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RESPONSE SURFACE MODELING OF PHYSICAL AND MECHANICAL PROPERTIES OF COTTON SLUB YARNS

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Abstract:

The objective of this study was to model the physical and mechanical properties of 100% cotton slub yarns commonly used in denim and other casual wear. Statistical models were developed using central composite experimental design of the response surface methodology. Yarn's linear density, slub thickness, slub length and pause length were used as the key input variables while yarn strength, elongation, coefficient of mass variation, imperfections and hairiness were used as response/output variables. It was concluded that yarn strength and elongation increased with increase in linear density and pause length, and decreased with increase in slub thickness and slub length. Yarn mass variation and total imperfections increased with increase in slub thickness and pause length, whereas yarn imperfections and hairiness decreased with increase in slub length. It was further concluded that due to statistically significant square and interaction effects of some of the input variables, only the quadratic model instead of the linear models can adequately represent the relationship between the input and the output variables. These statistical models will be of great importance for the industrial personnel to improve their productivity and reduce sampling.

Keywords:

Modeling, fancy, slub, mechanical properties, cotton ring spun yarn

1. Introduction

Fancy yarns comprise a class of specialty textile yarns with intentionally induced irregular physical characteristics such as diameter, bulk, color, and so on. Fancy yarns are used for obtaining different interesting appearances and aesthetic characteristics in high-fashion clothing including denim, curtains, carpets, upholstery fabrics, and so on. [1-4]

Slub yarn is a type of fancy yarn in which slubs (i.e., thick places in the yarns) are produced by systematically changing yarn's linear density during the spinning process. [5] These slub yarns with many variations are widely used in denim garments to give special looks and aesthetic effects. [6] Different aspects of slub yarns have been investigated by the researchers in the past. Liu *et al.* has demonstrated an accurate and rapid approach for automatically measuring slubs. [7]. Testore *et al.* studied the relationship of basic parameters of slub yarn with the resultant yarn's appearance. [8] Lu *et al.* investigated the influence of yarn twist on the mechanical and physical properties of the slub yarn and concluded that the slub length is a key factor to decide the yarn twist. [9] Some mechanical properties of slub yarn have been analyzed using statistical methods. [4] It has been reported that the twist distribution in every section of slub yarn is inversely proportional to the square of linear density of the corresponding section. [9] The parameters of rotor spun slub yarn were investigated and it was found that rotor diameter, yarn count, slub thickness and performance of the servomotor significantly affect the slub length. [10]

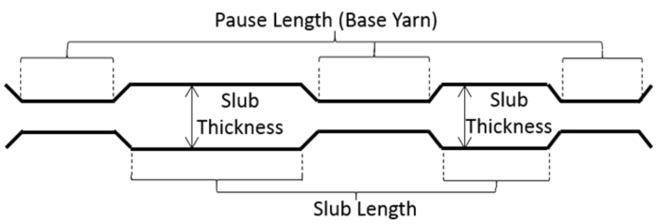

Figure 1. Structure of slub yarn.

The important parameters of slub yarn include the slub length, slub distance (pause length/base yarn), mass increase or mass decrease within a slub (slub thickness) or within a pause (pause thickness) and the repetition pattern of the slub yarn as shown in Figure 1. Different practical methods are available to determine the repetition pattern of the slub yarn, including the use of a black board and Uster mass diagram report shown in Figure 2. [11, 12]

The literature review does not reveal any model that characterizes the effect of key slub parameters on the resulting yarn characteristics. This paper endeavors to fill this gap and attempts to model some of the key physical and mechanical properties of the 100% cotton slub yarn. The range of linear densities covered in this study corresponds to the slub yarns commonly used for making denim fabrics. The design of experiment is based on the response surface methodology (RSM) and the central composite design (CCD) has been

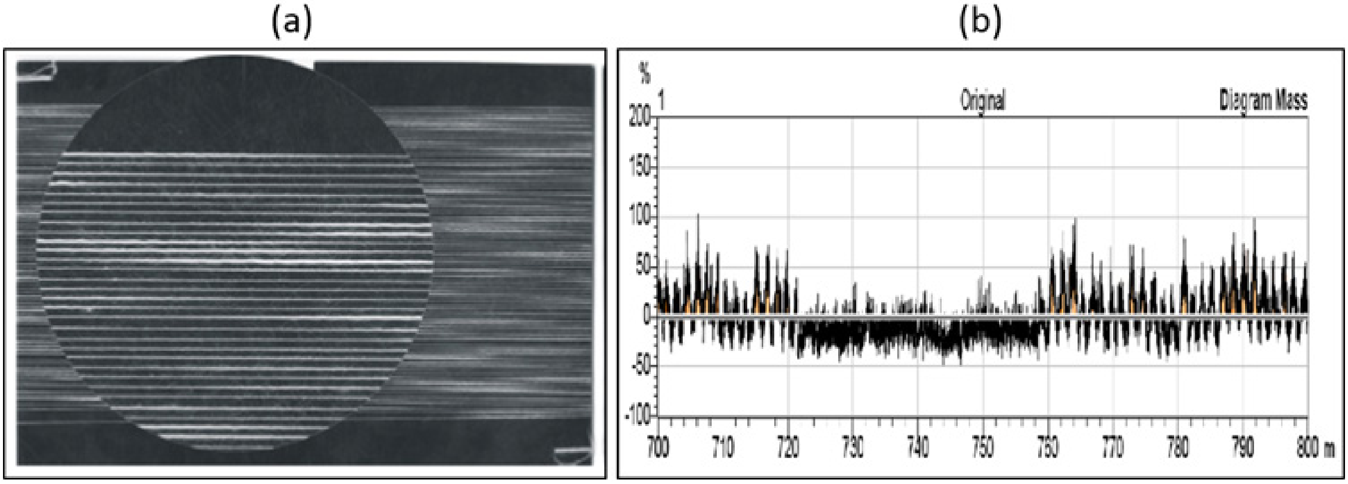

Figure 2. Repetition pattern of slub yarn: (a) On black board, (b) On Uster mass diagram.

employed to cover not only the linear effects but also the quadratic effects of key slub parameters on the resulting physical and mechanical properties of the yarn.

2 Experimental

2.1 Materials & methods

Pakistani cotton variety NIAB 999 was used to make 100% cotton slub yarn for this study. The properties of cotton fibers, as determined on a High Volume Instrument USTER HVI SPECTRUM, are given in Table 1. Cotton fibers were processed in the blow room (Trutzschler 2001) and carding (DK-903, Trutzschler) section of a spinning mill. Slivers obtained from the carding machines were given two drawing passages on the draw-frames (DX-8, Toyoda & RSB D-22, Rieter) to get more uniform slivers of 4.53 gram/meter. The drawn slivers were processed through the roving machine (FL-16, Toyoda) to get roving linear density of 842.85 tex at the flyer speed of 950 rpm, and twist level of 33.47 twist/meter. The roving was then spun into slub yarns having average linear densities of 98.33, 84.28, 73.75, 65.55 and 59 tex, with twist level of 463, 499, 534, 567 and 597 twists/meter. Caipo CSTU slub attachment with Toyoda RY ring frame was used to make all the slub yarn samples for this study. The slub yarn factors and their levels are given in Table 2.

For all the samples, break draft was 1.34, roller gauge 44−51 mm, ring traveler number C-1HW DR # 9, ring diameter 45 mm, spindle speed 10000 rpm and machine lift 20.32 cm. Ring bobbins of the produced yarns were conditioned under standard atmospheric conditions according to ISO 139:2005 before testing for unevenness, imperfections, and hairiness on USTER TESTER-4 as per ISO 16549:2004 and yarn strength and elongation at break on USTER TENSORAPID-3 according to ISO 2062:1993 standard method. For authentic results, intensive sampling was carried out. 20 yarn bobbins were randomly selected from 120 bobbins for each level of experiment and each result is an average of 60 readings taken from 20 samples.

Table 1. Properties of cotton used in this study

Properties	Units	Values
Spinning Consistency Index	Index	125
Micronaire	µg/meter	190.16
Staple Length (UHML)	mm	27.5
Uniformity Index	Index	82.6
Short Fiber Index (SFI)	%	8.4
Strength	g/tex	30.1
Elongation	%	5.3
Moisture content	%	8.5
Degree of Reflectance	Rd value	72.5
Degree of Yellowness	+b value	8.8
Nep Count per gram	cnt/g	154
Seed coated neps	cnt/g	20
Maturity Index	Index	0.97

3 Results and discussion

3.1 Statistical Analysis

The statistical software Minitab-17 was used for the central composite design (CCD) and analysis of the experiments as well as to develop the response surface regression models for predicting the selected yarn parameters (i.e., yarn strength, elongation %, CV_m, IPI and hairiness). Table 3 gives the complete central composite design used in this study and values of the yarn parameters obtained after experimentation. Analysis of variance (ANOVA) was performed to evaluate the statistical significance of model terms. A higher value of coefficient indicates a higher effect of corresponding term and vice versa. A minus (-) sign indicates that the response increases by decreasing the factor value and vice versa.

Table 2. Experimental factors and their levels in coded and uncoded units

No.	Factors	Factors ID	Units	Levels				
				-2	-1	0	+1	+2
1	Linear Density (LD)	x_1	Tex	98.5	84.4	73.9	65.7	59.1
2	Slub Thickness (ST)	x_2	%	140	170	200	230	260
3	Slub Length (SL)	x_3	cm	6	8	10	12	14
4	Pause Length (PL)	x_4	cm	5	20	35	50	65

Table 3. Summary of the experimental results

	INPUT FACTORS / SLUB PARAMETERS				OUTPUT YARN PARAMETERS				
EXP #	Yarn Linear Density	Slub thickness	Slub length	Pause length	Yarn Strength	Elongation	Yarn CV_m	Total IPI	Hairiness index
	(Tex)	(%)	(cm)	(cm)	(cN/tex)	%	(%)		
1	65.7	170	8	20	885	6.4	28.5	1354.5	9.5
2	84.4	230	8	20	990	6.8	43.8	5245.5	11.8
3	84.4	170	12	20	1125	7.1	28.7	838.5	10.8
4	65.7	230	12	20	720	4.7	43.8	7738.5	10.4
5	84.4	170	8	50	1210	7.3	25.0	1251.5	10.3
6	65.7	230	8	50	876	5.5	41.0	1903.5	9.5
7	65.7	170	12	50	935	6.0	28.0	1019.5	9.3
8	84.4	230	12	50	1055	7.1	43.3	2036.5	11.5
9	73.9	200	10	35	951	6.2	36.2	2228.0	10.4
10	73.9	200	10	35	950	6.3	36.1	2248.0	10.2
11	84.4	170	8	20	1130	7.0	28.3	1325.5	10.9
12	65.7	230	8	20	780	5.6	43.9	5611.0	9.7
13	65.7	170	12	20	890	6.2	29.0	1014.0	9.3
14	84.4	230	12	20	970	6.1	43.5	7303.0	11.5
15	65.7	170	8	50	945	6.2	25.5	1281.0	9.3
16	84.4	230	8	50	1120	6.6	40.6	1865.5	10.7
17	84.4	170	12	50	1200	6.8	27.0	981.5	10.0
18	65.7	230	12	50	823	5.7	44.7	2235.0	9.6
19	73.9	200	10	35	953	6.3	36.4	2225.5	10.2
20	73.9	200	10	35	952	6.2	36.1	2213.0	10.3
21	98.5	200	10	35	1259	7.0	36.0	2101.0	12.5
22	59.1	200	10	35	826	6.5	36.1	2356.0	9.3
23	73.9	140	10	35	1094	7.1	19.0	175.5	9.3
24	73.9	260	10	35	833	6.1	51.1	4413.0	11.1
25	73.9	200	6	35	1083	7.3	32.5	2482.5	10.2
26	73.9	200	14	35	989	7.2	37.8	2350.5	10.4
27	73.9	200	10	5	715	5.8	27.3	6864.0	10.4
28	73.9	200	10	65	1032	7.3	32.8	1430.0	9.9
29	73.9	200	10	35	954	6.3	35.7	2175.0	10.3
30	73.9	200	10	35	951	6.4	35.9	2195.0	10.3

The quadratic models for predicting various yarn parameters, comprising only the statistically significant terms, are given in Table 4. R-sq value indicates how much variation in the output yarn parameter is explained by the model. The higher the R-sq, the better the model fits the data.

3.2 Effect of Slub Parameters on Yarn Strength

The statistical analysis given in Table 4 reveals that the slub yarn strength mainly depends on slub length (coeff. = -73.2) followed by pause length (coeff. = 9.94), yarn linear density (coeff. = 6.33) and slub thickness (coeff. = -0.25). Please see Figure 3 for illustration of effect of yarn linear density, pause length, slub thickness and slub length on the slub yarn's strength.

It is clear that slub yarn's strength increases by decreasing slub length and slub thickness but decreases by decreasing the yarn linear density and pause length. It can be further noticed from the statistical analysis and response surface plots that the effects of slub length and pause length are not linear. The curvature effect is represented by the statistically significant square values like X_3^2 (P-value = 0.000) and X_4^2 (P-value = 0.000) respectively, as given in Table 5. The yarn strength decreases with the increase of slub length up to a certain level after which there is no further decrease in yarn strength by increasing the slub length. Similarly, yarn strength first increases steadily by increasing the pause length up to a certain level, after which there is no further increase in yarn strength by increasing the pause length.

The effect of linear density and slub thickness on yarn strength was found to be linear. The trend in the results of the effect of different slub parameters on yarn strength can be explained as follows.

As the yarn linear density decreases, diameter of yarn also decreases and consequently, the number of fibers per cross section decreases. So the yarn strength decreases for lower yarn linear density due to less number of fibers per cross section [13, 14] and consequently, less cohesive forces between the fibers. Slub is the self-generated thick place with specific length and thickness. A "pause" is the distance between two consecutive slubs with specific length. [8] The number of fibers in the slub portion is greater than that of the base yarn (i.e., pause portion) even though both portions have the same set of Twist Multipliers (TM). However, in actual twisting process, polar moment of inertia and torsional rigidity of the two portions have great difference due to the diameter difference. So the twist inserted in the slub portion (of larger diameter) is always less as compared to that in the pause portion (of lower diameter). [9]. As the yarn strength mainly depends on the twist of the yarn, [15] so by increasing the slub thickness and slub length, twist in the slub portion decreases; due to which, overall strength of the yarn also decreases. By increasing the pause length, the strength of yarn increases because the relative length of pause portion with higher twist increases in the yarn. However, the strength of cotton yarn increases with an increase of twist up to a certain point, beyond which, the strength and elongation of yarn tend to decrease. When twist in the base yarn (i.e., pause portion) reaches its maximum point, the twist shifts towards the

Table 4. Quadratic models (coded) for predicting the output yarn parameters

Output yarn parameters	Response surface modelling Equations	R-Sq
Strength	$681 + 6.33X_1 - 0.25X_2 - 73.2X_3 + 9.94X_4 + 0.0394X_{12} + 5.08X_{32} - 0.0902X_{42} - 0.185X_2X_3$	97.47%
Elongation	$9.19 + .0416X_1 - 0.0091X_2 - 0.881X_3 + 0.0115X_4 + 0.0421X_{32}$	64.73%
Unevenness	$-26.59 - 0.0152X_1 + 0.2622X_2 + 0.461X_3 + 0.4010X_4 - 0.0059X_{42}$	96.96%
Imperfections	$-8971 - 8.02X_1 + 70.1X_2 - 949X_3 + 342.3X_4 + 2.1X_{42} + 6.3X_2X_3 - 2.48X_2X_4 - 7.1X_3X_4$	97.27%
Hairiness	$6.64 + 0.0767X_1 - 0.0094X_2 - 0.403X_3 - 0.0135X_4 + 0.0022X_2X_3$	93.17%

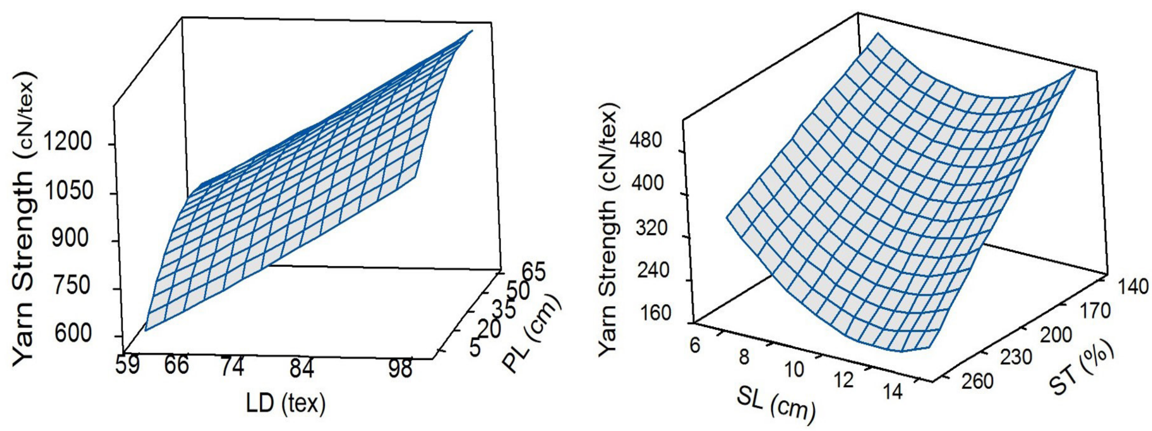

Figure 3. Response surface plots for yarn strength.

Table 5. Estimated coefficients (coded) and P-values of significant input variables for different output yarn parameters

	Yarn Strength		Elongation		CV_m		IPI		Hairiness	
Input variables	Coeff.	p-values	Coeff.	p-values	Coeff.	p-values	Coeff.	p-values	Coeff.	p-values
X_1 : LD (Tex)	-	-	0.04158	0.000	-	-	-	-	0.0767	0.000
X_2 : ST (%)	-62.89	0.000	-0.2721	0.003	7.867	0.000	1-389.5	0.000	0.3637	0.000
X_3 : SL (cm)	-16.99	0.004	-	-	0.923	0.004	-	-	-	-
X_4 : PL (cm)	54.47	0.000	0.1721	0.048	-	-	-1196.9	0.000	-0.2021	0.000
X_{12}	-	-	-	-	-	-	-	-	-	-
X_{32}	20.32	0.000	0.1686	0.035	-	-	-	-	-	-
X_{42}	-20.29	0.000	-	-	-1.321	0.000	464.5	0.000	-	-
X_1X_2	-	-	-	-	-	-	-	-	-	-
X_2X_3	-	-	-	-	-	-	377.9	0.001	0.1294	0.035
X_2X_4	-	-	-	-	-	-	-1116.2	0.000	-	-
X_3X_4	-	-	-	-	-	-	-211.7	0.039	-	-

slub portions and the strength of slub portions starts to increase. This may be the reason of curvature effect of slub length and pause length on the overall yarn strength.

3.2.1 Effect of Slub Parameters on Yarn Elongation

Yarn elongation refers to a percentage increase in the length of the yarn before breaking. It was found from the statistical analysis (as given in Table 4) that the slub yarn elongation mainly depends on slub length (coeff. = -0.881) followed by yarn linear density (coeff. = 0.416), pause length (coeff. = 0.0115) and slub thickness (coeff. = -0.0091). Please see Figure 4 for illustration of effect of yarn count, pause length, slub thickness and slub length on the slub yarn's elongation. It is clear from the figure that slub yarn's elongation increases by increasing the yarn's linear density and pause length but decreases by increasing the slub thickness and slub length. The effect of slub length is not linear and this curvature effect is represented by the statistically significant square value X_3^2 (P-Value = 0.035) as given in Table 5.

As the diameter of the yarn and number of fibers in the yarn cross section decrease with decrease in yarn linear density, the breaking elongation of yarn also decreases. [16]. During extension of staple yarn, every fiber within the yarn experiences differential tension depending on its radial position. The tension generated transverse force acts in the vertical direction of fiber axis, and causes frictional resistance to slippage and breakage. When tension generated on the gripped fiber reaches the fiber's breaking load, the fiber does not resist the stress any longer and breaks. If there are more number of fibers in the yarn cross section, there will be more frictional resistance to slippage and breakage because of more interaction and cohesive forces between the fibers.

The number of fibers in the slub portion is greater than the base yarn (pause portion), while the twist in the slub portion is less than the base yarn. As the yarn's elongation mainly depends on the twist of the yarn, [17] so by increasing the slub thickness and slub length, the twist in the slub portion decreases, due to which yarn elongation also decreases. The strength of cotton yarn increases with increase of twist up to a certain point; beyond that point, strength and elongation of yarn decreases. When the twist in the base yarn reaches its maximum point, it shifts towards slub portions and the elongation of slub portions also starts increasing. This is the reason for curvature found in the effect on slub length (see Figure 4).

3.2.2 Effect of Slub Parameters on Yarn Mass Variation (Unevenness)

Unevenness of slub yarn mainly depends on slub length (coeff. = 0.461) followed by pause length (coeff. = 0.401), slub thickness (coeff. = 0.2622), and linear density (coeff. = -00152), as given in Table 4. Please see Figure 5 for the illustration of effect of yarn's linear density, pause length, slub thickness and slub length on the unevenness of slub yarn. It is clear that the unevenness increases by increasing the slub length, slub thickness and pause length, but decreases with increase in the yarn's linear density. Unevenness first increases up to a certain point, after that it decreases by increasing the pause length. This non-linear effect (curvature effect) is represented by the statistically significant square value X_4^2 (P-value = 0.000), as given in Table 5. Unevenness is not affected by the small change in linear density, but if the change in liner density is bigger, then there may be significant change in the unevenness.

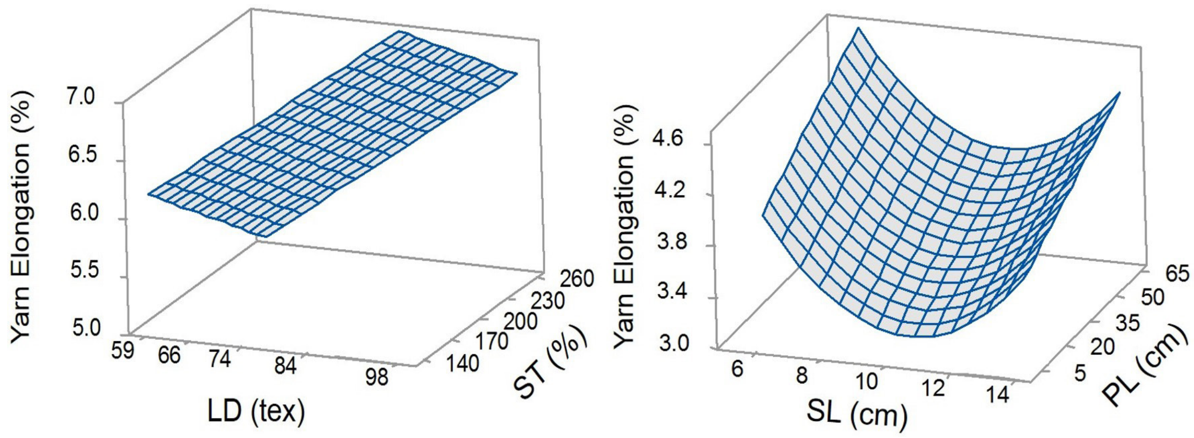

Figure 4. Response surface plot for elongation.

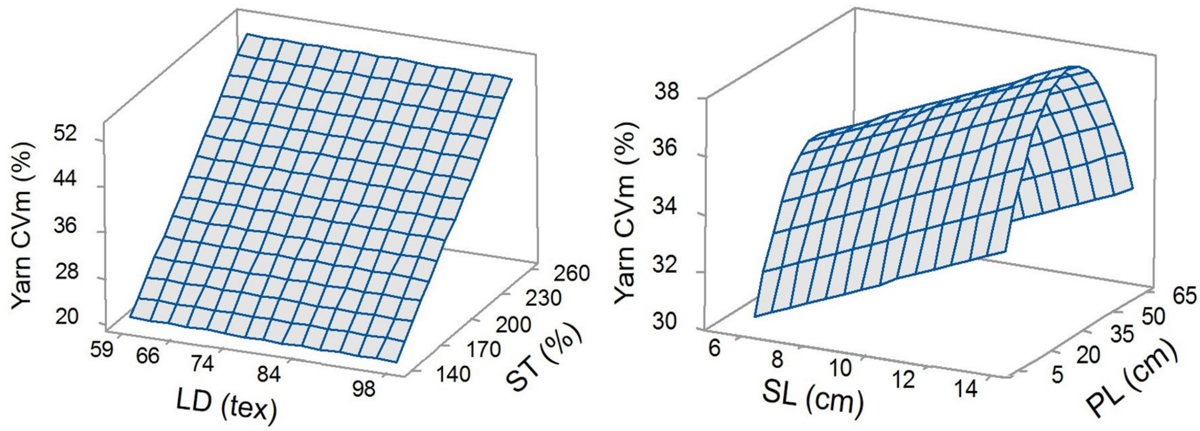

Figure 5. Response surface plots for CV_m.

One of the factors affecting the yarn unevenness is the number of fibers in the yarn cross section. Mass variation increases with decrease in yarn cross section and vice versa [18]. If the number of fibers in the yarn's cross section are less, slight variation in the thickness will be more prominent. As the slub thickness and slub length increases, there is more variation in the yarn's thickness resulting in more mass variation. Yarn unevenness also increases with increase in yarn's twist. So, unevenness increases initially with an increase in pause length because pause has more twist than slub portion. After a critical point, this twist starts to shift towards the slub portions and then unevenness starts to decrease.

3.2.3 Effect of Slub Parameters on Yarn Imperfections (IPI)

Imperfections are cumulative number of thick +50%, thin -50% and neps +200% per kilometer of yarn length. Total imperfections of slub yarn (IPI) mainly depend on slub length (coeff. = -948.9) followed by pause length (coeff. = 342.3), slub thickness (coeff. = 70.1), and linear density (coeff. = -8.02), as given in Table 4. Please see Figure 6 for the illustration of effect of yarn linear density, pause length, slub thickness and slub length on the IPI of slub yarn. It is clear from the figure and table that imperfections increase by increasing slub thickness and slub length at low pause length but decrease with increase in pause length. The effect of pause length is not linear and this curvature effect is represented by the statistically significant square value X_4^2 (P-value = 0.000) as given in Table 5.

As the slub thickness increases, the number of thick places in the yarn increases and consequently, imperfections increase. As pause length in the yarn increases, the number of thick places (slubs) per kilometer of the yarn decreases, due to which imperfections decrease up to a certain point; after that, imperfections start to increase due to formation of neps because of less twist in the base yarn. Imperfections are not affected by a small change in the linear density, but if the change in liner density is bigger, then there may be a significant change in the IPI.

3.2.4 Effect of Slub Parameters on Yarn Hairiness

Yarn hairiness mainly depends on yarn slub length (coeff. = -0.403), followed by linear density (coeff. = 0.0767), pause length (coeff. = -0.0135), and slub thickness (coeff. = -0.0094), as shown in Table 4. Please see Figure 7 for illustration of effect of yarn's linear density, pause length, slub thickness and slub length on the hairiness of slub yarn.

Hairiness characterizes the amount of fibers protruding from the yarn body. It decreases with a decrease in yarn's linear density [16] and increases with a decrease in slub thickness, slub length and pause length. This can be explained by the decrease in the twist in slub portion with an increase in the slub thickness, resulting in more protruding fibers and consequently, higher hairiness. Hairiness decreases with an increase in pause length due to higher twist in this portion, which results in a decrease in protruding fibers.

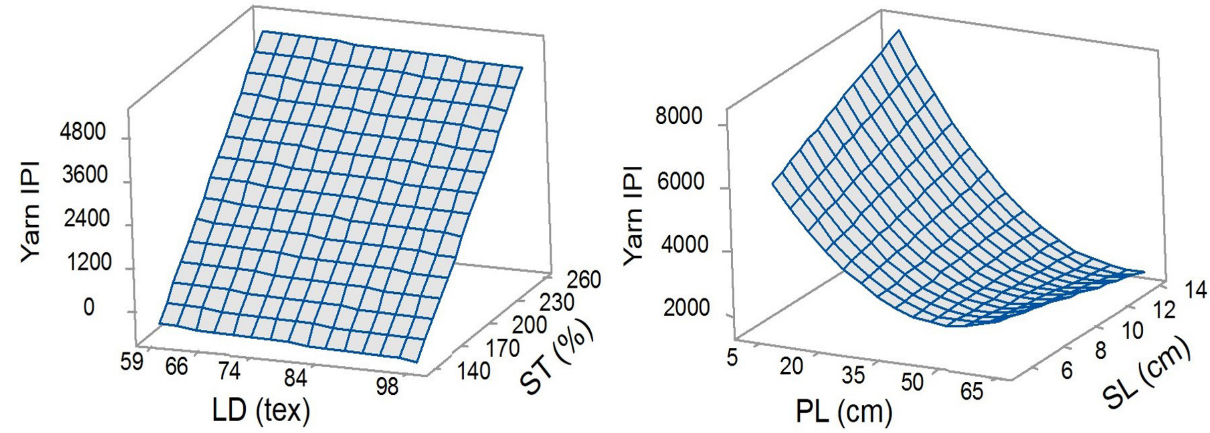

Figure 6. Response surface plots for imperfections.

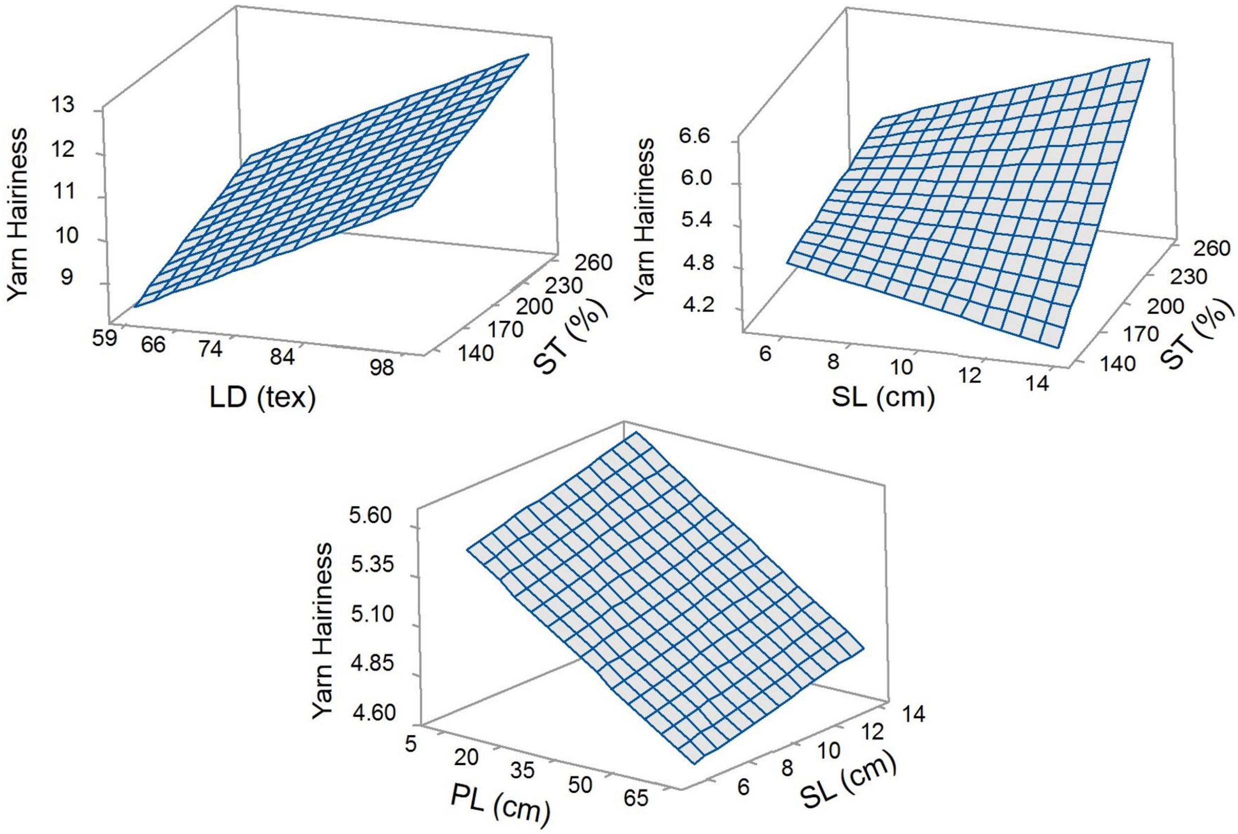

Figure 7. Response surface plots for hairiness.

The effect of interaction of slub length and slub thickness is not linear and this curvature effect is represented by the statistically significant interaction values of X_2X_3 (P-value = 0.035), as given in Table 5. Hairiness decreases by decreasing the linear density of slub yarn, due to a better twist distribution in finer yarns (lower linear density). Again, hairiness reduces on increasing slub length at less slub thickness, but this phenomenon reverses at higher slub thickness. This trend may be attributed to higher twist at less slub thickness and vice versa.

3.2.5 Validation of Models

To validate the developed statistical models, eight set of experiments were chosen that were different than the sets used in central composite design. 120 bobbins of each experimental set were prepared and 20 bobbins were chosen randomly for sampling. A comparison of actual output yarn parameter values and those predicted by developed models is given in Table 6. Mean absolute error percentage of yarn parameters like slub yarn strength, elongation, unevenness, imperfections and hairiness is 3.2, 7.3, 3.7, 8.5 and 3.5 respectively, which indicate a very strong ability and accuracy of the predicted models.

4. CONCLUSION

The effect of four major slub yarn parameters, that is, yarn's linear density, slub thickness, slub length and pause length, was adequately modeled using the central composite experimental design of response surface methodology. It was concluded that an increase in the yarn's linear density results in an increase in yarn strength, elongation and hairiness, but

Table 6. Comparison of predicted and actual values

Exp #	Input Variables				Strength			Elongation			CV_m			IPI			Hairiness		
	LD	ST	SL	PL	Pred.	Act.	% Diff.	Pred.	Act.	% Diff.	Pred.	Act.	% Diff.	Pred.	Act.	% Diff.	Pred.	Act.	% Diff.
1	84.4	200	12	35	1100	1130	-2.6%	6.79	6.2	9.5%	37.1	37.9	-2.1%	2371	2029	16.9%	11.1	10.7	3.8%
2	73.9	230	10	50	929	910	2.0%	6.20	5.85	6.0%	42.6	43.7	-2.6%	1785	1913	-6.7%	10.3	10.0	3.4%
3	65.7	170	8	20	876	925	-5.3%	6.24	6.61	-5.7%	26.9	28.3	-5.0%	1438	1321	8.9%	9.6	10.1	-4.8%
4	73.9	200	12	20	887	870	1.9%	6.21	5.5	13.0%	35.3	37.5	-6.0%	4245	3808	11.5%	10.4	10.9	-4.2%
5	98.5	200	10	35	1280	1255	2.0%	7.10	7.8	-9.0%	36.2	35.5	1.9%	2243	2138	4.9%	12.2	11.9	2.5%
6	59.1	200	10	35	811	850	-4.6%	5.50	5.7	-3.6%	36.2	37.1	-2.5%	2243	2230	0.6%	9.3	9.6	-2.7%
7	59.1	260	14	65	718	752	-4.5%	5.79	5.22	11.0%	50.8	49.8	2.1%	947	1045	-9.4%	9.9	10.2	-3.3%
8	98.5	140	6	35	1477	1440	2.5%	8.45	8.55	-1.2%	18.6	17.4	7.1%	720	658	9.4%	11.5	11.1	3.3%
					% Mean Error		3.2 %	% Mean Error		7.3 %	% Mean Error		3.7 %	% Mean Error		8.5 %	% Mean Error		3.5 %

a decrease in unevenness and imperfections. An increase in the slub thickness and slub length results in a decrease in yarn strength, elongation and hairiness, but an increase in yarn CV_m. An increase in pause length results in increasing the yarn strength, elongation, CV_m and IPI, but a reduction in yarn hairiness. It was further found that the effect of yarn's linear density on yarn strength is not linear. Similarly, the effect of slub length on yarn strength and elongation is not linear, and the effect of pause length on yarn strength, CV_m and IPI also has a curvature effect. Furthermore, in case of IPI, there is a statistically significant interaction between slub thickness and slub length, between slub thickness and pause length, and between slub length and pause length. Similarly, in case of yarn strength and hairiness, there is a significant interaction between slub thickness and slub length. These all results lead towards a concrete fundamental of modelling of fancy yarns.

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