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Role of fibre, yarn and fabric parameters on bending and shear behaviour of plain woven fabrics

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Influence of fibre blend, yarn count and fabric sett (thread density) on bending and shear rigidities of plain woven fabric has been studied. Fifteen plain woven square fabrics have been woven using 20, 30 and 40 Ne yarns of three different blends (100% cotton, 100% polyester and 50:50 polyester-cotton). The fabric samples are produced at three levels according to the Box and Behnken design of experiment methodology. Fabric bending and shear rigidities are measured by using Kawabata Evaluation System (KES) at low stress region. An increasing trend of fabric bending and shear rigidities are observed with lower proportion of polyester, coarser yarn count and higher fabric sett. Yarn count is found to be the most important parameter influencing fabric bending and shear rigidities followed by fabric sett and blend proportion of polyester. A strong degree of association is found between bending and shear rigidities of fabric.

Keywords: Bending rigidity, Blend ratio, Fabric sett, Plain woven fabric, Response surface model, Shear rigidity

1 Introduction

Hand characteristics and drape of fabrics play an important role in selection of fabrics intended for apparel use. For centuries, textile materials including fabrics were relegated to the class of non-engineering materials. Therefore, subjective evaluation of fabric hand was in practice. However, in last few decades, there has been a paradigm shift in evaluation of fabric hand largely due to the emergence of Kawabata Evaluation System (KES) which subjects the fabric under all possible low-stress mechanical deformations like tensile, bending, shear and compression. The bending and shear behaviour of fabrics have significant influence on fabric hand characteristics and drape.

Peirce[1] was the first to make an attempt for objective estimation of woven fabric stiffness in both warp and weft direction. Later on, many researchers[2-7] tried to evolve expressions of fabric bending rigidity. Some instruments were developed for the measurement of shear deformation in fabric[8-10]. Grosberg and Park[11] and Grosberg *et al.*[12] introduced a mathematical analysis for determining the initial shear modulus, frictional shear stress and shear rigidity of woven fabric. Leaf and Sheta[13] developed a mathematical model to predict the initial shear behaviour of plain woven fabric.

Bending and shear behaviour of woven fabrics are influenced by the constituent fibre, yarn and fabric parameters. Varshney *et al.*[14] reported that stiffness (bending and shear) reduced with the increase in proportion of polyester in polyester-viscose blends. Behera *et al.*[15] studied the drape of polyester filament based dress materials and found that the microdenier fabrics give a better drape property than normal denier fabric. In some study on the effect of crimp frequency, diameter and curvature of fibre on hand behaviour of fine merino wool fabrics, it is reported that a reduction in staple crimp frequency or mean fibre diameter or both resultantly increases softness of fabrics[16-18]. Several studies[19-22] were carried out on the handle of woven fabrics made from yarns spun using different spinning technologies and it was concluded that the fabrics made from open-end yarns show higher bending and shear rigidities than the fabrics made from ring-spun yarns. It was reported that yarn count has direct influence on fabric bending and shear behaviour and the effect of yarn twist varies for different kinds of fabrics[23-24]. Matsudaira *et al.*[24] and Mori and Matsudaira[25] pointed out that higher values of ends and picks densities (fabric sett) increase both

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bending rigidity and bending hysteresis in warp and weft directions respectively.

Aforesaid discussion reveals that several attempts have been made to establish the fundamental theories of woven fabric bending and shear behaviour. However, the effect of fibre type, yarn count and fabric sett on bending and shear rigidities of the fabrics has not been fully explored. Besides, the association between bending and shear rigidities when fibre, yarn and fabric parameters are changed needs to be verified. Hence, in this work, an attempt has been made to study the bending and shear rigidities of plain woven fabrics made from 100% cotton, 100% polyester and 50:50 polyester-cotton blended yarns by varying yarn count and fabric sett.

2 Materials and Methods

2.1 Materials

Ring-spun yarns made from 100% cotton, 100% polyester and 50:50 polyester-cotton blends were used in this study. J-34 cotton fibre having upper half mean length and micronaire of 28 mm and 4.5 respectively was used. The staple length and fineness of polyester fibre was 32 mm and 1.2 denier respectively. The yarn counts were 20, 30 and 40 Ne for each of the three blends making a total of nine types of yarns.

2.2 Fabric Preparation

Square fabrics having same yarn count and fabric sett in warp and weft directions were prepared using a single rigid rapier sample loom. Three parameters, namely proportion of polyester, yarn count and fabric sett were varied systematically. Three levels for each of these factors were chosen (Table 1). The symbols X_1, X_2 and X_3 correspond to proportion of polyester, yarn count and fabric sett respectively.

2.3 Testing of Yarns and Fabrics

Bending rigidity of yarns was measured by heart-loop test method[26]. The fabrics were analysed for fabric sett (warp and weft thread density) according to the ASTM D3775 using the counting glass. Areal density of fabrics was measured according to ASTM D3776. Fabric cover was determined optically by using Nikon SMZ1500 microscope. First, the images of fabric samples were captured. Then, the area of one weave repeat unit was measured by the area measuring tool of image processing software. The area of the pore within the weave repeat was also measured in the same way. Before testing, all fabric samples were conditioned at standard atmospheric condition for 48 h. Subsequently, the fabric bending rigidity and shear rigidity were measured using KES-FB 2 and KES-FB 1 modules of KES respectively. All fabric samples were cut into size of 20 cm × 20 cm and for each of the 15 samples, 10 specimens were prepared for testing. In KES-FB 2 module, the fabric specimen was bent between the curvatures of -2.5 and 2.5 cm^{-1}. Bending rigidity was measured from the slope of bending moment-curvature curve between 0.5 cm^{-1} and 1.5 cm^{-1}. In KES-FB 1 module, shear force was applied to create a shear angle between -8° and 8°. The shear rigidity was measured from the slope of shear stress-strain curve between 0.5° and 2.5° shear angle.

Table 1 — Yarn and fabric parameters for square fabrics

Controlled factors	Coded level		
	-1	0	+1
Proportion of polyester (X_1), %	0	50	100
Yarn count (X_2), Ne	20	30	40
Fabric sett (X_3), inch^{-1}	50	60	70

2.4 Response Surface Equations

Quadratic regression equation models were used to relate three independent parameters with two response variables, namely bending rigidity and shear rigidity. Following equation shows the general form of models:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_1 X_2 + \alpha_5 X_2 X_3 + \alpha_6 X_1 X_3 + \alpha_7 X_1^2 + \alpha_8 X_2^2 + \alpha_9 X_3^2 + \varepsilon \quad \ldots (1)$$

where Y is the measured response variable; X_1, X_2 and X_3, the coded input parameters to the model; $\alpha_0, \alpha_1, \alpha_2 ...., \alpha_9$, the regression coefficients; and ε, the error term.

The regression coefficients of the fitted quadratic equation models were determined along with adjusted coefficient of determination $\left(R^2_{adj}\right)$ of the fitted models, beta coefficient and percentage contribution of significant parameters. Beta (β) coefficients are the standardised coefficient from which percentage contribution of significant input parameters can be estimated. As beta coefficients are estimated by using dimensionless input parameters, these coefficients imply the contribution of input parameters. The percentage contribution (C_i) of the i^{th} input parameter can be estimated from the following equation:

$$C_i\,(\%) = R^2_{adj} \times \frac{|\beta_i|}{\sum_{i=1}^{k} |\beta_i|} \times 100 \quad \ldots (2)$$

where β_i is the beta coefficient of the i^{th} significant controlled factor; and k, the total number of significant controlled factors.

3 Results and Discussions

The bending and shear rigidities of all 15 fabric samples are presented in Table 2 along with the details of fabric parameters. Bending rigidity ranges from 0.018 gf.cm^2/cm to 0.119 gf.cm^2/cm and shear rigidity ranges from 0.31 gf/cm.deg to 4.15 gf/cm.deg. It is interesting to note here that fabric Sample 2 possesses the highest bending and shear rigidities, whereas fabric Sample 7 possesses the lowest values. The lowest bending and shear rigidities are observed in fabric made from 100% polyester yarns of 30 Ne yarn count with a fabric sett of 50 per inch. In contrast, the highest bending and shear rigidities are achieved in the fabric made from 50:50 cotton-polyester blended yarn of 20 Ne yarn count with fabric sett of 70 per inch.

Fabric Samples 3, 7 and 12 have comparable bending (0.018 – 0.019 gf.cm^2/cm) and shear rigidity (0.31 – 0.33 gf/cm.deg). Fabric Samples 3 and 7 have same sett of 50 inch^{-1} but different polyester fibre proportion (50% and 100% respectively) and yarn count (40 Ne and 30 Ne respectively). Coarser yarns tend to increase the bending rigidity of fabric, whereas the increase in proportion of polyester has the opposite effect. For fabric Sample 7, effect of coarser yarn count on bending and shear rigidities is compensated by higher proportion of polyester. On the other hand, fabric Samples 7 and 12 have same proportion of polyester i.e. 100% but different yarn count (30 Ne and 40 Ne respectively) and fabric sett (50 inch^{-1} and 60 inch^{-1} respectively). It appears that in Sample 12, effect of finer yarn count on bending and shear rigidities is compensated by higher fabric sett.

Fabric samples show consistent trend of increasing bending and shear rigidities with lower proportion of polyester, coarser yarn and higher fabric sett. Fabric Samples 1 and 2 have same polyester proportion (50%) and yarn count (20 Ne), but fabric sett increases from 50 inch^{-1} to 70 inch^{-1}. As a consequence, fabric bending rigidity becomes more than double (from 0.049 gf.cm^2/cm to 0.119 gf.cm^2/cm) and shear rigidity increases more than four folds (0.97 gf/cm.deg to 4.15 gf/cm.deg). Similar observations are made for fabric Samples 3 and 4; 5 and 6; and so on. Similarly, comparing the results of fabric Samples 1 and 3, it can be inferred that the fabric bending and shear rigidities increase as the yarn becomes coarser. From the results of fabric Samples 5 and 7, it can be concluded that fabric bending and shear rigidities increase with lower proportion of polyester.

Fabric Sample 2, having the highest bending and shear rigidities, possesses the highest areal density (202.4 g/m^2) and also highest fractional fabric cover (0.97). On the other hand, fabric Samples 3, 7 and 12, which have lower levels of bending and shear rigidities (0.018 – 0.019 gf.cm^2/cm and 0.31 – 0.33 gf/cm.deg respectively), are having lower areal

Table 2 — Fabric bending rigidity, shear rigidity, areal density and fractional cover

Sl. No.	Proportion of polyester (X_1), %	Yarn count (X_2) Ne	Fabric sett (X_3) inch^{-1}	Bending rigidity (B) gf.cm^2/ cm	Shear rigidity (G) gf/cm.deg	Areal density g/m^2	Fractional cover
1	50 (0)	20 (-1)	50 (-1)	0.049	0.97	140.8	0.89
2	50 (0)	20 (-1)	70 (1)	0.119	4.15	202.4	0.97
3	50 (0)	40 (1)	50 (-1)	0.019	0.32	68.7	0.70
4	50 (0)	40 (1)	70 (1)	0.032	0.83	99.4	0.85
5	0 (-1)	30 (0)	50 (-1)	0.035	0.52	96.4	0.79
6	0 (-1)	30 (0)	70 (1)	0.070	1.75	138.6	0.88
7	100 (1)	30 (0)	50 (-1)	0.018	0.31	87.7	0.73
8	100 (1)	30 (0)	70 (1)	0.033	0.96	126.6	0.90
9	0 (-1)	20 (-1)	60 (0)	0.103	2.65	173.4	0.94
10	0 (-1)	40 (1)	60 (0)	0.028	0.45	83.0	0.81
11	100 (1)	20 (-1)	60 (0)	0.047	1.26	164.1	0.93
12	100 (1)	40 (1)	60 (0)	0.018	0.33	77.3	0.76
13	50 (0)	30 (0)	60 (0)	0.038	0.86	114.4	0.90
14	50 (0)	30 (0)	60 (0)	0.037	0.87	114.4	0.90
15	50 (0)	30 (0)	60 (0)	0.036	0.88	114.2	0.91

Values in parentheses indicate coded values of input parameters.

density (68.7 – 87.7 g/m^2) and lower level of fractional fabric cover (0.70 – 0.76). Therefore, it can be inferred that the bending and shear rigidities of woven fabrics are closely associated with their areal density and fractional cover. Figure 1 depicts the scatter plot of fabric bending rigidity and shear rigidity against areal density of fabrics. It is evident that fabric bending and shear rigidities increase nonlinearly with the increase in fabric areal density. As the slope of the curves is dependent on areal density, the former increases with the increase in the value of the latter. This implies that at lower level of areal density, the rate of change in bending and shear rigidities with change in areal density is low. However, the rate increases at higher level of areal density as fabric approaches the jammed state due to increase in yarn diameter and fabric sett. In a jammed fabric, the yarns have limited freedom of movement making bending and shear deformations more difficult. Therefore, the bending and shear rigidities increase at a higher rate at higher levels of areal density.

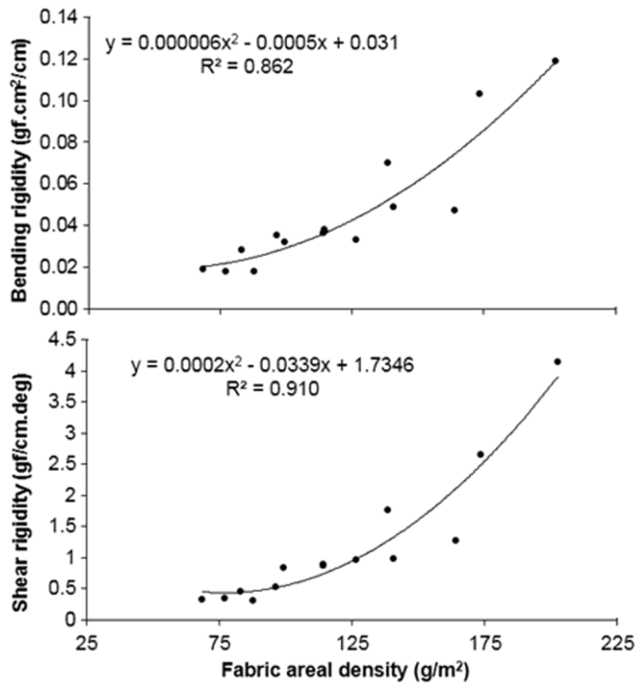

Fig. 1 — Fabric bending rigidity and shear rigidity *vs* areal density

3.1 Response Surface Models

The regression coefficients of response surface equations for bending and shear rigidities and corresponding significance level (*p*-values) of all the terms are shown in Table 3. The terms with *p*-values less than 0.05 are statistically significant at 95% confidance level. Only those regression coefficients, which are significant at 95% confidance level, are considered for further analysis.

All the three main parameters, namely proportion of polyester (X_1), yarn count (X_2) and fabric sett (X_3) have significant influence on both bending and shear rigidities of fabrics. As far as the interaction effects are concerned, $X_1 \times X_2$ and $X_2 \times X_3$ have significant influence on bending rigidity. However, only $X_2 \times X_3$ has significant influence on shear rigidity. Among the quadratic terms, X_2^2 is found to be statistically significant for both bending and shear rigidities.

Table 4 illustrates the response surface equations, their adjusted coefficient of determination $\left(R^2_{adj}\right)$ and percentage contribution of significant terms (%) for bending and shear rigidities. It is observed that the adjusted coefficient of determination are 0.97 and 0.91 for bending rigidity and shear rigidity respectively. Higher R^2_{adj} values imply a good fit of

Table 3 — Regression coefficients for different independent parameters using coded values

Term	Bending rigidity		Shear rigidity	
	Coefficient	*p*-Value	Coefficient	*p*-Value
Constant	0.038	0.0004*	0.88	0.004*
X_1	-0.015	0.0008*	-0.31	0.0415*
X_2	-0.028	<0.0001*	-0.89	0.0006*
X_3	0.017	0.0005*	0.70	0.0018*
$X_1 \times X_2$	0.011	0.012*	0.32	0.1087
$X_2 \times X_3$	-0.014	0.0049*	-0.67	0.0094*
$X_1 \times X_3$	-0.005	0.154	-0.15	0.4141
X_1^2	-0.0019	0.571	-0.19	0.3133
X_2^2	0.014	0.007*	0.49	0.0336*
X_3^2	0.0039	0.267	0.20	0.2806

*Statistically significant at 95% confidence level

Table 4 — Response surface equations for bending and shear rigidities

Parameter	Response surface equation	R^2_{adj}	β- Coefficient	% Contribution of significant terms
Bending rigidity gf.cm^2/cm	$B = 0.038 - 0.015X_1 - 0.028X_2 + 0.017X_3 + 0.011X_1X_2 - 0.014X_2X_3 + 0.014X_2^2$	0.97	$\beta_{X_1} = -0.38$	$C_{X_1} = 16.79$
			$\beta_{X_2} = -0.70$	$C_{X_2} = 30.92$
			$\beta_{X_3} = 0.42$	$C_{X_3} = 18.61$
			$\beta_{X_1X_2} = 0.21$	$C_{X_1X_2} = 9.10$
			$\beta_{X_2X_3} = -0.25$	$C_{X_2X_3} = 11.28$
			$\beta_{X_2^2} = 0.24$	$C_{X_2^2} = 10.50$
Shear rigidity gf/cm.deg	$G = 0.88 - 0.31X_1 - 0.89X_2 + 0.7X_3 - 0.67X_2X_3 + 0.49X_2^2$	0.91	$\beta_{X_1} = -0.23$	$C_{X_1} = 10.57$
			$\beta_{X_2} = -0.65$	$C_{X_2} = 29.89$
			$\beta_{X_3} = 0.51$	$C_{X_3} = 23.45$
			$\beta_{X_2X_3} = -0.34$	$C_{X_2X_3} = 15.90$
			$\beta_{X_2^2} = 0.25$	$C_{X_2^2} = 11.31$

response surface equation to the experimental data. It is also observed from the values of percentage contribution of significant terms that yarn count has the most dominant influence followed by fabric sett and blend proportion of polyester on fabric bending and shear rigidities. The prevailing preponderance of yarn count over the other parameters may be ascribed to the fact that fabric bending and shear deformations are always accompanied by yarn bending. For simplicity, if yarn is considered to be a solid circular rod, then its bending rigidity will be proportionate to 4th power of yarn diameter. Therefore, change in yarn count changes bending and shear rigidities of woven fabrics drastically.

Figure 2 depicts the influence of yarn count and fabric sett on fabric bending and shear rigidities respectively. It is observed that the fabrics made from coarser yarns and higher fabric sett eventuate greater values of fabric bending and shear rigidities. The coarser the yarn, the higher is the bending rigidity. Further, coarser yarns have greater region of contact at the interlacement points providing more frictional resistance between yarns during shearing of fabrics. Therefore, both bending and shear rigidities of fabrics increase as the yarn becomes coarser. As fabric sett increases, free space between the yarns reduces and more number of yarns resist the flexing process. In addition, higher fabric sett leads to more number of interlacement points between warp and weft yarns inside a given area. The interlacement points may be considered as pin joints between two sets of yarns in a

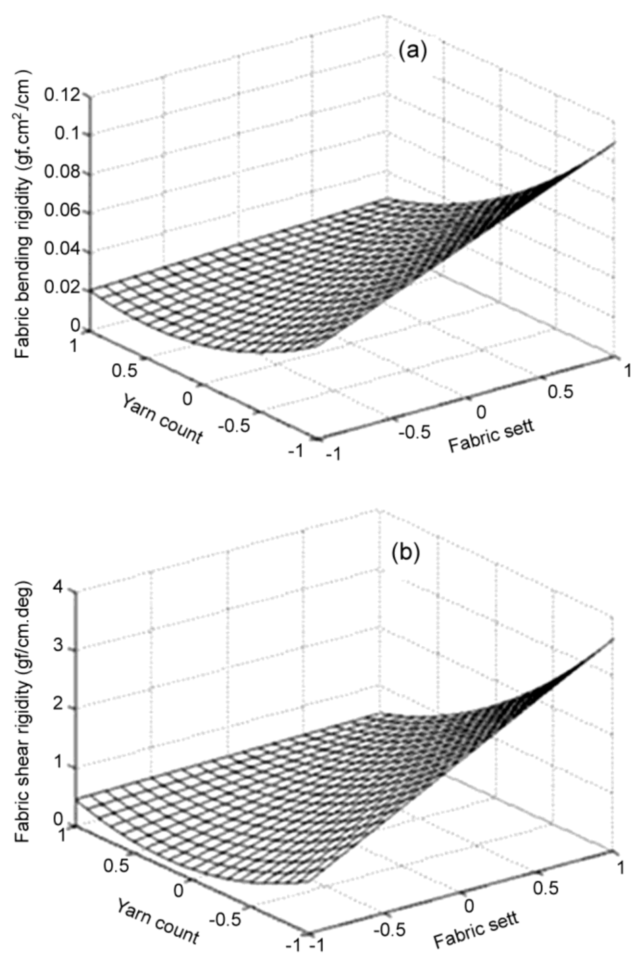

Fig. 2 — Effect of yarn count and fabric sett on fabric (a) bending rigidity and (b) Shear rigidity

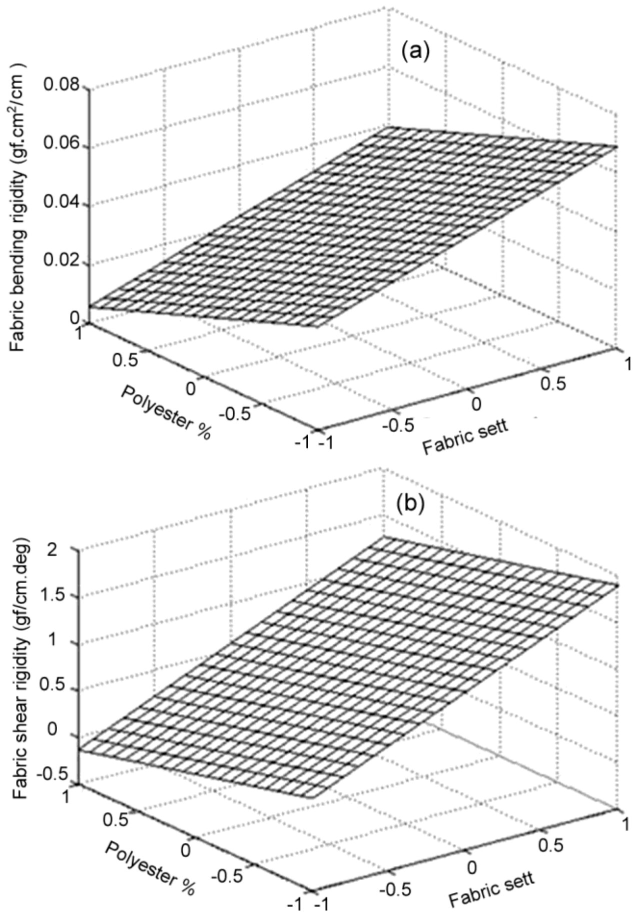

Fig. 3 — Effect of polyester proportion and fabric sett on fabric (a) bending rigidity and (b) Shear rigidity

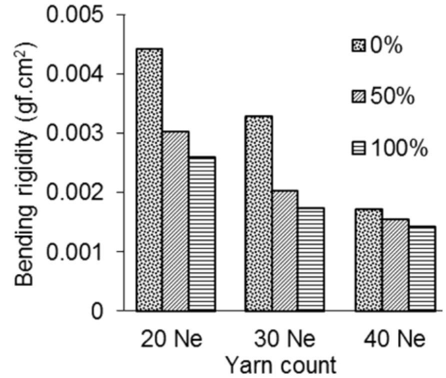

Fig. 4 — Bending rigidity of yarns for different proportion of polyester

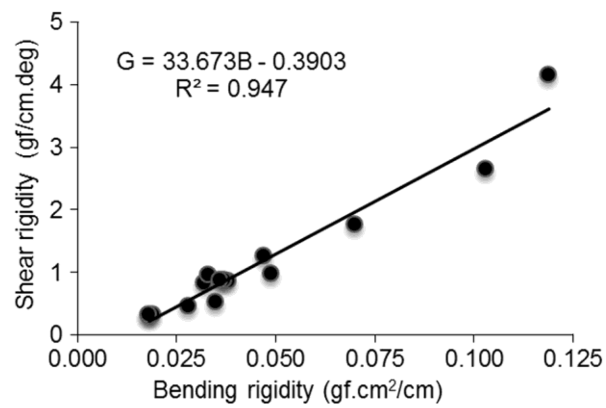

Fig. 5 — Fabric bending and shear rigidity

fabric. The concentration of pin joint points in a fabric offers more resistance against bending and shear. Hence, higher fabric sett results in more bending and shear rigidities. Higher fabric sett and coarser yarn count also act synergistically to increase the overall contact area between warp and weft yarns and thus the interaction term ($X_2 \times X_3$) becomes significant for bending and shear rigidities. This is also reflected in Figure 2 with sharp increase in bending and shear rigidities when yarn counts are coarser and fabric sett is higher.

Figure 3 depicts the effect of proportion of polyester in yarn and fabric sett on bending and shear rigidities respectively. It is observed that fabric bending and shear rigidities decrease as blend proportion of polyester in yarn increases. This may be attributed to the fact that yarn bending rigidity reduces as proportion of polyester increases in blended yarn because polyester fibre has less flexural rigidity than that of cotton[27]. Figure 4 depicts the measured bending rigidity of yarns at three different yarn counts and it is clearly observed that yarn bending rigidity reduces as the proportion of polyester increases in blended yarn.

Figure 5 represents the scatter plot of bending and shear rigidities of fabrics. It is evident that fabric bending rigidity and shear rigidity are linearly correlated. This can be attributed to the fact that the independent parameters, explored in this research, have similar influence on bending and shear rigidities. Besides, the directions of influence is also same, leading to a very high degree of association (R^2= 0.947) between bending and shear rigidities.

4 Conclusion

Influence of fibre blend, yarn count and fabric sett on bending and shear rigidities of plain woven fabrics has been analysed. Bending and shear rigidities of woven fabrics increase with lower proportion of polyester, coarser yarn count and higher fabric sett. In general, woven fabrics with higher bending rigidity show higher shear rigidity and vice versa. Experimental results show that fabrics having similar bending and shear rigidities can be produced by different combinations of fibre blend, yarn count and fabric sett. Yarn count is found the most dominating factor influencing fabric bending and shear rigidities, contribuirng around 30%, followed by fabric sett and proportion of polyester. It is observed that fabric bending and shear rigidities have a strong degree of positive association between them. Besides, bending and shear rigidities have strong dependence on fabric areal density and fractional cover.

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