Dimensional behavior of interlock knitted cotton fabrics

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The linear parameters k_c, k_w and k_s have been established for bleached interlock fabrics after subjecting the fabrics into reference state, and the width and length shrinkages are measured. Empirical models for wpcm and cpcm are generated applying general linear model technique and using all the independent variables of the experimental plan, viz. linear density of yarn, twist factor of yarn and stitch length of fabrics along with their two level interactions. The stitch density and aerial density (fabric weight per unit area) are estimated using the predicted values of wpcm and cpcm. Fabric shrinkages both width-wise as well as length-wise are modeled and the resulting models are validated establishing its satisfactory degree of fit. The values of k_c, k_w and k_r are found to be 5.64, 4.0 and 1.41 respectively. Stitch length is found to be the prime factor influencing the wpcm, cpcm and aerial density. The models established can be effectively utilized to adopt the corrective measures in the event of any abnormal shrinkages, both width-wise and length-wise.

Keywords: Cotton, Dimensional behaviour, Interlock fabric, Knitted fabric, Reference state, Shrinkage, Stitch length, Tightness factor, Yarn linear density

1 Introduction

The problem of dimensional instability of cotton knitted fabrics is serious and recurring one, disturbing the quality of the product, such as knitted garments. Such a fabric having unpredictable and high amount of shrinkage is unacceptable to a garment manufacturer and customer as it compromises with the size and fit of the garment seriously. Under such circumstances, prediction of shrinkage of cotton knitted fabrics seems to be a viable solution which can give necessary guidelines in designing of the garments.

The search for dimensional control of knitted fabrics began when Pierce[1] deduced simple relationships between linear dimensions of fabric, loop length and diameter of yarn based on assumed configuration of loop. Doyle[2] found that the stitch density depends only on the loop length and is independent of the yarn and knitting variables. Munden[3] has shown that the dimensions of plain-knitted wool fabrics, in a state of minimum energy, can be expressed in terms of constants like k_c, k_w, k_s and k_r for courses per unit length, wales per unit length, stitch density and shape factor respectively, establishing the fact that loop length is the major factor determining the fabric dimensions.

Additionally, fibre content and state of relaxation can also be identified as variables, which produce different constant values of k_c, k_w, k_s and k_r. Munden[4] initially defined two distinct and differently relaxed states viz. the dry-relaxed state and the wet-relaxed state. But Knapton *et al.*[5] found that neither the dry nor the wet-relaxed state for plain knit loop shape are predictable. They suggested some form of 'fully-relaxed' state which allows the loops to find their least strained shape. Later on, this fully relaxed state was elaborately explained by Heap *et al.*[6,7]. Through their extensive investigative programme, they crystallised the idea of 'Reference State' or 'fully relaxed state' as the state of knitted fabric in which fabric is completely stable and the state is achieved after one wash and tumble drying followed by four cycles of rinsing and tumble drying.

In the quest of dealing the dimensional issues of double knitted structure, Nutting and Leaf [8], through a theoretical approach, proposed that the yarn diameter is a significant factor in determining fabric dimensions, contrary to Munden's basic approach. Smirfitt[7] was the first to show that for more practical purposes the dimension properties of wool 1×1 rib structure could also be described by k parameters, which are similar but not identical to those found for the plain knit structure. Smirfitt[9], Natkanski[10] and Knapton *et al.*[11] found the values of these k parameters in the fully

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relaxed state and they were found to be almost identical. A further study by Knapton and Fong[12] on interlock fabric, using wool yarns with three different ranges of loop length or structural cell-stitch length (SCSL), has shown that the k values are not constant in dry and wet relaxed states, but are significantly dependent on loop length. However, in the fully relaxed state, no significant dependency of k values on SCSL was observed.

With the backdrop of abovementioned facts, it has become quite clear that using a combination of the k values above and the appropriate loop length, it is possible to calculate courses and wales per unit length or width, as well as the loop density. The determination of these basic parameters will help in designing a theoretical model which can guide us having an estimate of fabric shrinkages in linear as well as in aerial dimensions. Under such situation, there will be no more serious problem of fitness when the knitwear is made from fabrics manufactured and finished in usual industrial conditions. The dimensional study of various knitted structures, like plain, 1×1 rib and 2×2 rib has been reported in literature[13-15], but such vital information about cotton interlock knitted structure is scanty. Moreover, a predictive system with sufficiently high accuracy for interlock fabric needs to be developed which is based on all basic controllable material and process parameters. This is so because the form (size and

shape) of a knitted fabric stitch, decided jointly by integrity and friction of yarn, depends on the several factors like the fibre raw material, yarn structure, the yarn twist, the stitch length, the yarn linear density and external conditions. Contribution of finishing process as well as the yarn count and stitch length are also generalized through a study on interlock together with plain and 1x1 rib structures by Heap *et al.*[6,7].

This investigation includes study on the dimensional behavior of interlock fabrics made from yarns with different linear density and twist factors and having variation in stitch length, and finally developing an empirical model which is simple, reliable and accurate enough to be able to predict the final dimensions including shrinkages and weight per unit area, even before starting to knit.

2 Materials and Methods

Combed cotton yarns with three linear densities, namely 24.61 tex (24[s] Ne), 19.68 tex (30[s] Ne) and 16.4 tex (36[s] Ne), each with twist factors 33.5 (3.5 TM), 36.4 (3.8TM) and 39.2 (4.1 TM) respectively were chosen. These 9 yarn samples were tested for their properties and the results are summarized in Table 1.

The experimental set-up was planned after a short survey in the knitters by selecting the yarn linear densities (or tex), yarn twist factors (or twist multipliers) and stitch lengths (cm) as well as fabric

Table 1 — Tenacity, elongation, unevenness and imperfections for yarns

Tex (count)	Tex-twist factor (TM)	Yarn linear density (tex) mean (CV%)	Tenacity mN/tex	Elongation %	Uneven-ness U%	Imperfections/1000m		
						Thin places	Thick places	Neps
24.61 (24[s])	33.5 (3.5)	24.10 (2.36)	164.2	4.37	9.08	0	22	162
	36.4 (3.8)	23.76 (2.0)	198.7	4.79	8.36	0	8	133
	39.2 (4.1)	23.74 (1.93)	201.5	4.65	8.51	0	17	152
19.68 (30[s])	33.5 (3.5)	29.68 (1.78)	210.9	4.25	9.09	0	18	60
	36.4 (3.8)	29.64 (2.33)	177.3	4.14	9.12	0	15	80
	39.2 (4.1)	30.22 (1.61)	201.2	4.64	9.43	3	30	115
16.4 (36[s])	33.5 (3.5)	16.36 (0.96)	145.7	3.87	9.7	0	45	65
	36.4 (3.8)	16.64 (1.35)	169.5	3.95	9.82	0	48	122
	39.2 (4.1)	16.53 (0.84)	177.4	4.1	10.25	2	57	80

weight (g/m^2 or GSM) in dry relaxed state. Three levels of yarn linear density values, each with 3 levels of twist factors were selected. Each of these nine samples of yarns was knitted at four levels of stitch lengths employing gauge of machine as 24. Thus, the plan of experiment consisted of 36 fabric samples.

2.1 Sample Preparation and Testing

The yarns were knitted on an interlock circular knitting machine having 24 inch (61 cm) diameter, equipped with 48 feeders, positive feed devices and adjustable fabric pulley take-down system. During preparation of fabric samples, care was taken to keep the yarn tension constant at 12cN for all 48 feeders. A cylinder of 24 gauge was used with nominal stitch lengths of 3.0mm, 3.2mm, 3.4mm and 3.6mm by changing the cam setting and positive feed device in the machine.

The bleaching was carried out in industry under normal industrial parameters and all fabric samples were processed in the same bath, for which the fabric samples were stitched together end to end. Subsequently, the fabrics were given compaction treatment and each fabric sample was separately set in the compaction machine to achieve the nominal finishing targets. The following wet-processing route was adopted:

Scour & bleach (soft flow) → Centrifuge → Tubular dry → Compressive shrinkage (Compaction)

The procedure detailed by Heap *et al*.[6] was adopted for full relaxation treatment using a fully automatic front loading domestic washing machine and a tumbler dryer. All fabric samples were undertaken for this treatment which consisted of (i) a standard wash at 60^{0}C using surf excel matic detergent, rinse and spin, followed by standard tumble drying for 30minutes at 60^0 C until dry; and (ii) four cycles of rinsing and tumble drying, making five cycles in all.

Relevant parameters, such as loop length, courses per inch, wales per inch and fabric weight were recorded after conditioning these samples for 72 h in a standard atmosphere of 27± 2^0 C and 65 ± 2% relative humidity.

For measurement of shrinkage, a 50cm^2 was drawn on each sample using an indelible marker before the start of the washing procedure at three different places. After the completion of the relaxation procedure and conditioning, the length and width of the square were again measured to determine the length-wise and width-wise shrinkage separately.

3 Results and Discussion

The relevant data for the fabric samples are furnished in Table 2.

In order to verify the basic structural consideration of knitted fabrics, attempt has been made to explore the relationship between wpcm/cpcm and reciprocal of stitch length and between stitch density and reciprocal of square of stitch length (Figs 1 and 2)

The above plots show a linear relationship between reciprocal of stitch length and cpcm and wpcm in the reference state with high values of co-efficient of determination (r^2), which confirms that the inverse relationship exists between wales and courses per cm with stitch length for interlock fabrics. The plot of stitch density against reciprocal of square of stitch length (l^2) is also found to be linear with high values of r^2. These relationship outcomes are in line with the observations of earlier investigators. Furthermore, the corresponding values of dimensional constants are 4.0 for k_w and 5.64 for k_c with the ratio $k_r = k_c/ k_w$ = 1.41,indicating that if material, machine, process parameters are kept same and identical sequences of machines are used, these values will remain unchanged.

3.1 Development of an Empirical Model for Interlock fabrics

The prediction of shrinkage depends upon the establishment of reliable empirical models for wpcm and cpcm at reference state and dry relaxed state so that the predicted shrinkage% becomes the percentage difference of wpcm or cpcm between the two states. The general linear model (GLM) is pursued using SYSTAT 12$^®$ software. The independent variables are tex twist factor (TF), yarn linear density(tex) and stitch length (l) and the dependent variable is wpcm or cpcm, all of which are a part of the plan of experiment. The main independent variables and their interactions at two levels are considered applying the backward elimination method at 5% significance level. The following results are obtained.

For bleached interlock fabrics at reference state (RS), the equations generated are:

$$wpcm (RS) = 17.213 - 0.076*SL*T + 0.006*TF*T - 0.027*TF*SL \qquad …(1)$$
$$R^2 = 0.818, \qquad SE = 0.294$$
$$cpcm (RS) = 53.716 - 1.124* T - 11.966*SL + 0.333*SL*T + 0.003*TF*T \qquad …(2)$$
$$R^2 = 0.923, \qquad SE = 0.39$$

For the same structure of fabrics at dry relaxed state (DR), the equations generated are:

Table 2 — Bleached interlock fabric parameters knitted with 24 gauge cylinder and dial of machine

Yarn & machine parameters[a]	Reference state				Dry relaxed state				Measured shrinkage, %	
	Stitch length cm	Wales per cm	Courses per cm	Fabric weight g/m²	Stitch length, cm	Wales per cm	Courses per cm	Fabric weight, g/m²	Width	Length
24.6/33.6/3.0	0.297	13.77	17.59	342.25	0.297	13.48	17.27	330.4	2.6	6.6
24.6/33.6/3.2	0.313	12.85	17.48	323.46	0.315	12.56	17.16	304.3	2.5	6.6
24.6/33.6/3.4	0.337	12.49	15.44	292.82	0.335	12.2	15.12	275.34	3.3	5.6
24.6/33.6/3.6	0.347	11.94	14.96	290.78	0.347	11.65	14.64	264.78	3.8	6.2
24.6/36.4/3.0	0.298	13.74	17.62	346.64	0.296	13.45	17.3	332.26	2.6	5.5
24.6/36.4/3.2	0.312	13.2	17.28	341.3	0.315	12.91	16.96	321.68	2.5	6.7
24.6/36.4/3.4	0.333	12.57	15.99	318.06	0.335	12.28	15.67	295.48	3.0	4.7
24.6/36.4/3.6	0.344	12.1	15.48	303.02	0.346	11.81	15.16	274.92	3.3	6.5
24.6/39.2/3.0	0.3	13.77	17.54	353.08	0.297	13.48	17.22	336.86	2.9	5.9
24.6/39.2/3.2	0.312	13.4	17.84	336.75	0.314	13.11	17.52	307.9	2.5	6.7
24.6/39.2/3.4	0.331	12.57	16.89	328.36	0.326	12.28	16.57	295.46	3.4	6.1
24.6/39.2/3.6	0.345	12.11	15.5	327.44	0.347	11.82	15.18	290.94	3.3	5.6
19.7/33.6/3.0	0.297	13.75	17.48	269.64	0.298	13.46	17.16	263.66	3.4	5.3
19.7/33.6/3.2	0.309	13.12	16.3	250	0.315	12.83	15.98	230.22	3.0	6.9
19.7/33.6/3.4	0.323	13.2	16.07	246.42	0.329	12.91	15.75	228.74	3.1	7.9
19.7/33.6/3.6	0.346	12.69	14.49	226	0.345	12.4	14.17	221.26	3.3	7.3
19.7/36.4/3.0	0.298	14.18	17.84	282.12	0.299	13.89	17.52	264.34	4.4	3.9
19.7/36.4/3.2	0.311	13.67	16.7	273.78	0.316	13.38	16.38	241.6	4.3	5.3
19.7/36.4/3.4	0.325	12.87	16.18	252.08	0.332	12.58	15.86	241.76	4.0	5.1
19.7/36.4/3.6	0.345	12.65	15.0	235.7	0.347	12.36	14.68	206.0	4.1	6.9
19.7/39.2/3.0	0.297	14.42	17.86	287.38	0.299	14.13	17.54	259.84	3.3	4.7
19.7/39.2/3.2	0.31	14.11	16.89	266.06	0.317	13.82	16.57	249.3	3.2	5.6
19.7/39.2/3.4	0.323	13.4	16.15	258.64	0.332	13.11	15.83	248.9	3.6	5.6
19.7/39.2/3.6	0.341	12.67	15.04	146.8	0.347	12.38	14.72	220.48	3.1	6.2
16.4/33.6/3.0	0.293	14.14	17.84	223.02	0.297	13.85	17.52	202.14	4.2	5.9
16.4/33.6/3.2	0.315	13.44	16.54	195.34	0.317	13.15	16.22	189.64	4.6	6.4
16.4/33.6/3.4	0.326	12.87	14.57	196.34	0.333	12.58	14.25	178.1	4.5	5.6
16.4/33.6/3.6	0.346	12.65	13.86	176.08	0.349	12.36	13.54	171.24	4.1	7.0
16.4/36.4/3.0	0.297	14.07	17.97	211.14	0.298	13.78	17.65	196.18	4.9	3.7
16.4/36.4/3.2	0.312	12.97	16.66	211.24	0.316	12.68	16.34	193.92	4.2	4.6
16.4/36.4/3.4	0.327	12.81	14.54	201.58	0.333	12.52	14.22	180.14	4.2	6.0
16.4/36.4/3.6	0.345	12.77	14.07	188.6	0.348	12.48	13.75	163.8	4.3	6.4
16.4/39.2/3.0	0.294	14.11	18.2	221.16	0.298	13.82	17.88	199.66	3.1	4.5
16.4/39.2/3.2	0.314	12.85	16.6	215.66	0.316	12.56	16.28	192.8	3.2	4.0
16.4/39.2/3.4	0.329	12.55	14.48	200.48	0.334	12.26	14.16	179.44	4.3	4.8
16.4/39.2/3.6	0.344	12.75	14.13	184.76	0.347	12.46	13.81	178.98	4.1	4.7

[a]Yarn linear density (tex)/ twist factor/ nominal stitch length (mm).

$$\text{wpcm (DR)} = 16.923 - 0.076*SL*T + 0.006*TF*T - 0.027*TF*SL \qquad \ldots (3)$$
$$R^2 = 0.819, \quad SE=0.307$$

$$\text{cpcm (DR)} = 53.396 - 1.124*T\ 11.966*SL + 0.333*SL*T + 0.003*TF*T \qquad \ldots (4)$$
$$R^2 = 0.925, \qquad SE=0.398$$

where SL is the stitch length in cm; T, the yarn linear density in tex; TF, the tex twist factor of yarn; RS indicates values in reference state; and DR indicates values in dry relaxed state.

The measured values of stitch lengths are those in reference state for generating Eqs (1) and (2), and those in dry relaxed state for Eqs (3) and (4) are taken from Table 2.

Calculated width shrinkage % = [wpcm (DR) – wpcm (RS)]/wpcm (DR)*100 $\qquad \ldots (5)$

Calculated length shrinkage % = [cpcm (DR) – cpcm (RS)]/cpcm (DR)*100 $\qquad \ldots (6)$

The high values of r, r^2 and adjusted r^2 and the low values of standard errors demonstrate that the above equations are well-capable to predict the wpcm and cpcm for both the cotton bleached interlock fabrics.

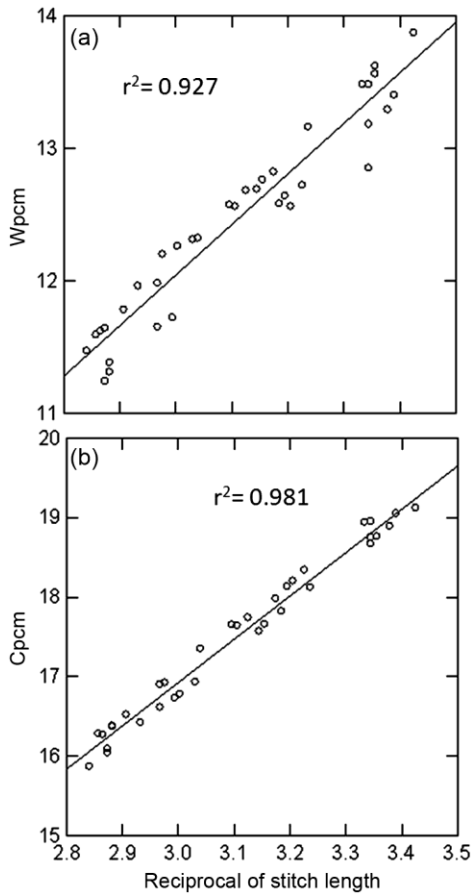Almost negligible interaction among various controlling parameters influencing both wpcm and

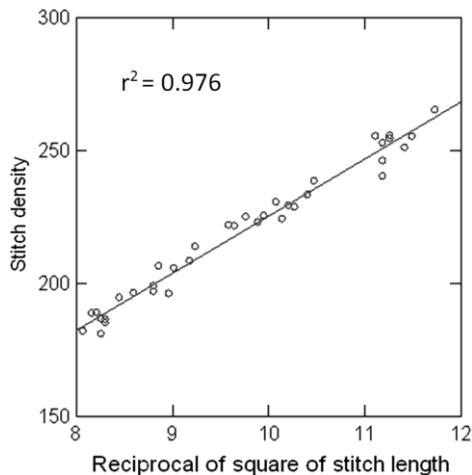Fig. 1 — Plot of wpcm and cpcm against reciprocal of stitch length (*l*)

Fig. 2 — Plot of stitch density against reciprocal of square of stitch length (*l²*)

cpcm is quite evident. But the main effect of stitch length and yarn linear density in cpcm is quite significant. A model is tried to be developed based on only reciprocal of stitch length which is represented by Eqs (7) - (10). It has been observed that stitch

length alone can explain 79.5% and 82.4% of variations occurring in cpcm in RS and DR states respectively. The corresponding SE is 0.608 and 0.563 in these finished states. Through this interpretation, it can be construed that stitch length is the only decisive parameter which can decide the cpcm in the structure. It is also an observable fact that the incorporation of linear density along with stitch length in the model can bring a considerable improvement in r^2 as well as in the values of SE.The negative contribution of yarn linear density towards cpcm can also be felt in the sense that coarser yarn makes the structure bit tighter and chances of loop distortion are comparatively low during downstream processing as well as in measurement. Similar comments can be made about wpcm observing that the stich length is well capable of explaining most of the variations occurring in wpcm.

The Eqs (7) – (10) representing the model to be developed based on the reciprocal of stitch length are given below:

$$\text{wpcm (RS)} = 2.889 + 3.277 * SL^{-1} \qquad \dots(7)$$
$$R^2 = 0.8, \qquad SE = 0.299$$

$$\text{cpcm (RS)} = -4.314 + 6.57 * SL^{-1} \qquad \dots(8)$$
$$R^2 = 0.795, \qquad SE = 0.608$$

For the same structure of fabrics at DR state, the equations generated are shown below:

$$\text{wpcm (DR)} = 3.115 + 3.137 * SL^{-1} \qquad \dots(9)$$
$$R^2 = 0.750, \qquad SE = 0.334$$

$$\text{cpcm (DR)} = -4.609 + 6.616 * SL^{-1} \qquad \dots(10)$$
$$R^2 = 0.824, \qquad SE = 0.563$$

where SL is the stitch length in cm; RS indicates values in reference state; and DR indicates values in dry relaxed state.

3.2 Forecasting Shrinkage and Weight of Interlock Fabrics

The calculated values of wpcm and cpcm are obtained for bleached interlock fabrics from the predictive empirical Eqs (1) - (4) and the calculated shrinkage% are derived from Eqs (5) and (6). Also, the actual values of width and length shrinkages are determined as outlined in the Section 2.1. The scatter plots are constructed to explore the extent of association between the measured and calculated values of shrinkages (Fig.3).

In the bleached interlock fabrics, the calculated and measured values of width shrinkage bear a good degree of association between them with co-efficient of determination (r^2-values) of 0.772,
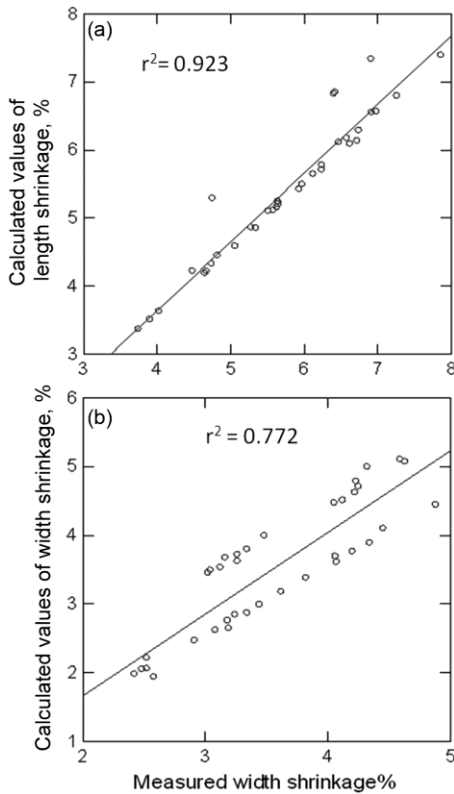
Fig. 3 — Association of calculated and measured values of (a) length and (b) width shrinkage for bleached interlock fabrics
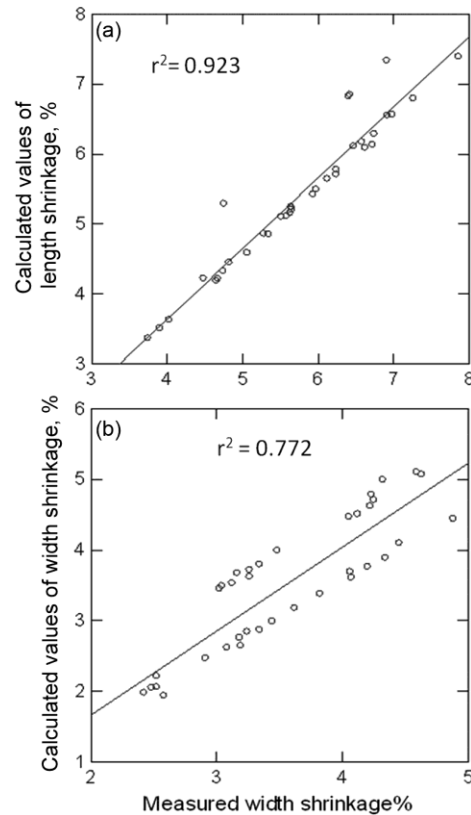

Fig.4 — Association between measured and calculated values of weight of bleached interlock fabric in (a) dry relaxed state and (b) reference state

while the calculated and measured values of length shrinkage have an r^2-value of 0.923, implying that the relevant models are quite adequate to explain length and width shrinkages. It can be presumed from these figures that for bleached interlock fabrics the predictive equations are sufficiently dependable for prediction.

Fabric weight (g/m^2) is another important property which is affected by shrinkage and it is measured in dry relaxed and reference states (Table 2). There exists a simple relationship for calculated weight of interlock fabric from the given parameters which is given in following equation:

Calculated fabric weight (g/m^2) = 2*wpcm* cpcm* stitch length (cm)*tex/10 … (11)

In order to explore the extent of association between measured weight and calculated weight, the values of calculated weights are generated using the values of the parameters from Table 2 and linear regression method is applied between measured weights and calculated weights. The scatter plots and r^2 values are shown in Fig.4

As shown in the figures, for fabrics in dry relaxed and reference states the value of r^2 is very high, indicating an excellent association between measured and calculated weights and, therefore, the Eq. (11) is well capable to predict the weight of bleached interlock fabrics, although, the prediction is better in reference state than in dry relaxed state as indicated by r^2 values.

3.3 Validation of Predictive Model for Interlock Fabrics

A part of the experiment is replicated to validate the predictive Eqs (1) and (2) as well as Eqs (7) and (8) for bleached fabrics in reference state, by randomly procuring four yarn samples from a different source and four fabric samples are knitted with different stitch lengths. These fabric samples are bleached and finished to nominal width following the same routes of chemical processing as carried out for the main part of the experiment. The measured fabric parameters of the replicated samples in the reference state, the calculated values from the models and the error% are furnished in Tables 3 and 4.

From Table 3, the error% for selected bleached interlock fabrics lies between -3.53 and 0.59 for

Table 3 — Error% for bleached interlock fabrics based on Eqs (1) and (2)

Yarn and machine parameters[a]	Values from model		Measured values		Error %	
	wpcm	cpcm	wpcm	cpcm	wpcm	cpcm
19.7/39.2/3.2	13.38	16.27	13.46	16.10	0.59	-1.56
19.7/36.4/3.4	12.79	15.02	12.7	15.35	-0.70	2.15
16.4/39.2/3.0	13.86	17.37	13.37	17.61	-3.53	1.38
16.4/33.6/3.2	13.33	15.80	12.86	15.49	-3.52	-1.96

[a]Parameters units and their sequence are same as in Table 2.

Table 4 — Error% for bleached interlock fabrics based on Eqs (7) and (8)

Yarn and machine parameters[a]	Values from model		Measured values		Error%	
	wpcm	cpcm	wpcm	cpcm	wpcm	cpcm
19.7/39.2/3.2	13.46	16.88	13.46	16.10	0.00	-4.84
19.7/36.4/3.4	12.97	15.90	12.7	15.35	-2.13	-3.58
16.4/39.2/3.0	14.04	18.03	13.37	17.61	-5.01	-2.38
16.4/33.6/3.2	13.29	16.54	12.86	15.49	-3.34	-6.78

[a]Parameters, units and their sequence are same as in Table2.

wpcm and -1.96 and 2.15 for cpcm. The error% values occur between -5.01 and 0.0 for wpcm and -6.78 and -2.38 for cpcm when only stitch length is taken as a variable for predictive model (Table 4). Hence, model based on yarn and fabric parameters gives better predictability compared to one based on mere stitch length.

The empirical Eqs (1) and (3) show that stitch length, tex and twist factor are the contributing factors in prediction of wpcm and width shrinkage. Therefore, in order to rectify any abnormal value in width shrinkage that may arise during the manufacture of this type of fabric one is required to look mainly into the stitch length setting of the knitting machine together with the yarn characteristics, i.e. yarn linear density and twist factor. For analyzing any abnormal value of length shrinkage, empirical Eqs (2) and (4) reveal similar reasons.

4 Conclusion

4.1 The values of linear parameters of bleached interlock cotton fabrics under reference state are 5.64 for k_c and 4.0 for k_w and with the loop shape factor k_r is 1.41.

4.2 Stitch length is the prime factor in determining the cpcm and wpcm and subsequently the length shrinkage, width shrinkage and areal density.

4.3 Apart from stitch length, among all other variables, the contribution of yarn linear density is remarkable, especially in adjusting the course density and the resultant length shrinkage.

4.4 It is here suggestive in nutshell that in order to adopt the corrective measures in the event of any abnormal value of width and length shrinkages, stitch length, yarn linear density and tex twist factor are required to be examined for bleached interlock fabrics in line with the predictive model developed.

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