Optimizing the Shrinkage and Bursting Strength of Knitted Fabrics after Resin Finishing

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Summary: Application of crosslinking resins is one of the effective methods used for improving the dimensional stability of cotton knitted fabrics. However, such an application often results in severe deterioration in the bursting strength of the treated fabrics. This study was undertaken for modeling and optimization of the shrinkage control and bursting strength of Lacoste Pique cotton knitted fabrics, using response surface methodology. A central composite experimental design was used to find out the optimum resin and softener concentrations along with the best curing time for maximum shrinkage control with minimum possible loss in the fabric bursting strength.

Key words: Resin finishing, dimensional stability, modeling, optimization, shrinkage, bursting strength.

Introduction

Cotton knits are quite popular in many sportswear, active wear and casual wear because of their excellent comfort and fit owing to their good air permeability, and better stretch and recovery properties as compared to woven fabrics [1]. However, poor dimensional stability has been recognized as a serious problem in cotton knitwear even after decades of developments in modern manufacturing techniques [2-8]. Although almost all single-knit structures have a large tendency to shrink but Lacoste Pique can shrink excessively, particularly in length direction, due to its comparatively open structure [2]. Many different techniques have been tried to overcome this shortcoming of cotton knits. Some of these techniques improve the dimensional stability by modifying the fiber, yarn or fabric structure while others rely on surface modification by topical application of different chemicals [9-13].

Use of different crosslinking resins, such as dimethylol dihydroxyethylene urea (DMDHEU) has provided an acceptable solution to the poor dimensional stability problem [13, 14]. Topical application of these crosslinking products increases the degree of set in yarns, allowing the yarns to maintain their loop shape even after repeated laundering, thus resulting in enhanced dimensional stability [15]. However, application of such products may severely deteriorate the bursting strength of the treated fabric [16] . This problem becomes even more severe when crosslinking products are used to control the shrinkage of open-structure fabrics like Lacoste Pique. This is because higher concentration of crosslinking agent is required to control the high level of shrinkage in such structures. So, in such cases a balance has to be maintained to attain optimal dimensional stability with minimum loss in bursting strength. Moreover, application of crosslinking agents on fabrics also increases their stiffness and results in harsher handle [17]. Hence, application of fabric softening agents such as polysiloxanes and polyethylene emulsions becomes a necessity, which also helps in retaining the fabric strength [18]. Again, a critical balance has to be maintained to have optimum dimensional stability and fabric strength. Mostly, hit and trial experiments are done in this regard, resulting in huge loss of time and resources.

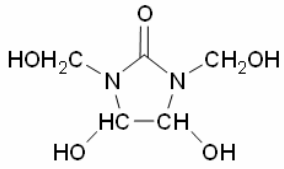

Fig. 1: Chemical structure for Methylolation product of Glyoxalmonourein.

The aim of this study was to model and optimize the shrinkage control and bursting strength of Lacoste Pique fabrics after application of crosslinking resin and softener using response surface methodology. This methodology has been successfully used in the past for several modeling and optimization problems [19, 20].

Results and Discussion

Table-2 gives the complete central composite design used in this study and values of the response variables obtained after experimentation. The three experimental design factors are: resin concentration (g/l), softener concentration (g/l) and resin curing time (sec.). The three response variables are: length-way fabric shrinkage (SL %), width-way fabric shrinkage (SW %) and fabric bursting strength

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(BS). Analysis of variance (ANOVA) was performed to evaluate the statistical significance of model terms. Any model terms having p-value larger than 0.05 (indicating statistical significance at 95% confidence level), were discarded. The estimated coefficients and p-values of the significant terms for different response variables are given in Table-3. A Plus (+) or no sign indicates that the response increases by increasing the factor value and vice versa. A higher value of the coefficient indicates higher effect of corresponding term and vice versa. The quadratic models for predicting various response variables, comprising only the statistically significant terms, are given in Table-4. R-sq values represent the percentage of change in the response variables that can be explained by the terms included in the models (equation). A higher value of the R-sq indicates higher adequacy of the corresponding model.

Table-1: Coded and actual values of the design factors.

Factor Symbol	Factor	Coded and Actual Levels				
		- 2	- 1	0	+ 1	+ 2
X_1	Resin (g/l)	25	50	75	100	125
X_2	Softener (g/l)	15	30	45	60	75
X_3	Curing Time (sec.)	45	90	135	180	225

Table-2: Central composite experimental design for finishing treatments.

No.	Factors			Responses		
	X_1	X_2	X_3	Y_1	Y_2	Y_3
	Resin (g/L)	Softener (g/L)	Time (Sec.)	SL (%)	SW (%)	BS
1	-1	-1	-1	7.9	5.4	57
2	1	-1	-1	4.6	2.4	51
3	-1	1	-1	8.0	5.6	64
4	1	1	-1	4.8	2.5	56
5	-1	-1	1	6.8	4.6	56
6	1	-1	1	4.1	2.3	49
7	-1	1	1	7.0	4.9	62
8	1	1	1	4.3	2.4	54
9	-2	0	0	9.9	6.9	66
10	2	0	0	4.0	1.5	49
11	0	- 2	0	5.3	3.3	51
12	0	2	0	5.6	3.7	63
13	0	0	-2	6.6	4.1	57
14	0	0	2	5.0	3.3	53
15	0	0	0	5.5	3.6	55
16	0	0	0	5.5	3.6	54
17	0	0	0	5.5	3.6	55
18	0	0	0	5.5	3.6	54
19	0	0	0	5.6	3.6	55
20	0	0	0	5.5	3.6	54

SL = shrinkage in length; SW = shrinkage in width; BS = Bursting Strength

Effect of Resin and Softener Treatment on Fabric Shrinkage

The statistical analysis given in Table-3 shows that all the three experimental factors, i.e. resin concentration, softener concentration and curing time significantly affect the fabric shrinkage (p-value < 0.05) both in length and width directions. Fabric shrinkage decreases by increasing resin concentration and curing time but has a slightly increasing trend with increase in softener concentration. The response surface equations for predicting the length-way (SL) and width-way shrinkage (SW) are given in Table-4.

The effect of resin concentration, softener concentration and curing time on the fabric shrinkage is graphically depicted in Fig. 2 and 3. It is clear from the Figures that an increase in resin concentration results in decrease in fabric shrinkage. This may be attributed to decrease in free hydroxyl groups in the cotton cellulose due to crosslinking with the resin. Shrinkage of cotton fabrics is primarily caused due to their ability to absorb moisture because of the presence of hydroxyl groups in the cellulose. Water acts as a lubricating and relaxing agent to release the stresses induced in the fibers and yarns during yarn and fabric manufacturing processes. Owing to water absorption, the movement of cellulose polymer chains is also facilitated in the amorphous regions by disrupting the internal hydrogen bonding between the cellulose chains. When the fabric gets dried after wetting, the hydrogen bonds between the cellulose chains are reformed at new relaxed positions. With the increase in resin concentration, the hydroxyl groups of adjacent cellulose chains are crosslinked, thus making the fibers less prone to water absorption and chain disturbances, resulting in decrease in fabric shrinkage. It can also be observed from Fig. 2 and 3 that the effect of increasing resin concentration is not linear. With an initial increase in resin concentration, the shrinkage decreases readily but then rather steadily after further increase in the concentration. This is because with an initial crosslinking, the availability of free hydroxyl groups decreases for further crosslinking.

Table-3: Estimated coefficients and p-values of significant model terms for different response variables.

Model terms	Length-way Shrinkage (SL)		Width-way Shrinkage (SW)		Bursting Strength (N)	
	Coeff.	p-values	Coeff.	p-values	Coeff.	p-values
Constant	5.56761	0.000	3.64429	0.000	54.8482	0.000
X_1 - Resin (g/l)	-1.46766	0.000	-1.36359	0.000	-3.9844	0.000
X_2 - Softener (g/l)	0.08047	0.000	0.09109	0.000	2.8906	0.000
X_3 - Time (sec.)	-0.39984	0.000	-0.21484	0.000	-0.8906	0.000
X_1^2	0.35502	0.000	0.14873	0.000	0.7433	0.000
X_2^2	-	-	-0.03627	0.001	0.6183	0.000
X_1X_2	-	-	-	-	-0.4688	0.025
X_1X_3	0.14344	0.02	0.17594	0.000	-	-

Table-4: Quadratic models for predicting the response variables.

Response	Equation	R-Sq %
Length-way Shrinkage (%)	$15.4148 - 0.161123\ X^1 + 0.00536458\ X_2 - 0.0184479\ X_3 + 5.68023E^{-4}\ X_1^2 + 1.275E^{-4}\ X_1X_3$	99.60
Width-way Shrinkage (%)	$10.7019 - 0.111351\ X_1 + 0.0205818\ X_2 - 0.0165035\ X_3 + 2.37961E^{-4}\ X_1^2 - 1.6121E^{-4}\ X_2^2 + 1.56389E^{-4}\ X_1X_3$	99.92
Bursting Strength (N)	$68.8371 - 0.281518\ X_1 + 0.0391369\ X_2 - 0.0197917\ X_3 + 0.00118929\ X_1^2 + 0.00274802\ X_2^2 - 0.00125X_1X_2$	99.16

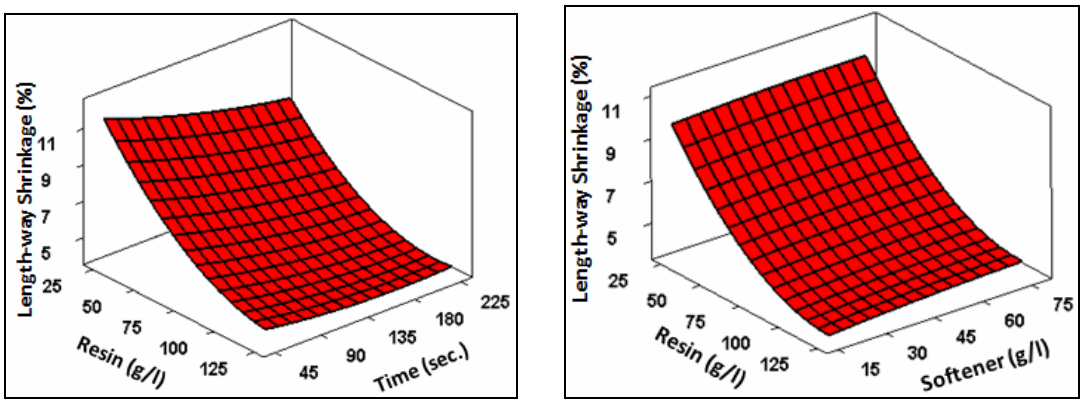

Fig. 2: Effect of resin and softener treatment on length-way fabric strinkage.

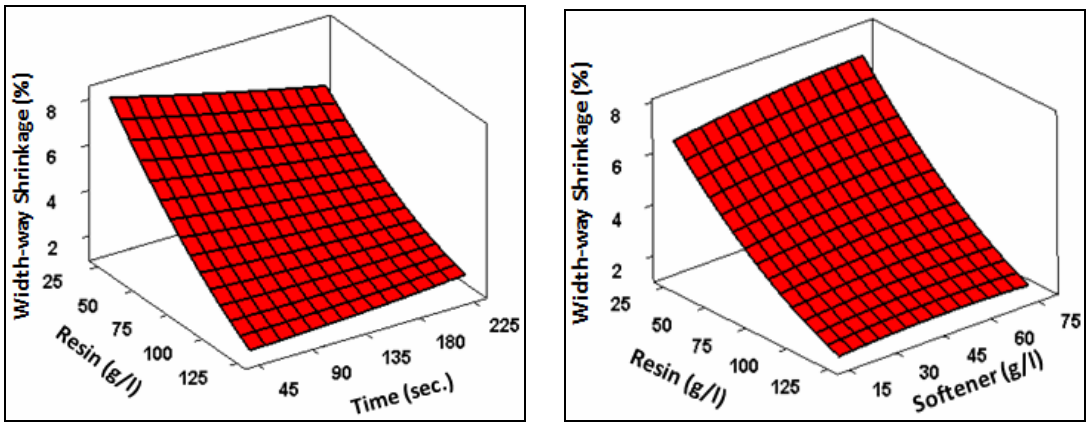

Fig. 3: Effect of resin and softener treatment on width-way fabric strinkage.

A statistically significant interaction was found between the resin concentrations and curing time, i.e. the effect of curing time was found to be dependent on the resin concentration. At lower resin concentration, the effect of increasing time is considerably significant in reducing the fabric shrinkage due to effective resin crosslinking. However, a higher resin concentration somewhat compensates the time shortage and even for less curing time shrinkage is effectively reduced. Although the effect of softener on fabric shrinkage was found to be statistically significant in hindering the shrinkage control by resins, the effect was practically not significant, as is clear from Fig. 2 and 3.

Effect of Resin and Softener Treatment on Fabric Bursting Strength

According to the statistical analysis given in Table-3 all the three experimental factors, i.e. resin concentration, softener concentration and curing time significantly affect the fabric bursting strength (p-value < 0.05). Fabric bursting strength decreases by increasing resin concentration and curing time but increases with increase in softener concentration. The response surface equation for predicting the fabric bursting strength after finishing is given in Table 4.

The effect of resin concentration, softener concentration and curing time on the fabric bursting strength is graphically depicted in Fig. 4. It is clear from the figures that an increase in resin

concentration results in decrease in fabric bursting strength. This may be attributed to several factors including increase in fiber embrittlement, decrease in yarn elongation and slippage properties, fabric stiffening or some cellulosic degradation during acidic resin finishing conditions. A statistically significant interaction was found between the curing time and resin concentration. It can be noticed from Fig. 4 that the effect of increasing finishing time is more prominent at lower resin concentration. However, at higher resin concentration there is much bursting strength loss even at shorter finishing time.

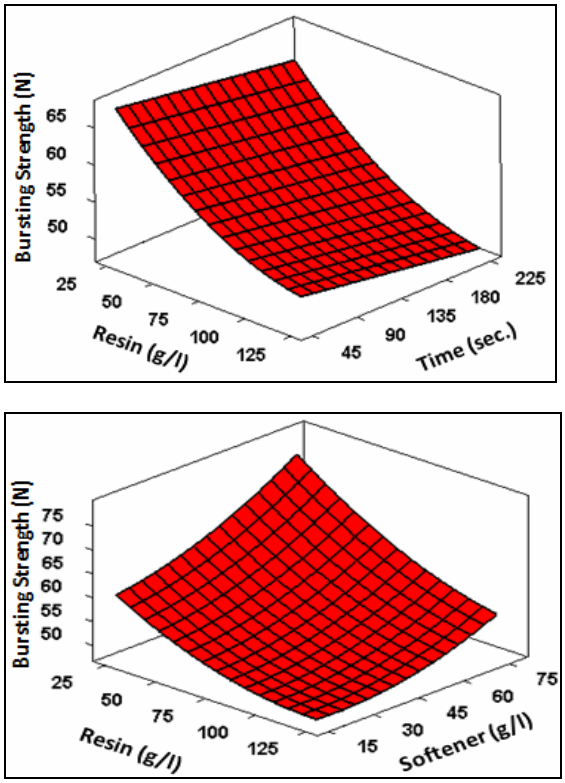

Fig. 4: Effect of resin and softener treatment on fabric bursting strength.

The addition of softener results in improvement in the fabric bursting strength. This may be attributed to decrease in fiber and yarn brittleness and stiffening, and increase in yarn slippage properties due to softener application. The effectiveness of increasing softener concentration for improvement in the fabric bursting strength is better at lower resin concentration but poor at higher resin concentration. This may be due to the fact that any loss of fabric bursting strength due to stiffening and brittleness induced by the resin may be compensated or recovered by the softener but any loss that would have occurred due to cellulose degradation could not be recovered by the application of softeners.

Response Optimization

A multiple response optimization approach proposed by Derringer and Suich was used, which is based on response surface methodology and makes use of desirability functions [21]. According to this approach, each response variable was expressed in terms of an individual desirability function di, which could take its value between 0 and 1. When the response variable was at its target or goal, di would become 1, and if the response variable was outside the acceptance range, di would become zero. The overall aim was to set the process variables to such levels that the overall desirability function (D) was maximized. By assigning a weight (r) to a response variable, relative importance of being close to the target could also be assigned. Selecting r>1 placed greater importance on being close to the target value, while choosing 0<r<1 made the target less important. The individual desirability was calculated using the following equation [21]:

$$d_i = f_i(y)^{W_i}$$

where W_i is the weight for response and the function $f_i(y)$ depends on whether one desires to hit a target, minimize the response, or maximize the response. In this study, the goal was to minimize the fabric shrinkage and maximize the bursting strength. To minimize the response, $f_i(y)$ was calculated according to the following equation:

$$f_i(y) = \begin{cases} 1 & y < T \\ \left(\dfrac{U-y}{U-T}\right) & T \le y \le U \\ 0 & y > U \end{cases}$$

To maximize the response, $fi(y)$ was calculated using the following equation:

$$f_i(y) = \begin{cases} 0 & y < L \\ \left(\dfrac{y-L}{T-L}\right) & L \le y \le T \\ 1 & y > T \end{cases}$$

where y is the response value, and U and L are the upper and lower boundaries (i.e. minimum and maximum acceptable values for the response), respectively, and T is the target. The composite desirability was calculated according to the equation given below:

$$D = (d_1^{I_1} * d_2^{I_2} * \ldots * d_n^{I_n})^{1/(I_1+I_2+\ldots+I_n)}$$

where di is the desirability of individual response i, and I_i is the importance of the response i.

For the optimization of resin finishing, models for all the three response variables (i.e.

length-way shrinkage SL, width-way shrinkage SW and bursting strength BS) were combined into single multi-response optimization model using MINITAB® statistical software. Search parameters of the multiple response optimization approach described above are summarized in Table-5. The overall optimization goal was to minimize the shrinkage while maintaining the maximum possible bursting strength. The shrinkage targets were set at 4.5% with maximum 5% limits and the bursting strength target was set at 60 N with minimum 55 N limit, as these targets meet requirements for most of the end uses [22]. The optimum process conditions determined by the multiple response optimization model through MINITAB® are given in Table-6 along with the predicted response values. The overall desirability value 0.98 indicates that the predicted responses were up to 98% close to our desired target. The individual desirability values d1, d2 and d3 indicate how close the individual responses were to the desired targets. The optimum resin finishing conditions thus found after response optimization were 90 g/l resin, 75 g/l softener and 190 seconds curing time for obtaining the shrinkage and bursting strength values nearest possible to the desired targets. After determining the optimum process conditions, confirmatory experiments were run and the best values of the response variables that could actually be obtained were 5.1% length-way shrinkage, 3.2% width-way shrinkage and 98 N bursting strength. The results of the validation experiments are given in Table-7.

Experimental

Fabric

The fabric used in this study was Lacoste Pique structure, knitted from 100% cotton 26 Ne (22.7 tex) yarn. The fabric was knitted on a 24 gauge (needles/inch) knitting machine with 30 inch diameter. The tightness factor (K) of the fabric was 17.0, loop length 0.28 cm and areal density 170 g/m^2 with 30 courses and 24 wales per inch.

Chemicals and Auxiliaries

Fixapret CPF (Methylolation product of Glyoxalmonourein by BASF), was used as cellulose crosslinking agent (resin). Magnesium chloride ($MgCl_2$, commercial grade) was used as catalyst. Siligen SIE (Aminofunctional Polysiloxane by BASF), was used as a softener.

Fabric Pre-treatment

The pre-treatment of the fabric was done in industrial-scale jet dyeing machine at 110°C for 15 minutes using 2g/l hydrogen peroxide (50 % w/w), 2 g/l caustic soda, 0.4 g/l sequestering agent (Alkaquest AM 700 by Alka Chemicals Pakistan), 0.5 g/l bleaching stabilizer (Stabilizer CT by Chromatex Pakistan), 0.7 g/l wetting agent (Rucowet VL by Rudolf Pakistan) and 0.5 g/l anti-creasing agent (Rucoline JES by Rudolf Pakistan). The bleached fabric was then thoroughly washed, rinsed and neutralized by using 1.5 g/l acetic acid.

Fabric Dyeing

The bleached fabric was dyed with 0.64 % o.w.f. Synazol Navy Blue KBF, 0.195 % o.w.f. Synazol Turquoise Blue HFG, and 0.163 % o.w.f. Everzol Yellow 3RS H/C reactive dyes using 40 g/l sodium sulphate, 20 g/l soda ash, 0.5 g/l leveling agent (Sera Gal P-LP by Dyestar) and 0.5 g/l anti-creasing agent (Rucoline JES by Rudolf Pakistan). The dyeing process was completed by setting the time/temperature profile as per the dye manufacturer's recommendations. The dyed fabric was then rinsed and washed-off using 1.5 g/l non-ionic detergent (Hostapal NI Extra by Clariant Pakistan), followed by neutralization with 1 g/l acetic acid.

Table-5: Search parameters used in response optimization.

Length-way Shrinkage (SL %)		Width-way Shrinkage (SW%)		Bursting Strength (N)	
Target	Maximum	Target	Maximum	Target	Minimum
4.5	5	4.5	5	60	55

Table-6: Process conditions determined after response optimization.

Overall Desirability (D)	Optimum Process Conditions			Optimum Values for Response Variables					
	Resin (g/l)	Softener (g/l)	Time (sec.)	SL%	d1	SW%	d2	BS (N)	d3
0.98	90	75	190	4.6	0.97	2.7	1.0	59	0.98

Table-7: Results of the validation experiments.

Sr. No.	Resin(g/l)	Softener(g/l)	Time(sec)	Shrinkage (%)				Bursting Strength (psi)	
				Length		Width			
				Observed	Predicted	Observed	Predicted	Observed	Predicted
1	90	70	145	5.13	4.8	3.15	2.87	60	58.51
2	80	56	140	5.5	5.25	3.57	3.38	55	56.21
3	82	42	175	5.1	4.85	2.8	3.1	53	52.42
4	110	70	150	3.95	4.24	2.15	2.01	57	55.84
5	90	75	190	5.1	4.6	3.2	2.7	58	59

Resin Finishing

The coded and actual levels of variables used in resin finishing are given in Table-1. The finishing treatments were done according to the experimental design given in Table-2. An unblocked full central composite experimental design was used, using α value of 2. Total number of runs was 20, comprising 8 runs at factorial/cube points, 6 at axial points and 6 replicates at center points. The recipes were prepared with the specified amount of the resin, softener and $MgCl_2$ catalyst (20% of the amount of resin used as recommended by resin manufacturer). The application of the recipes was done on the laboratory stenter at 75% pick-up, followed by drying at 120°C for 2.5 minutes and curing at 160°C for the times specified in the experimental design

Testing of the Treated Fabric

All the treated fabric samples were subjected to conditioning according to ASTM D1776 prior to testing. The length and width-way shrinkage of the samples was determined after washing the samples according to AATCC TM-135. The bursting strength of the samples was tested according to ASTM D3786.

Statistical Analysis and Modeling

The design of experiments, statistical analysis and modeling was done using Minitab® 16.1.0 statistical software package. Response surface regression analysis was used. All the linear, square and interaction terms were analyzed for statistical significance. The terms which were not statistically significant were discarded and quadratic models were developed taking into account only the significant terms. The adequacy of the models was checked using residual plots and coefficient of determination (R-sq values).Validation experiments were also conducted to further confirm the adequacy and validity of the models.

Conclusions

The concentration of resin and softener, and fabric curing time was optimized to obtain the best shrinkage control with minimum loss in the bursting strength of Lacoste Pique knitted fabrics. It was confirmed that the shrinkage of the fabric is significantly reduced by increasing the resin concentration and curing time along with severe loss in the fabric bursting strength. Increase in softener concentration resulted in improvement in the fabric bursting strength but with some loss in the shrinkage control ability of the resin. Furthermore, there was a statistically significant interaction between the resin concentration and curing time as well as between the resin and softener concentrations, which could only be found through statistically designed experiments rather than varying-one-factor-at-a-time experiments. Due to these significant interactions, central composite designed was found to be highly effective for determining the optimum finishing conditions for best shrinkage control with minimum loss in the fabric bursting strength.

References

1. H. Cao, D. H. Branson, S. Peksoz, J. Nam and C. A. Farr, *Textile Research Journal*, **76**, 587 (2006).
2. L. Onal and C. Candan, *Textile Research Journal*, **73**, 187 (2003).
3. D. L. Munden, *Journal of the Textile Institute Proceedings*, **51**, P200 (1960).
4. L. Quaynor, M. Nakajima and M. Takahashi, *Textile Research Journal*, **69**, 285 (1999).
5. R. Postle, *Journal of The Textile Institute*, **59**, 65 (1968).
6. J. J. F. Knapton, E. V. Truter and A. K. M. A. Aziz, *Journal of The Textile Institute*, **66**, 413 (1975).
7. A. Demiroz Gun, C. Unal and B. T. Unal, *Fibers and Polymers*, **9,** 588 (2008).
8. G. Agarwal, L. Koehl, A. Perwuelz and K. Lee, *Fibers and Polymers*, **12**, 670 (2011).
9. V. W. Tripp, A. T. Moore, I. V. de Gruy and M. L. Rollins, *Textile Research Journal*, **30**, 140 (1960).
10. L. Yeqiu, H. Jinlian, Z. Yong and Y. Zhuohong, *Carbohydrate Polymers*, **61**, 276 (2005).
11. T. Tóth, J. Borsa, J. Reicher, P. Sallay, I. Sajó and I. Tanczos, *Textile Research Journal*, **73**, 273 (2003).
12. B. Gordon and D. L. Bailey, *Journal of American Association of Textile Chemists and Colorists*, 25 (1984).
13. V. Lukanova and V. Ganchev, *Fibres and Textiles in Eastern Europe*, **13,** 51 (2005).
14. C. S. Whewell, *Review of Progress in Coloration and Related Topics*, **14**, 157 (1984).
15. W. S. Lo, T. Y. Lo and K. F. Choi, *Journal of The Textile Institute*, **100**, 530 (2009).
16. I. S. Kang, C. Q. Yang, W. Wei and G. C. Lickfield, *Textile Research Journal*, **68**, 865 (1998).
17. C. Q. Yang, L. Qian and G. C. Lickfield, *Textile Research Journal*, **71**, 543 (2001).
18. K. O. Jang and K. Yeh, *Textile Research Journal*, **63**, 557 (1993).
19. W. J. Hill and W. G. Hunter, *Technometrics*, **8**, 571 (1966).
20. K. Murugesan, A. Dhamija, I.-H. Nam, Y.-M. Kim and Y.-S. Chang, *Dyes and Pigments*, **75**, 176 (2007).
21. R. S. G. Derringer, *Journal of Quality Technology*, **12**, 214 (1980).
22. C. Blum and J. G. Wurm, in C. Blum and J. G. Wurm (Editors), *Springer Netherlands*, 217 (1986).