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Contribution of bending and shear behavior of woven fabrics in the characterization of drape

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The drape, bending and shear properties of a group of woven fabrics have been studied along with the effects of fabric structural parameters on these properties. In addition, the influential effect and relative contribution of bending and shear behavior in the determination of drape is also evaluated. The results show that the crossing over firmness factor, which is related to the weave structure and also the weft density, significantly influences the drape, bending and shear behavior of fabrics. With the aid of linear regression analysis of the relationship among drape coefficients, bending and shear modulus, the correlational model for prediction of drape based on bending and shear has also been developed. With regards to this model, it can be claimed that the relative contribution of fabric bending in determination of drape is greater than that of shear.

Keywords: Bending, Cotton, Drape, Polyester, Shear, Weave structure, Weft density, Woven fabric

1 Introduction

The drape of the fabric is a very important property that needs to be analyzed before choosing a fabric in order to produce garments. Drape is defined as "the extent to which a fabric will deform when it is allowed to hang under its own weight". It is one of the subjective performance characteristics that is evaluated by human reactions and is expressed in qualitative terms. It also plays a major role in a garment's aesthetic appearance.

Textile researchers have found that fabric drape is a complex problem, depending on physical and low stress mechanical properties. Objective measurements of drape indicate that bending and shear are the most important mechanical properties that have an impact on the drape of fabrics. Fabrics may drape in different ways, which depend on the fibretype, kind of yarn, fabric structure, weave pattern and finishing treatment.

Limitations in traditional methods have encouraged researchers to seek alternative methods to investigate the drapability of fabrics. Mohammed *et al.*[1] investigated the draping of fabrics over a hat mold consisting of a hemispherical dome surrounded by a flat base. Matsudaira *et al.*[2] analyzed the static and dynamic drape behavior of polyester Shingosen fabrics and proposed novel factors for characterization of the dynamic drapability of fabrics. Mizutani *et al.*[3] developed a new apparatus for fabric drape called "drape elevator", which can measure drape shape, including node generation at various stages during drape formation. Shyr *et al.*[4] developed a new automatic system for measuring the static and dynamic drape coefficient based on the principles of Cusick's drapemeter and a rotating disk with various speeds. In a research by Lin *et al.*[5], it was revealed that the nonlinear logistic function can be successfully applied to fit the drape coefficient curves throughout the static state and the dynamic stable zone. Matsudaira *et al.*[6] investigated the effect of yarn density in the fabric structure, yarn twist and count on the dynamic drapability of polyester fabrics utilized as fine women's dress material. Tsai *et al.*[7] presented a method for direct acquisition of drape contours of various fabrics, which can effectively enhance the gray scale contrast between the fabric and background, while using backlight in a dark room. Tandon and Matsudaira[8] predicted the drapability of lightweight wool fabrics with the aid of drape coefficient predictive equations. Besides, several dynamic drapabilities were normalised for static drapability as defined by the "Index of Drape Fluidity". Few researchers tried to investigate the effect of seams on the drape of fabrics. Hu and Chung[9] observed that in heavy weight fabrics, an

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increase in seam allowance would result in an increase in the drape coefficient.

As mentioned above, bending and shear properties have a greater impact on drape of the woven fabric. Different studies have been carried out concerning the relationship among fabric drape, bending and shear parameters. Tokmak *et al.*[10] found that the KES-F and FAST systems have a good correlation with each other and the drape of a fabric is primarily dependent on the fabric's bending and shear properties. Omeroglu *et al.*[11] observed that the bending rigidity of fabrics produced from hollow fibres is higher than the fabrics produced from regular solid fibers. The bending rigidity and drapability of the fabrics with similar cross-sectional shapes are in close relation with each other. Süle[12] declared that the bending rigidity of the fabrics directly depends on the warp tension and weft density. Skelton[13] reported that during the heat-setting process, the inter-yarn forces are relaxed and the bending hysteresis of the fabric is reduced. Gibson and Postle[14] showed that finishing, thickness and other constructional variables of the fabric have an influence on the bending deformation, but shear properties are largely determined by the type of fabric construction itself.

Some of the researchers focused on the developed methods and models for determining the bending and shear parameters. Ghoshand Zhou[15] reviewed different methods and principles to evaluate the bending characterization of woven fabric. Zheng *et al.*[16] developed a new shear tester of woven fabric based on the trellis shear model. Uren *et al.*[17] developed a new shear frame and investigated the effects of raw material and setting on in-plane shear behavior of woven fabrics. Chichani and Guha[18] proposed a two-step finite element approach for modeling the shear angle and shear stress of woven fabric. The results of the model showed good correlation with the results of the picture frame shear experiment. Plaut[19] derived formulas for effective bending rigidity and bending length, based on the deformation of fabric strips in simple tests. Some of the researchers tried to find appropriate relationships among mechanical properties and the KES system of measuring. As an example, Hu and Zhang[20] presented an analytical solution for the distribution of shear stresses and strains in fabric specimens tested on the KES-F tester. The difference between modified and tested shear modulus values is because of the fact that the measured deformation is larger than the pure shear deformation. Ancutiene *et al.*[21] tried to find the relationship between bending rigidity defined by KES-F and FAST systems. The results showed that weave pattern has a more significant effect on the bending rigidity in the KES-F and FAST bending testers. Hu *et al.*[22] found that the bending hysteresis of heavy fabrics has larger deviations from lighter fabrics. Spivak *et al.*[23] investigated the relationship between bias extension and simple shear, and make possible the calculation of values of equivalent shear strain and shear stress, considering the measured values of tensile strain and tensile stress in bias extension. The current study is carried out based on their conclusions. Kothari *et al.*[24] investigated the effects of finishing and wetting and the changes in four shear parameters including initial shear modulus, frictional shear stress, shear rigidity and residual shear strain on the shear behavior of grey and finished wool and wool blend woven fabrics.

The aim of this study is to investigate the effect of weave pattern and weft density on the bending modulus, shear modulus and drapability of woven fabrics. Understanding of the mechanical properties, which have a greater influence on drape of the fabric, will help in better evaluation of the drape behavior of fabrics used as garments.

2 Materials and Methods

2.1 Materials

In all the samples, 100 den polyester yarn was used as warp and 30 Ne pure cotton yarn was used as weft. Weaving properties of the samples, such as the weaving machine settings and the finishing treatment, were kept completely the same. The fabrics were subjected to dry and wet relaxation at around 160°C. The samples consist of three different weave patterns including plain, twill 2/1 and twill 3/1, with three nominal weft densities including 25, 28 and 31 cm^{-1}, while the warp density of all samples was kept the same (50 cm^{-1}). By combining three weave patterns and three weft densities, 9 different samples were obtained in total. Table 1 shows the constructional properties of the fabrics.

2.2 Testing Procedure

Considering the aim of the study, experiments for measuring the drape, bending and shear parameters have been performed according to the following details:

Drape

In this study, the drape coefficients of the fabrics, as the major parameter of drape, were calculated

Table 1 — Constructional properties of fabric samples

Weave	Weft density cm^{-1}	Warp density cm^{-1}	Thickness, mm under pressure of 1 lb/in^2	Areal weight g/m^2
Plain	25	50	0.27	106
Plain	28	50	0.26	114
Plain	31	50	0.26	122
Twill 2/1	25	50	0.29	106
Twill 2/1	28	50	0.30	113
Twill 2/1	31	50	0.31	121
Twill 3/1	25	50	0.32	108
Twill 3/1	28	50	0.32	115
Twill 3/1	31	50	0.32	120

through the utilization of Cusick drapemeter, imaging and the image processing procedure. According to BS 5058 standard, a circular fabric sample with 30 cm diameter was placed on a circular disk of 18 cm diameter. Due to gravity and shadow of the drape, the fabric drape shape was observed on a flat horizontal surface. Then the drape coefficient was calculated according to following equation:

$$\text{Drape coefficient} = \frac{A-\pi R_2^2}{\pi R_1^2-\pi R_2^2} \times 100 \quad \ldots (1)$$

where A is the area of the shadow of the fabric; R_1, the radius of the fabric sample; and $R_2$the radius of the fabric holder disk.

For performing the image analysis method, the photographs of the draped fabrics were taken from a constant position of the camera towards the shadow and similar illuminating condition, using a digital camera. The photographs were analyzed using MATLAB software and the drape coefficient of the samples was determined according to Eq. (1).

Bending

For measuring the bending modulus, it is required to measure the bending length and bending rigidity. The lengths of overhung fabric samples were measured using a Shirley stiffness tester. The tests were performed for each fabric sample according to ASTM D1388. The bending rigidities were calculated according to following equation:

$$G = WC^3 \times 10^3 \quad \ldots (2)$$

where G is the fabric bending rigidity (mg.cm); W, the mass per unit area (g/cm^2); and C, the bending length (cm). Finally, the bending modulus of the samples was determined according to following equation:

$$B = \frac{12G\times10^{-6}}{t^3} \quad \ldots (3)$$

where B is the fabric bending modulus (kg/cm^2); t, the thickness (cm) under the pressure of $1\frac{lb}{in^2}$; and G, the bending rigidity (mg.cm).

Shear

The bias extension test was carried out instead of the simple shear test. The samples were prepared in the dimension of $25 \times 5\ cm$, and the yarns were initially oriented at $\pm 45^o$ to the loading direction. The sample was gripped at two ends on the Instron testing machine and a tensile force was applied in a bias condition. The force required to deform the fabric was recorded at the jaw as a function of jaw displacement. A pre-tension of 20g was applied to all of the samples.

Calculations of shear strain and shear stress were performed according to following equations, presented by Spivak *et al.*[23]:

$$\text{Shear strain } (\sigma) = 2e + e^2 \quad \ldots (4)$$

$$\text{Shear stress } (R) = \frac{f}{2(1+e)} \quad \ldots (5)$$

where σ is the shear strain; R, the shear stress; f, the tensile force ($\frac{N}{m}$); and e, the strain in the bias-extension test. In order to evaluate the shear modulus of the fabrics, the tangent of the first linear part of the curve (0-10% strain) was calculated and considered as the shear modulus of the fabric. The results of the experiments were analysed and are reported in the following section.

3 Results and Discussion

It is a known fact that woven fabric's mechanical properties are affected by the fabric structural parameters, thus in this part the influential contribution of fabric structural factors on the drape, bending and shear behavior of the woven fabrics is investigated. Also, the relationships among these properties are studied.

The results of drape, bending and shear experiments are listed in Table 2 and will be discussed and analysed in the following sections.

3.1 Effect of Fabric Structural Parameters on Drape

As it has been mentioned in the previous section, in order to evaluate the drape coefficient of the investigated fabrics, the draping shadow obtained from the experimental procedure is analysed using image processing techniques. As shown in Fig. 1, the drape coefficient of the studied fabrics varies in the

Table 2 — Experimental test results

Weave	Weft density cm^{-1}	Drape coefficient, %		Bending Modulus, kg/cm^2		Shear modulus, N/m	
		Average	CV%	Average	CV%	Average	CV%
Plain	25	72.23	2.81	47.0	2.76	122.14	8.86
Plain	28	75.96	3.18	65.1	2.15	177.28	7.24
Plain	31	78.96	2.63	84.4	2.31	229.65	9.37
Twill 2/1	25	65.44	2.67	38.0	2.38	87.26	5.08
Twill 2/1	28	68.5	3.45	41.6	4.01	130.95	3.78
Twill 2/1	31	69.65	4.65	46.2	3.16	159.24	5.06
Twill 3/1	25	61.51	4.03	28	3.48	75.73	9.10
Twill 3/1	28	67.42	5.12	36.3	2.47	90.77	7.48
Twill 3/1	31	68.84	3.56	44.9	2.12	108.99	8.85

range of 65- 85%. In view of the effect of weave structure, the results show that the highest drape coefficient belongs to the plain followed by twill 2/1 and twill 3/1 fabrics respectively. It should be noted that the values of drape coefficient for twill 2/1 and twill 3/1 are close to each other.

In investigating the reason behind this trend, the effects of different structural parameters have been examined. It is concluded that the explanation of this trend is related to firmness of the fabric structure. In order to express the firmness of the fabrics, the parameter of crossing over firmness factor (CFF) of the fabric is used, introduced by Morino *et al.*[25]. This factor (CFF) is expressed using the following equation:

$$\mathrm{CFF} = \left(\frac{\text{Number of Crossing Over Lines in a Complete Repeat}}{\text{Number of Interlacing Points in a Complete Repeat}}\right) \quad \dots (6)$$

By employing this equation [Eq. (6)], the values for the three weaves of plain, twill 2/1 and twill 3/1 are calculated as 2, 1 and 0.67 respectively, which are in agreement with the trend observed in Fig. 1.

By increasing the value of CFF, the firmness of the fabric rises, thus the mobility of yarns in the fabric structure becomes harder. As a result, the drapability of the plain weave due to its tighter construction is poorer than that of the twill weaves. In comparison of twill 2/1 and twill 3/1, it is anticipated that the drape coefficient of twill 3/1 is less than that of twill 2/1 due to the lower value of CFF.

According to Fig. 1, it is clear that for all the studied patterns, a rise in the weft density of the fabric, due to increasing the contact and entanglement of yarns in the fabric structure, leads to an increase in the value of drape coefficient. The change in weft density from 25 cm^{-1} to 31 cm^{-1} results in 4 - 7 % increase in the drape coefficient. Statistical analysis of results at the confidence range of 95% reveals that the effect of both weave structure and weft density on the drape coefficient is significant.

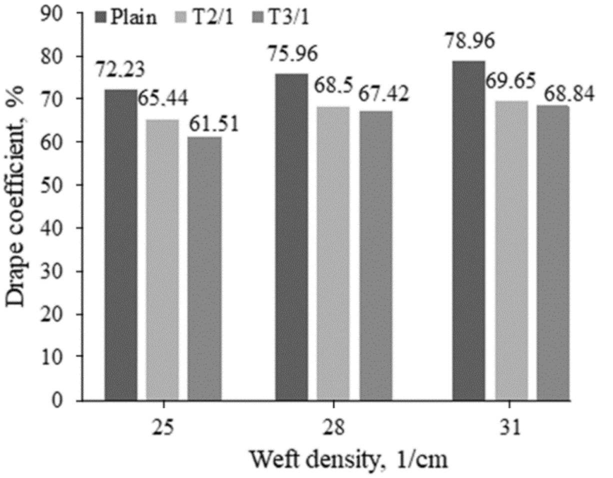

Fig. 1 — Effect of fabric structure on drape coefficient

Considering the results presented above, it can be concluded that the drape coefficient of the fabric is mainly determined by the two prominent factors, namely the crossing over firmness factor (CFF) and the density. Therefore, the contributing share of the mentioned factors in determination of drape coefficient is investigated using the backward linear regression method at the confidence range of 95%. The values of CFF and weft density have been normalized to locate the data between 0 and 1. In this regard, in order to normalize each of the mentioned parameters, following equation is utilized:

$$\frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad \dots (7)$$

In this equation, X_{min} refers to the minimum value for each parameter; and X_{max} presents the maximum calculated value for each factor.

With regards to the regression analysis, the drape coefficient in relation to the CFF and weft density can be obtained from the following equation, (R^2= 0.764):

$$\mathrm{DC\%} = 0.43 \times \mathrm{CFF} + 0.263 \times \mathrm{density} + 0.165 \quad \ldots (8)$$

According to Eq.(8), it can be seen that the contribution effect of CFF in specification of the fabric drape coefficient is greater than the weft density and the DC% is affected by the crossing over firmness factor of the fabric to a greater extent.

By employing Eq. (8), it is possible to predict and compare the drape coefficient of various woven fabrics by considering the CFF and density of the fabrics, without experimental measurement of the drape coefficient.

3.2 Bending Modulus in Terms of Fabric Structure

Bending modulus is one of the important properties of fabric, which indicates the flexural ability of the fabric and its resistance towards the bending forces. It is a measure of fabric stiffness. The bending behavior of the fabrics tested in this study is shown in Fig. 2.

First, the effect of fabric weave pattern on bending modulus is investigated. As it is obvious in Fig. 2, for all the weft density groups, the plain weave has the highest stiffness, while the lowest stiffness belongs to twill 3/1. The difference between the bending modulus of twill 2/1 and twill 3/1 is less than the difference among the plain and the twill weaves.

The bending performance of a fabric is the product of the bending behavior of the constituent yarns of the fabric, their interaction in tolerating the bending forces in the fabric structure and the frictional restraint. Since in the current study the characteristics of the yarns remains constant, the interaction between yarns has an important effect on the flexibility of the fabric. The interaction between yarns during the bending process of the fabric and also the frictional restraint in the fabric structure, is directly related to the weave structure which defines the crossing over firmness factor. The statistical analysis results indicate that the effect of CFF is significant on the bending modulus of the fabric (significance level of 0.05). Among the investigated weave structures in various density groups, the lowest CFF with a value of 0.67 belongs to twill 3/1, which has the minimum bending modulus, while an increase in the firmness of the fabric (CFF) results in a higher bending modulus.

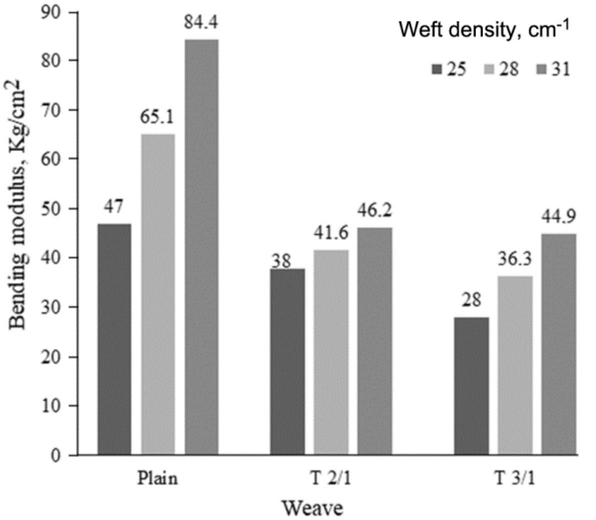

Fig. 2 — Effect of weave structure and weft density on the bending modulus

Moreover, with regards to the results shown in Fig. 2, for all the investigated weave structures, the fabric with a weft density of 31 cm^{-1} has the highest bending modulus followed by the density groups of 28 and 25 cm^{-1} respectively. The significance of the effect of weft density on the bending modulus of the fabrics is clarified through statistical analysis of the results at the confidence range of 95%.

The growth in the firmness and density of the fabric causes an increase in the inter structure friction due to more contacting points between the yarns and thus causes an increase in the frictional couple (M_0), as defined by Grosberg[26]. In order to deform a fabric to a specific curvature during bending, the frictional couple should be overcome. The frictional couple M_0 for bending of a cloth is as follows:

$$M_0 = \frac{1}{8}\mu V d \quad \ldots (9)$$

where μ is the friction coefficient between yarns; V, the inter-structural force; and d in our case can be assumed as yarn diameter. Due to an increase in the value of CFF and weft density, the values of V and consequently M_0 rise. The increment of M_0, means that higher bending forces should be applied to the fabric to overcome the frictional couple and thus bend the fabric.

The stiffness affecting structural parameters, CFF and density and the level of the involvement of these factors in determination of the bending resistance performance of the fabric, can be discussed through the statistical linear regression method. The linear regression analysis for this investigation with the normalized values of CFF and density is shown in following equation:

$$\text{Bending modulus} = 0.503 \times \mathrm{CFF} + 0.226 \times \mathrm{density} - 0.023 \quad \ldots (10)$$

It should be noted that the linear regression coefficients are obtained with $R^2=0.862$ (significance level of 0.05). With regards to the coefficients of CFF and density [Eq. (10)], the crossing over firmness factor has a dominant role in the characterization of the bending resistance of the fabric.

3.3 Analysis of Shear Behavior of Fabrics

The shear mechanism is one of the important properties which influences drape. When a shearing force is applied to the fabric (in-plane of the yarns), slippage at interlacing points of the warp and weft yarns occurs, which results in changes of yarn angular position towards each other. This phenomenon permits the deformation of fabric to complex shapes, as what happens during the draping of fabric. Thus, it is important to analyze the shearing performance of the fabric and its effect on the drape.

As it has been mentioned before, in order to investigate the shearing behavior of fabrics, the bias uniaxial extension of the fabrics has been carried out to calculate the shear stress and strain using Eqs (4) and (5), presented by Spivak *et al.*[18]. As an example, the shearing stress-strain diagram of twill 2/1 with the weft density of 25 cm^{-1} is shown in Fig. 3. In order to evaluate the shear modulus of the fabrics, the tangent of the first linear part of the curve (0-10% strain) is calculated and considered as the shear modulus of the fabric.

In exploration of the impact of fabric structural parameters, such as weave pattern and weft density (Fig. 4), it is affirmed that by increasing the weft density of the fabric, there is a steady rise in the value of shear. The mentioned trend is obtained for all the studied weave structures.

In addition, the highest shear modulus is achieved for the plain weave structure with CFF of 2, while the lowest shear modulus is achieved for twill 3/1 with CFF value of 0.67. The shear modulus of twill 2/1 stands between plain and twill 3/1.

The shear deformation of a fabric depends on the inner frictional forces in the fabric structure. By increasing the firmness of a fabric with regards to the fabric weave structure and also the density of the fabric, the contact points between the yarns in the fabric construction increase, which results in harder slippage of the yarns in contact with each other. Hence, the resistance against shear deformation grows. The regression analysis of the effect of CFF and yarn density on the value of shear modulus with $R^2=0.78$ at a significance level of $\alpha=0.05$ for the normalized data is visible in following equation:

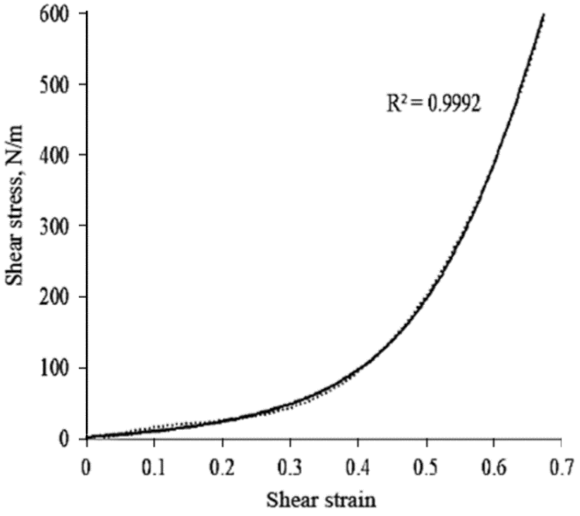

Fig. 3 — Shear stress-strain curve for twill 2/1 fabric

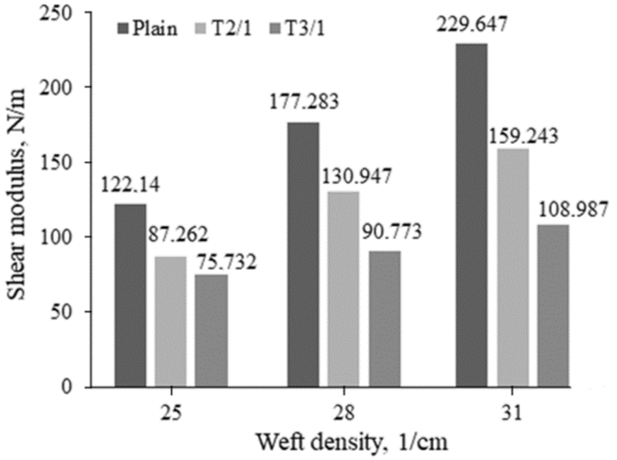

Fig. 4 — Influence of fabric structural parameters on shear modulus

$$\text{Shear modulus} = 0.398 \times \text{CFF} + 0.350 \times \text{density} - 0.025 \quad \ldots (11)$$

Statistical analysis of results reveals that the impact of both firmness factor and density is significant on the shear modulus of the fabric. As it is obvious in Eq. (11), the contribution of CFF and density in determination of shear modulus of the studied fabrics is nearly the same.

3.4 Contributing Effect of Shear and Bending on Drape

In order to study the relationship between the bending behavior of the fabric with the drape and also the association of the shear and drape coefficient of a fabric, the linear correlation diagrams of the mentioned properties are investigated. Figure 5 shows high correlation between the bending modulus and drape

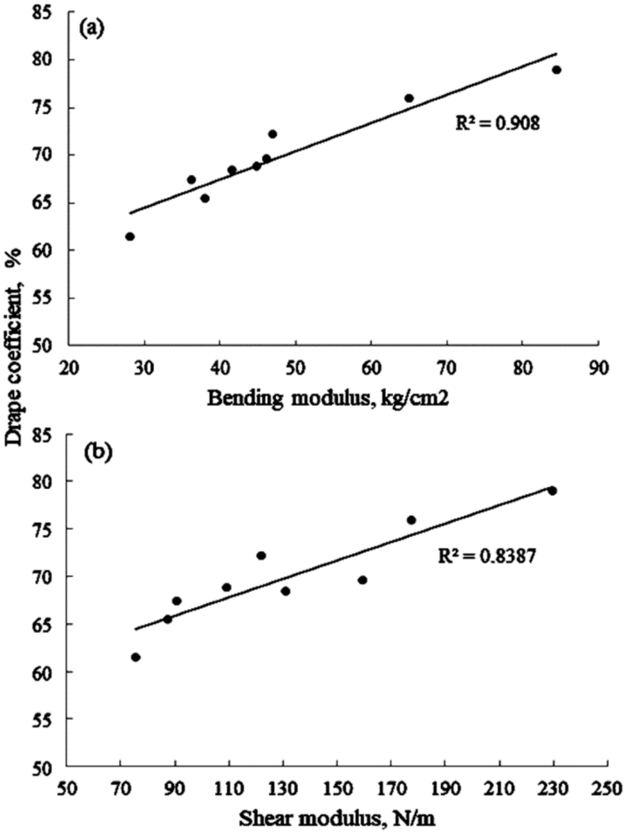

Fig. 5 — Correlation between drape coefficient and a) bending modulus and b) shear modulus

coefficient (R^2=0.908). Moreover, it can be concluded from Fig. 5(b) that there is an acceptable connection between shear modulus and drape coefficient. Due to the constructional properties of the woven fabrics, with the rise of the bending and shear modulus, the value of the drape coefficient increases, which means that the drapeability which is the deformation of the fabric as a result of hanging by its own weight decreases.

In addition, statistical analysis of the influence of bending and shear modulus has been carried out by the one-way ANOVA at the confidence range of 95% and it is revealed that both bending and shear characteristics of the fabric significantly affect its draping behavior.

In the end, with the intention of defining the contributing effect of each of these two characteristics on drape, the backward linear regression analysis at the significance level of 0.05 is performed. To this end, all the mentioned properties (drape coefficient, shear modulus and bending modulus) are normalized between 0 and 1, and the regression model is achieved as follows:

$$\text{Drape Coefficient} = 0.707 \times \text{Bending Modulus} + 0.125 \times \text{Shear Modulus} + 0.225 \qquad \ldots (12)$$

From Eq.(12) and by comparing the influencing factors of bending and shear, it can be concluded that although the effect of both shear and bending modulus is significant on drape, the dominant role in determination of the draping performance of the fabric belongs to the bending modulus. On the whole, it is anticipated that the overall fall and hanging ability of the fabric with regards to its weight is related to the bending resistance of the fabric, while the conformation and the appearance as well as shape of the draped fabric are characterized by the shear modulus and the slippage and performance of yarns in the plane of load exertion.

Furthermore, with the aid of the regression equation between drape, shear and bending, it is possible to predict the drape of the fabric by consideration of their bending and shear modulus.

4 Conclusion

In the current study, a thorough investigation into the variations of three major properties of woven fabrics, such as the drape, bending and shear, and their relation with each other has been carried out. The mentioned analysis is important in determining the fabric mechanical performance and also selection of suitable fabrics for various applications.

4.1 In consideration of the effect of fabric structural parameters such as the weave pattern and weft density on the drape coefficient of the fabric, it is concluded that the crossing over firmness factor, which is a product of interlacing pattern of the yarns, has a direct impact on the drape coefficient. The highest drape coefficient is obtained for the plain weave followed by the twill weaves. Moreover, increasing the weft density of the fabric results in a higher drape coefficient.

4.2 The bending modulus and also the shear modulus of the woven fabric are also related to the weave structure and weft density, as an increase in the firmness, contact points and the resultant inner-structure friction leads to higher resistance against bending and shear deformations.

4.3 Statistical analysis of the mentioned properties reveals that the effect of fabric constructional parameters on drape, bending and shear is significant at the confidence range of 95%.

4.4 Finally, the contributing effect of bending and shear modulus in determination of fabric draping performance is also investigated. Analysis of the results clarifies that the leading property in specification of the drape coefficient is the bending modulus of the fabric, whereas the shear modulus is the restricted determinant of drape coefficient, while its effect cannot be ignored.

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