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The Relationship between Fabrics Bending Rigidity Parameters Defined by KES-F and FAST Equipment

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The aim of performed research was to investigate textile materials bending rigidity parameters B_{KESF} and B_{FAST} defined at low-stress loads by KES-F (Kawabata Evaluation System for Fabrics) and FAST (Fabric Assurance by Simple Testing) testers, respectively and to set the relationship between these two bending rigidity parameters. Tests were performed with thick and heavy-weight woven outer fabrics (thickness varied in the range of 1.01 mm – 2.28 mm) having comparatively high area density which varied in the range of 211 g/m^2 – 398 g/m^2. In parallel comparative analysis of B_{KESF} and B_{FAST} bending rigidity parameters provided in literature references was performed. Data of 80 different fabrics was analysed. The results of the investigation present the dependencies which allow to convert B_{FAST} bending rigidity values into B_{KESF} values. The differences between light-weight and heavy-weight fabrics are analyzed from the standpoint of KES-F and FAST testing results.

Keywords: bending rigidity, heavy-weight fabric, FAST, KES-F.

1. INTRODUCTION

In order to bring garment manufacturing processes to higher technological level, clothing and textile industry turns to virtual simulations, which do not only present realistic views of a garment, but also mimic mechanical and physical characteristics of textiles [1]. Only precisely simulated fabric behaviour enables consumers to truly judge upon its virtual counterpart. The accuracy of virtual garment simulations is dependent on exact input of parameters for a correct description of the fabric behaviour [1]. Mechanical properties can also be used to determine the behavior of the fabrics during clothing exploitation [21]. Today the main mechanical properties for virtual garment simulations, i. e. tensile, bending, compression and shear properties at the low-stress level loads can be obtained by objective fabric characterisation methods.

In this research the main attention is focused on fabric bending. A variety of testing methods exists to define woven fabrics bending rigidity, which can be divided into two groups. In the first group specified deformation is applied after which loading force, moments or energy producing bending deformation is measured. Meantime the second group is based on specimen's deformation measurement under its own weight [2]. The most widely applied KES-F (Kawabata Evaluation System for Fabrics) tester of pure bending belongs to the first group [3] and the most popular commercial FAST (Fabric Assurance by Simple Testing) bending tester belongs to the second group [4]. Both systems were designed to measure fabric mechanical properties at low-stress level loads but they differ in several aspects [5]. Both systems adopt different testing principles. KES-F system measures deformation/recovery behaviour while FAST system determines deformation level at a single point on the deformation curve. Thus FAST system can not measure hysteresis, which can be important from the standpoint of fabric resilience.

KES-F system is essential for in-depth research of fabric mechanical properties at low-stress level loads [5, 6]. However, criticism still exists due to high cost of these instruments [5, 7]. The price of FAST system is only about one eight of the price for the KES-F system [6]. The later together with its simple usage makes FAST testing system more attractive for the industry [8, 9]. From the practical side, textiles mechanical parameters defined at low-stress loads, which correspond to real wearing conditions, are extensively used in comprehensive garments 3D behaviour simulation software. Data obtained by KES-F is applied in worldwide used 3D Fit software of Lectra company. Meantime FAST tester data is used in V-Stitcher software by Gerber Technology company. In the most recent developments of such software, e. g. 3D Runway by Optitex company, the possibility to apply the data obtained by both testers – KES-F and FAST, is realised.

In our earlier research [10] it was proved that KES-F tensile and shear parameters can be also defined by standard tensile testing machine. Uniaxial tension test is the most advanced for fabric shear properties investigations during bias tension [22]. Linear equations for obtained tensile and shear parameters recalculation to corresponding KES-F parameters were derived (coefficient of correlation $r = 0.84 – 0.98$). It is important to note that recalculated parameters with significant accuracy can be applied in 3D clothing simulations instead of those defined by KES-F tester. Also a number of researchers tried to compare and to find the relationship between the results obtained by both KES-F and FAST systems [1, 11 – 16]. Ly *et al.* [6] found the results measured by two systems to be highly correlated with each other, though significant difference in testing methods exists between them. Yick *et al.* [11] compared mechanical properties of 22 shirting

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materials (area density 96 g/m^2 – 170 g/m^2) and defined that despite considerable differences in the measurement principles of KES-F and FAST testing systems there is a highly significant correlation (correlation coefficient for bending rigidity is 0.97, for extensibility 0.96 and for shear rigidity 0.90) between obtained parameters.

Thus the aim of this research was to set the dependency between KES-F bending rigidity B_{KESF} and FAST bending rigidity B_{FAST} parameters for heavy-weight fabrics and to compare it with the results provided by different references.

2. MATERIALS AND METHODS

Tests were performed with four thick woven wool blended (wool – WO) outer fabrics of reinforced broken twill weave type (Table 1). The main characteristics of weave types are presented in Figure 1.

Table 1. Characteristics of woven outer fabrics

Code	Yarn compo-sition, %	Area density W, g/m^2	Thickness, mm	Density, 1/cm		Linear density, tex
				Warp	Weft	
ST8	80 wool, 20 PA	251	1.16	9.5	8.7	Warp 121 Weft 117
ST10	80 wool, 20 PA	244	1.01	10.4	10.2	Warp 98 Weft 115
SM	50 wool, 50 AC	211	1.55	16.2	12.0	Warp 63 Weft 72
R	80 wool, 20 PES	398	2.28	16.5	12.9	Warp 116 Weft 118

PA – polyamide, AC – acetate, PES – polyester (yarn composition was presented by fabric producers).

Thickness was measured using KES-F compression equipment at a pressure of 49 Pa. The number of measurements was 6, relative measurement error did not exceed 7 %. Density of threads in warp and weft fabric directions was measured according to standard LST EN 1049-2:1998. The number of measurements was 6, relative measurement error did not exceed 4.5 %. Area density defined according to standard LST ISO 3801:1998. Linear density defined according to standard ISO 7211/5-1984. Relative measurement error did not exceed 5.5 %.

All tests were performed in standard conditions: temperature 20 °C ± 2 °C and humidity 65 % ± 5 % (according to standard LST EN ISO 139: 2005).

Bending properties of the investigated samples were defined by KES-F and FAST testers. The principle of pure bending is applied in KES-F system whereby fabric specimen is bent in an arc of constant curvature which is changed continuously [5]. The width of the specimen in KES-F is 200 mm and the distance between clamps is 10 mm. From the bending moment/curvature curve bending rigidity B_{KESF}, 10^{-4} Nm^2/m was determined (Fig. 2). Bending rigidity represents the resistance of fabric against flexion [3, 17]. Bending rigidity parameter B_{KESF} is the average slope of the linear regions of the bending hysteresis curve between the radius of curvature of ±0.5 cm^{-1} and ±1.5 cm^{-1} (B_f and B_b) (Fig. 2).

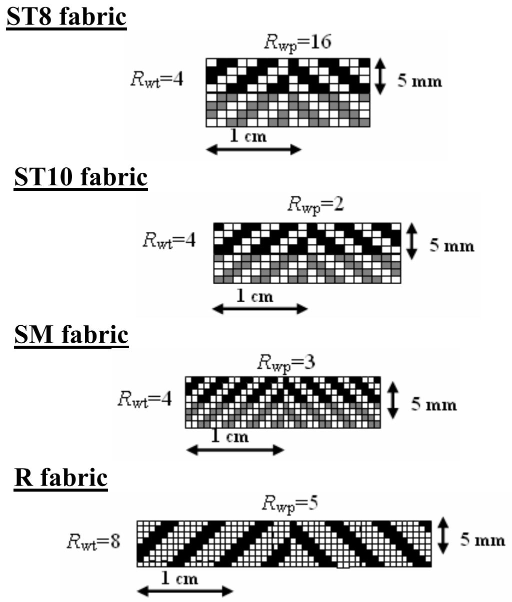


Fig. 1. Broken twill weave characteristics of tested fabrics (R_{wp} and R_{wt} – number of threads in warp and weft repeats (repeats are darkened))

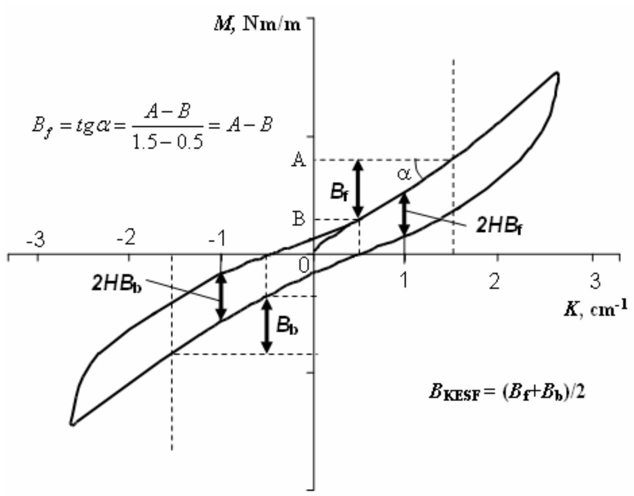


Fig. 2. Bending moment/curvature curve in KES-F system

Meantime using FAST bending meter bending length c, mm is defined on the basis of which bending rigidity B_{FAST}, μNm is calculated (Fig. 3). Cantilever bending principle described in British Standard method (BS: 3356, 1990) is applied in this system [18]. Bending rigidity is calculated as:

$$B_{FAST} = W \cdot c^3 \cdot 9.807 \cdot 10^{-6}, \quad (1)$$

where W – is the area density in g/m^2.

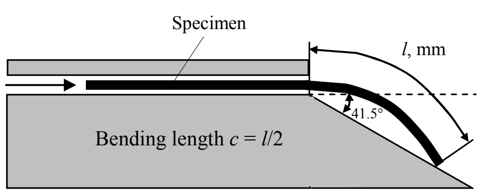


Fig. 3. Specimen bending in FAST system

The correlation analysis was applied to find equation for KES-F bending rigidity B_{KESF} values replacement by FAST bending rigidity B_{FAST} values. For this reason

KES-F bending rigidity values were recalculated to the units of FAST bending rigidity parameters, i. e. μNm = 10^{-6} Nm.

Furthermore comparative analysis was performed between the results of tested materials and those obtained by other researchers who studied dependencies for bending rigidity values derived by KES-F and FAST testers. Thus 80 different fabrics including the fabrics of current investigation were analyzed.

3. RESULTS AND DISCUSSION

Fabric bending rigidity is the main input parameter in virtual garment simulation software, which uses KES-F mechanical properties. Due to high KES-F apparatus price, FAST bending meter could be applied instead of it, but bending parameters should be recalculated. In this research four thick outer fabrics were tested using both KES-F and FAST bending testers. Testing results are provided in Table 2, in which 10^{-4} Nm²/m B_{KESF} units obtained by KES-F are recalculated in to 10^{-6} Nm²/m in order to facilitate their comparison with B_{FAST} testing results.

Table 2. The values of bending rigidity for tested fabrics

Tester	Bending rigidity	Direction	Fabric			
			ST8	ST10	SM	R
FAST	B_{FAST}, 10^{-6} Nm	Warp	25.00	17.11	10.60	55.64
		Weft	18.58	11.19	7.62	32.20
KES-F	B_{KESF}, 10^{-6} Nm²/m	Warp	30.01	17.93	12.85	73.53
		Weft	22.48	11.57	8.22	41.34

Investigations with KES-F tester were performed with standard number of specimens for this testing method, i. e. – 3. Meantime, the number of specimens for FAST tester was 6. Coefficient of variation in both cases did not exceed 7 % and relative measurement error did not exceed 12.5 %.

Investigation results have shown that the values of FAST bending rigidity parameter B_{FAST} can be recalculated to the values of KES-F bending rigidity parameter B_{KESF} due to strong correlation between them, i. e. $R^2 = 0.99$ (Fig. 4). For comparative analysis the results of Yick K. L. [11] who studied light-weight cotton and cotton blended (CO and CO blended) shirting fabrics are presented together with our investigation results of heavy-weight WO blended outer fabrics which significantly expanded the range of bending rigidity values. It is evident from Fig. 4 that for low bending rigidity values directly proportional relationship exists between B_{FAST} and B_{KESF} parameters, i. e. the values are close to 1 : 1 line (linear $y = x$ dependency). However with the increase of bending rigidity the values of B_{KESF} become higher for tested materials by 3.4 % – 32.2 % compared to the values of B_{FAST} parameter.

Thus, the assumption can be made that for fabrics with higher bending rigidity larger differences between bending parameters defined by KES-F and FAST testers exist. Yick K.L. *et al* [11] tested 22 shirting fabrics and defined that bending rigidity values of B_{KESF} parameter are lower compared to B_{FAST} parameter by 8 % – 39 %. Area density of tested fabrics in this research varied from 96 g/m² to 170 g/m² and B_{FAST} bending rigidity parameter from $2.5 \cdot 10^{-6}$ Nm up to $12.72 \cdot 10^{-6}$ Nm.

On the basis of shirting fabrics testing results, linear equation $B_{\mathrm{KESF}} = 0.88 B_{\mathrm{FAST}} - 0.60$ for B_{FAST} values recalculation into B_{KESF} values was derived. Meantime in our research the attempt was made to apply this equation for outer fabrics bending rigidity parameters recalculation but the result was unsatisfactory due to high discrepancies which were from 19 % up till 34 %. Also it should be mentioned that higher discrepancies were characteristic for higher bending rigidity values.

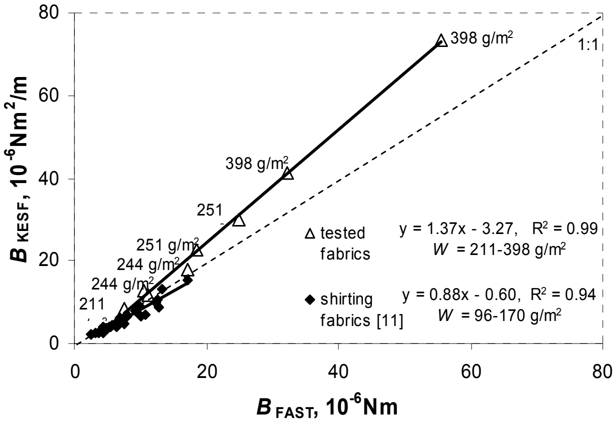


Fig. 4. The relationships between B_{FAST} and B_{KESF} parameters for tested WO blended outer fabrics and CO and CO blended shirting fabrics tested by Yick K. L. [11]

Using linear equation $B_{\mathrm{KESF}} = 1.37 B_{\mathrm{FAST}} - 3.27$ (Fig. 4) the recalculation of KES-F bending rigidity from FAST bending rigidity for tested heavy-weight outer fabrics was performed and perfect coincidence of calculated and measured bending rigidity values was achieved (Fig. 5).

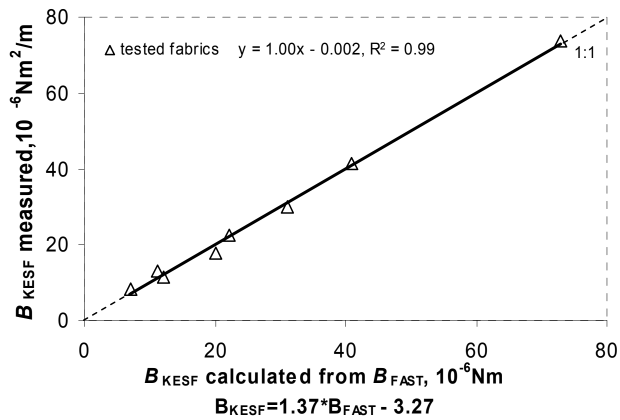


Fig. 5. The relationship between calculated and measured KES-F bending rigidity values for tested fabrics

It must be noted that area density of tested fabrics in our research varied from 211 g/m² to 398 g/m² and it was nearly two times higher than that in Yick K. L. [11] research. From the standpoint of area density it was also observed that for our group of tested samples which was composed of the same broken twill weave type fabrics very strong dependency exists between sample area density and bending rigidity parameters defined by KES-F and FAST testers in both warp and weft directions (Table 3).

Table 3. The dependency between area density W and bending rigidity values defined by KES-F and FAST testers for tested WO blended outer fabrics and for CO and CO blended shirting fabrics tested by Yick K. L. [11]

	Composition	Weave type	Area density W, g/m^2	Direction	FAST		KES-F	
					Linear equation	R^2	Linear equation	R^2
Tested fabrics	WO blended	twill (2/2)	211 – 398	warp	$y = 0.24x – 38.33$	0.98	$y = 0.33x – 56.87$	0.98
				weft	$y = 0.13x – 17.27$	0.93	$y = 0.17x – 26.59$	0.92
				mean	$y = 0.18x – 27.80$	0.97	$y = 0.25x – 41.73$	0.96
Yick K.L. [11]	CO and CO blended	plain, twill (2/1)	96 – 170	warp	–	0.23	–	0.33
				weft	$y = 0.07x – 4.04$	0.77	$y = 0.06x – 4.33$	0.80
				mean	$y = 0.06x – 1.52$	0.57	$y = 0.06x – 2.47$	0.71

Meantime such strong dependencies were not found for Yick K.L. [11] shirting fabrics testing results, especially in warp direction ($R^2 = 0.33$ and $R^2 = 0.23$) as it is presented in Table 3. This can be explained by the fact that the group of shirting fabrics was composed of very different materials, particularly in their structure. Hence the assumption can be made that more reliable dependency for KES-F bending rigidity B_{KESF} values conversion into FAST bending rigidity B_{FAST} values can be obtained for purposively selected group of fabrics with similar characteristics, e. g. weave type.

The above described relationships between the values of bending rigidity B_{FAST} and B_{KESF} parameters have motivated to analyse wider scope of fabrics in this regard. For this aim KES-F and FAST bending rigidity testing results from other research works [1, 11 – 16] were taken for analysis. Totally 80 fabrics different in yarn composition, area density and weave type were studied.

It can be seen from the provided summary of all analysed results (Fig. 6) that even though the researchers have tested very different fabrics, they have obtained significant liners dependencies between bending rigidity B_{FAST} and B_{KESF} parameters ($R^2 = 0.85 – 0.99$), except Kenkare *et al.* ($R^2 = 0.42$) [12] and Tokmak *et al.* ($R^2 = 0.77$) [14].

At the first step of our analysis the attempt was made to set one generalized relationship between bending rigidity B_{FAST} and B_{KESF} parameters for all analyzed fabrics but the obtained result was unsatisfactory $R^2 = 0.65$.

Fig. 6 shows that the main part of analysed materials fall in the zone of comparatively low bending rigidity values, i. e. up to $B_{FAST} = 40·10^{-6}$ Nm and up to $B_{KESF} = 30·10^{-6}$ Nm^2/m. Only the results of two authors [13, 16] provide results for materials with higher bending rigidity values, e. g. $B_{FAST} = 120·10^{-6}$ Nm and more.

The materials used by these two authors are interesting from the standpoint that it was the same CO fabric of plane weave, treated with different concentrations of the similar stiffeners. Also it must be noted that both testing results can be described by very close linear dependencies ($B_{KESF} = 0.25B_{FAST} + 5.49$ and $B_{KESF} = 0.35B_{FAST} + 6.11$) with almost the same accuracy ($R^2 = 0.88$ and $R^2 = 0.85$, respectively) (Fig. 7, a). Besides, this dependency is significantly below 1 : 1 line, i. e. with the significant increase of bending rigidity B_{FAST} parameter the changes of B_{KESF} parameter are not distinct.

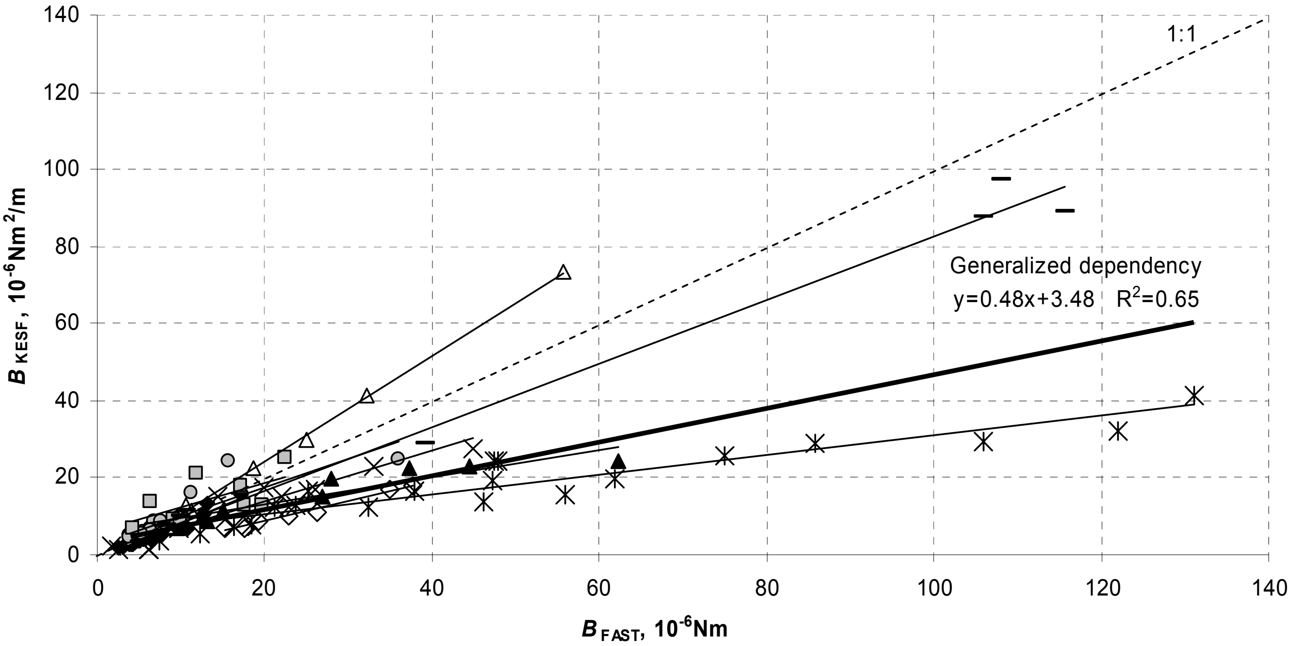
Noteworthy is the fact that the results of both authors can be described by one relatively significant generalized dependency $B_{KESF} = 0.25B_{FAST} + 6.77$ ($R^2 = 0.84$) as it is presented in Fig. 7, a. This equation can also be applied for the recalculation of KES-F bending rigidity values from FAST bending rigidity for CO fabrics treated with different concentrations of similar stiffeners (Fig. 7, b).

During bending rigidity conversion the discrepancies exceeded 20 % – 30 % only for three points. For the rest of the points it did not exceed 15 %. All this confirms again the above made assumption that more reliable dependency for KES-F bending rigidity values conversion into FAST bending rigidity B_{FAST} values can be obtained for specified group of fabrics. In this case the group was composed of the same fabric samples exposed to different final treatment conditions.

At the second stage of our analyses the attempt was made to separate all analyzed fabrics by yarn composition and by weave type (Fig. 8). Results have shown that such yarn compositions as CO and CO blended or WO and WO blended do not have very significant effect ($R^2 = 0.69$ and $R^2 = 0.67$, respectively) for the relationship between bending rigidity parameters B_{FAST} and B_{KESF}. Meantime this relationship becomes much more significant analyzing materials from the standpoint of weave type, i. e. plain and twill ($R^2 = 0.86$ and $R^2 = 0.94$, respectively). Thus the assumption can be made that weave type has more significant effect for the dependency between KES-F bending rigidity B_{KESF} and FAST bending rigidity B_{FAST} values.

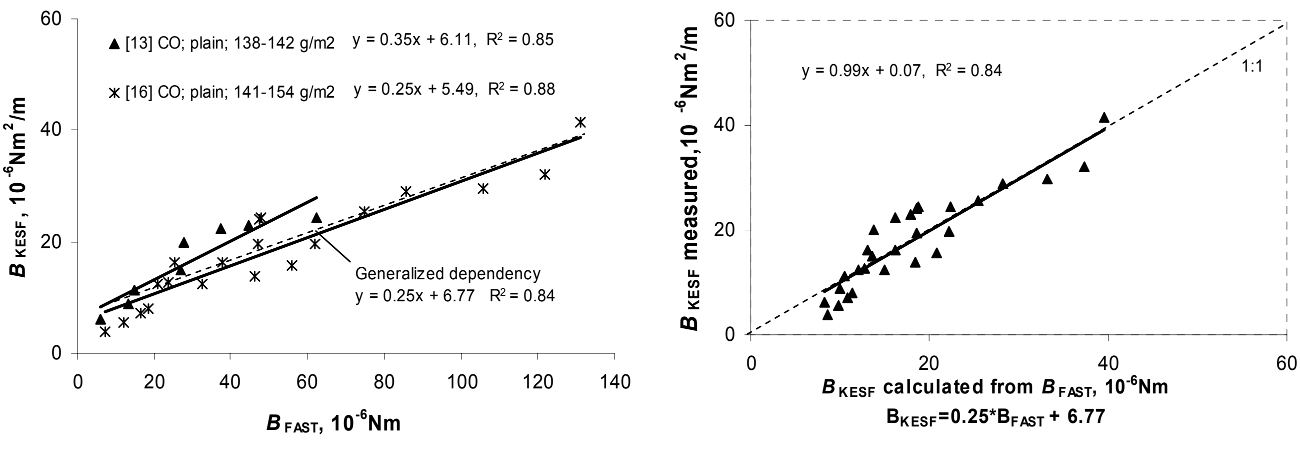
It was mentioned before that after the conversion of FAST bending rigidity parameter B_{FAST} into KES-F bending rigidity parameter B_{KESF} higher discrepancies exists for higher rigidity fabrics. This fact gives the reason to sort fabrics into two groups in respect to their area density. In Fig. 9 testing results of all weave type fabrics are separated into two groups by area density: up till 200 g/m^2 and over 200 g/m^2 ($R^2 = 0.88$ and $R^2 = 0.93$, respectively). For heavy-weight fabrics (over 200 g/m^2) no plain weave fabrics fell into this category. Meantime light-eight fabrics up to 200 g/m^2 area density are of plain or twill weave type.

It is clear from Fig. 6 that nearly all results of analysed fabrics correspond to the above described tendency set by Yick K.L. *et al* [11], i. e. that the values of B_{KESF} are lower compared to the values of B_{FAST} parameter and all dependency lines are below 1 : 1 line.



Marking	Author, reference	Composition	Weaving	Area density, g/m^2	Linear equation	R^2
△	Tested fabrics	WO blended	twill (2/2)	222 – 398	$y = 1.37x - 3.27$	0.99
◆	Yick K.L. *et al.* [11]	CO and CO blended	plain, twill (2/1)	96 – 170	$y = 0.88x - 0.60$	0.94
—	Yick K.L. *et al.* [11]	CO	twill	199 – 217	$y = 0.83x + 0.16$	0.99
▲	Naujokaityte L. *et al.* [12]	CO	plain	138 – 142	$y = 0.35x + 6.11$	0.85
×	Luible C. *et al.* [1]	CO, LI, WO, SE, PES	plain, twill, sateen, weft knit	– (not given)	$y = 0.65x + 0.72$	0.92
●	Tokmak O. *et al.* [14]	WO and WO blended	plain, twill (2/1, 2/2), basket (2/2, 4/4), rib (2/2)	140 – 320	$y = 0.75x + 2.50$	0.77
◇	Wang X. [15]	WO blended	plain, sateen	152 – 291	$y = 0.52x - 1.60$	0.98
✳	Valatkiene L. [16]	CO	plain	141 – 154	$y = 0.25x + 5.50$	0.88
■	Kenkare N. S. [12]	CO, synthetic	plain, twill, sateen, rib, corduroy, lawn, sheeting	95 – 292	$y = 0.63x + 6.02$	0.42

Fig. 6. The relationships between bending rigidity values defined by KES-F and FAST testers of different researchers [1, 11 – 16]



a b

Fig. 7. The relationship between bending rigidity values defined by KES-F and FAST testers of CO plain weave type fabrics treated by similar stiffeners [13, 16] (a) and the relationship between calculated and measured KES-F bending rigidity values (b)

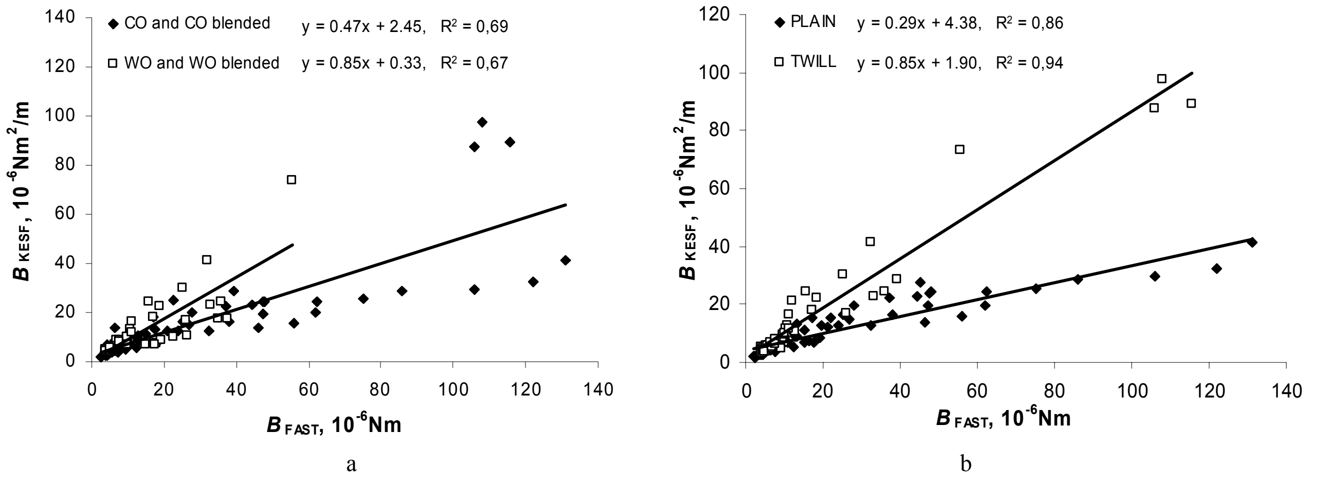


Fig. 8. The relationships between bending rigidity values defined by KES-F and FAST testers and sorted by: a – fabric composition; b – weave type

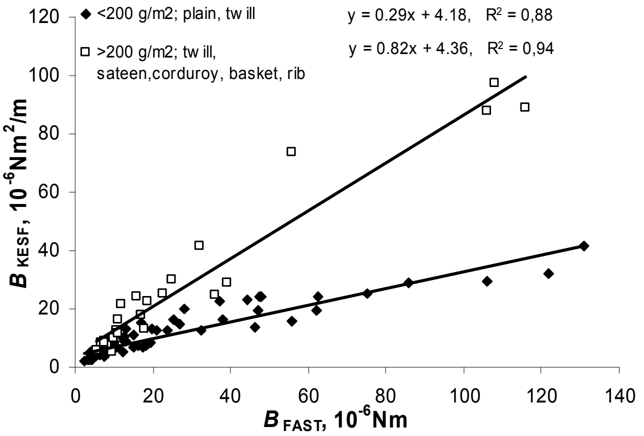


Fig. 9. The relationship between fabrics bending rigidity values defined by FAST and KES-F testers and sorted by area density

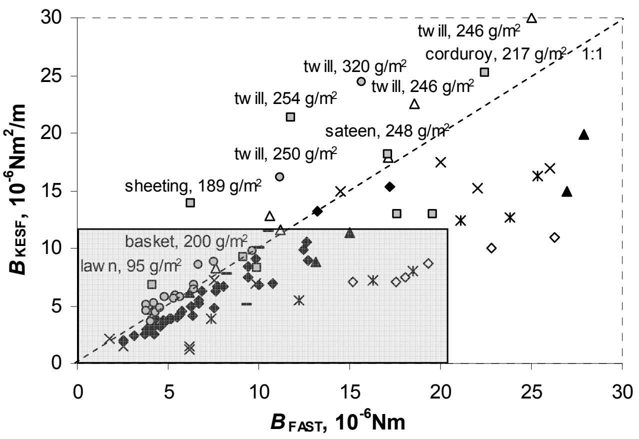


Fig. 10. The relationship between FAST and KES-F bending rigidity values up to $30{\cdot}10^{-6}$ Nm (grey zone – recommended limits of bending rigidity values in quality control charts for fabric tailorability)

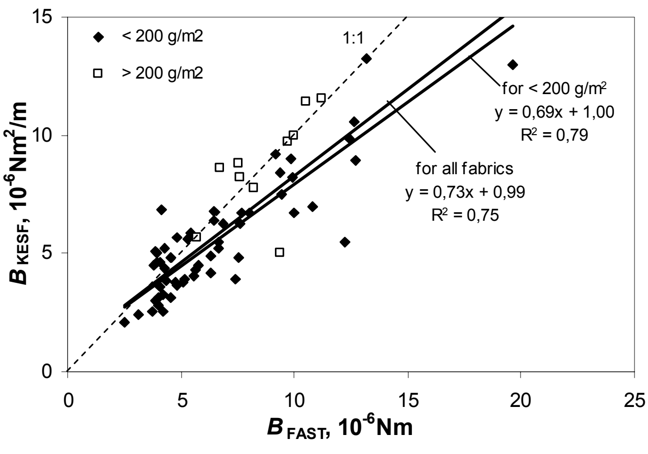


Fig. 11. The relationships between KES-F and FAST bending rigidity values for all analysed fabrics and light-weight (< 200 g/m^2) fabrics

As it was mentioned above, the main part of investigated samples fall in the zone of comparatively low bending rigidity values, i. e. up to $B_{\text{FAST}} = 40{\cdot}10^{-6}$ Nm and up to $B_{\text{KESF}} = 30{\cdot}10^{-6}$ Nm^2/m. During analysis it was interesting to notice that in this zone dependencies between B_{KESF} and B_{FAST} are above 1 : 1 line for those fabric samples area density of which also exceeds 200 g/m^2 (Fig. 10). Here we can find not only twill but sateen, sheeting, basket, corduroy fabrics and other heavy-weight textile materials.

From practical standpoint the above mentioned bending rigidity limits must be specified taking into the account that bending rigidity values in SiroFAST control chart for tailorability are up to $21{\cdot}10^{-6}$ Nm. In KES-F quality chart bending rigidity is not included, but bending rigidity values higher that $12.35{\cdot}10^{-6}$ Nm can cause tailorability problems [19]. Pavlinic and Gersak [20] defined that bending rigidity over $10{\cdot}10^{-6}$ Nm is high and can arise problems in garment manufacturing. Therefore it is purposeful to set the dependencies up to these limits, i. e. $21{\cdot}10^{-6}$ Nm for B_{FAST} and $12.35{\cdot}10^{-6}$ Nm for B_{KESF} (Fig. 10). The relationships between KES-F and FAST bending rigidity values within these limits for all analysed fabrics and light-weight (area density < 200 g/m^2) fabrics separately are presented in Fig. 11.

It is evident from Fig. 11 that for analysed fabrics there is almost no difference weather the dependency is set for all samples or only for light-weight samples ($R^2 = 0.75$ and $R^2 = 0.79$, respectively). Thus, it can be concluded that in the range of low bending rigidity values the recalculation of KES-F bending rigidity values from FAST bending rigidity values can be performed using one of the presented linear equations. Advisably: for all fabrics is $B_{KESF} = 0.73B_{FAST} + 0.99$ and for light-weight fabrics is $B_{KESF} = 0.69B_{FAST} + 1.00$.

CONCLUSIONS

The investigation of KES-F and FAST bending rigidity parameters for heavy-weight fabrics together with comparative analysis of data provided in literature references show that the dependencies between bending rigidity parameters defined for light-weight fabrics can not be applied for heavy-weight fabrics. For broken twill weave heavy-weight fabrics linear equation $B_{KESF} = 1.37B_{FAST} – 3.27$ can be used to recalculate KES-F bending rigidity values from FAST bending rigidity values.

More reliable dependency for KES-F bending rigidity B_{KESF} values conversion into FAST bending rigidity B_{FAST} values can be obtained for purposively selected group of fabrics with similar characteristics. The groups can be composed of the same weave type fabrics or the same fabric samples exposed to different final treatment conditions.

The analyses of fabrics from the standpoint of yarn composition, weave type and area density allowed to notice that weave type has more significant effect for the dependency between KES-F bending rigidity B_{KESF} and FAST bending rigidity B_{FAST} values. It is purposive to separate fabrics into two groups in respect to their area density, i. e. up till 200 g/m^2 and over 200 g/m^2.

From practical standpoint the relationships between FAST and KES-F bending rigidities in the limits of bending rigidity values recommended in quality control charts for fabric tailorability, i. e. $21\cdot10^{-6}$ Nm for B_{FAST} and $12.35\cdot10^{-6}$ Nm for B_{KESF} are very close for all analysed fabrics and separately taken light-weight fabrics, thus can be recalculated from the same linear equation.

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