***F*-ratio**	***P*-value**
C (Concentration)	640.59	1	640.590	60.68	0.0000
T (Time)	60.327	1	60.3277	5.71	0.0358
CC	5.0131	1	5.01312	0.47	0.5050
CT	14.241	1	14.2418	1.35	0.2700
TT	36.072	1	36.072	3.42	0.0916
Blocks	66.658	1	66.6589	6.31	0.0288
Total error	116.129	11	10.5571		
Total	939.032	17			

Table 7. Analysis of variance of *R* (dynamic friction).

The influence of the linear component was extremely significant (P = 0.0000); by contrast, that of time was much weaker but still significant (P = 0.0358). Therefore, both factors were actual contributors to changes in *R*. Also significant was the influence of the factor “block” (P = 0.0288), which indicates that *R* differed significantly among fabric specimens and hence that the parameter is influenced by fabric surface. Figures 8 and 9 show the variation of *R* with the process variables and their interaction, respectively.

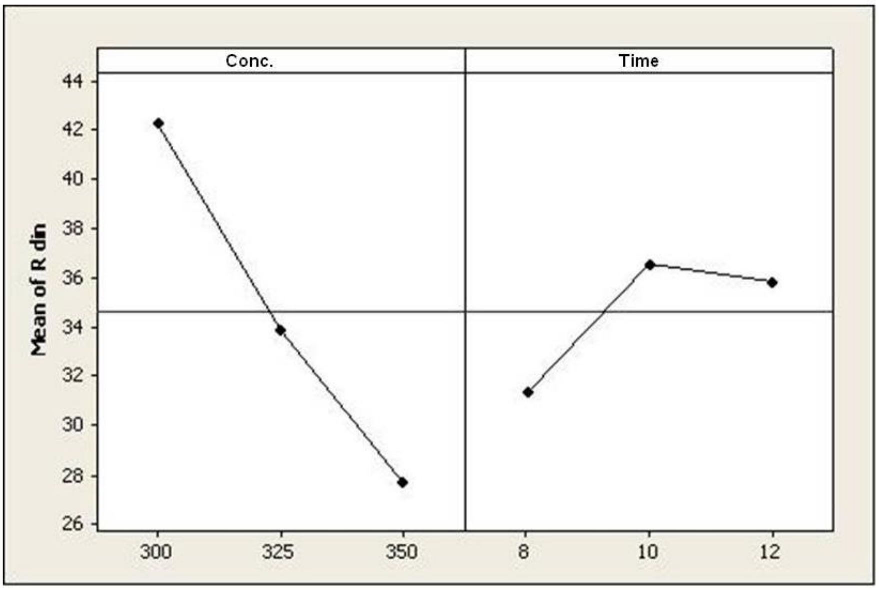

Figure 8. Main effects plot for *R* (dynamic friction).

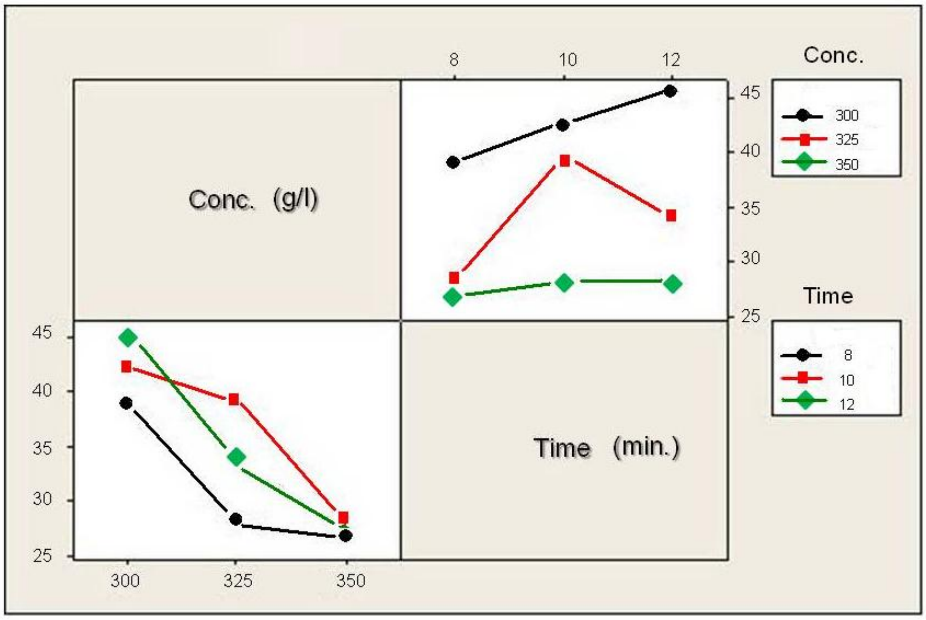

Figure 9. Interaction effects plot for *R* (dynamic friction).

Because the coefficient of determination for the linear model (eq. 10) was 82.48%, the model can be used for predictive purposes. The corresponding response surface is shown in figure 10.

$$Rdin = 147.0 - 1.18968 \cdot Concentration + 24.8087 \cdot Time + 0{,}0017912 \cdot Concentration^2 - 0{,}026685 \cdot Concentration \cdot Time - 0.75074 \cdot Time^2 \quad (10)$$

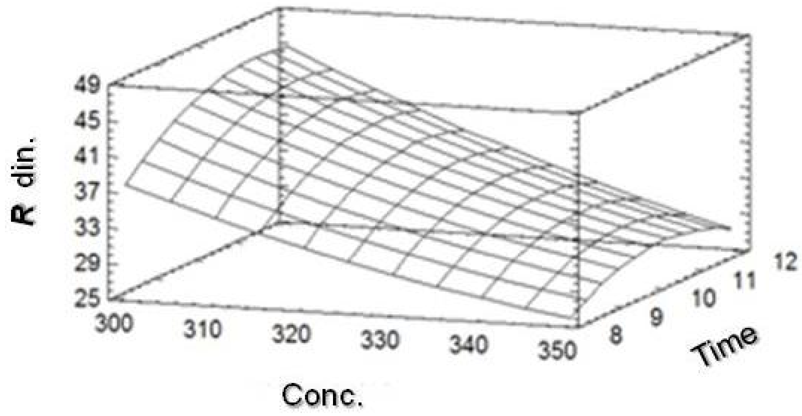

Figure 10. Estimated response surface.

Since only the concentration and time were significantly influential, eq. 10 can be simplified by suppressing all non-linear terms in it:

$$Rdin = 118.35 - 0.292253 \cdot Concentration + 1.12108 \cdot Time \qquad (11)$$

The analysis of variance of the regression gave a *P*-value of 0.0000. The coefficient of determination for the simplified model was 71.26%.

The coefficient of linear correlation between the static and dynamic forms of the friction parameter, *R*, was 0.64; therefore, only 41% of the variability in one form was explained by the other. The two are graphically related in figure 11.

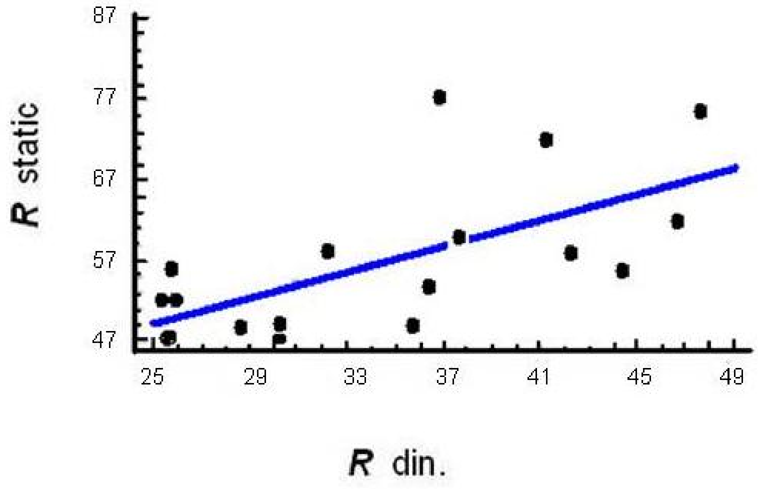

Figure 11. Relationship between the static and dynamic forms of *R*.

Industrially, the silk-like finishing process is usually monitored through fabric weight loss. The relationship between weight loss and the friction parameter, *R*, is given by eq. 12 and depicted in figure 12. The *P*-value for the ANOVA was less than 0.05

(specifically, 0.0474), so the relationship between fabric weight loss and *R* was significant at the 95% confidence level.

The coefficients of correlation and determination were –0.47 and 22.378%, respectively. Therefore, the simplified model explained 22.738% of the variance in fabric weight loss.

$$R = 1/(0{,}0322848 - 0{,}388581/Lost\ Weight) \quad (12)$$

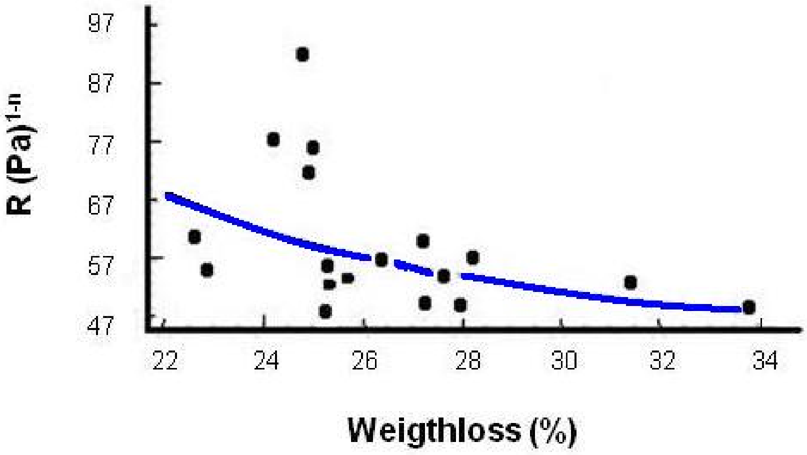

Figure 12. Variation of *R* with fabric weight loss.

Conclusions

We examined the influence of variables in the silk-like finishing process on the frictional properties of silk-finished woven fabrics. Fabric-to-metal friction proved a more accurate indicator of the influence of silk-like finishing variables than fabric-to-fabric friction. Also, silk-finished fabrics were found to obey the law of friction of Bowden & Tabor (1954).

The results of this work allow us to draw the following conclusions:

(a) The NaOH concentration strongly influences static and dynamic friction in silk-like finished fabrics; however, the treatment time only influences static friction.
(b) The NaOH concentration × time interaction influences static friction. Thus, *R* increases with increasing alkali concentration only at short times.
(c) Static friction is influenced by quadratic components and factor interactions. On the other hand, dynamic friction is only affected by the linear components of the factors, which indicates the static friction is a more complex phenomenon than dynamic friction.
(d) The process variables NaOH concentration and exposure time can be used to predict the frictional performance of silk-like finished fabrics through the dynamic form of parameter *R*.
(e) Fabric weight loss by effect of a silk-like finishing treatment influences the fibre-to-metal coefficient of friction for the fabric. As previously shown by several studies, the resulting decrease in fabric strength is a consequence of changes in microroughness and fibre surface area —and hence in fabric yarns—, but is not influenced by the reduction in material strength.

(f) Fabric weight loss is widely used industrially to control the silk-like finishing process. However, determining the weight loss is a mean to an end rather than the main aim —which is altering the fabric surface to mimic a silky feel. Because the treatment modifies the frictional properties of the fabric, parameter *R* affords direct monitoring of the finishing process.

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