Malgorzata Matusiak

Evaluation of the Bending Stiffness of Seersucker Woven Fabrics

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Lodz University of Technology,
Faculty of Material Technologies and Textile Design,
Institute of Architecture of Textiles,
116 Żeromskiego Street, 90-924 Lodz, Poland,
e-mail: malgorzata.matusiak@p.lodz.pl

Abstract
Bending stiffness is an important property of textile materials, especially from the point of view of the utility comfort of the clothing user. The stiffness of fabrics determines their ability to create folds under the influence of gravity. At the same time, it influences the aesthetic effect of clothing usage, in particular its fitting to the user's body. Fabric stiffness is also important from the point of view of the sensorial comfort of clothing usage. In the work presented seersucker woven fabrics of different structure were measured in the range of their stiffness. The fabrics investigated differ from each other in the aspect of the repeat of the seersucker effect and linear density of weft yarn. Measurement of bending stiffness was performed using two measurement methods: Peirce's Method (Fabric Stiffness Tester) and an MOO3F Digital Pneumatic Stiffness Tester. On the basis of the results, an analysis was performed to assess the influence of the repeat of the seersucker effect and linear density of weft yarn on stiffness parameters determined using both methods. Results confirmed that the linear density of weft yarn and the repeat of the seersucker effect influence the bending stiffness of fabrics determined by both testing methods applied. Some problems resulting from the surface geometry of the seersucker woven fabrics were indicated and discussed.

Key words: *seersucker woven fabrics, bending stiffness, circular bending stiffness.*

Introduction

Seersucker woven fabrics are characterised by a unique structure and surface topography [1, 2]. On their surface puckered strips in the warp direction occur alternately with flat strips. The width of the puckered and flat strips and the intensity of the puckering effect can be different. Seersucker woven fabrics are manufactured on a loom equipped with two warp beams. One beam carries warp yarns for the flat (basic) strips, while the other carries warp yarns for the puckered strips. During weaving, adjustments are made to make the puckered strip warp yarns feed forward faster than the flat stripe warp yarns. This results in different tension of warp yarns and subsequently a localised buckling of the fabric in the areas of fast-feeding yarns. This makes the pucker in the wrinkled strips in the warp direction.

Seersucker woven fabrics are popular due to their aesthetic and utility properties. Some researchers suggest that clothing made of them is able to ensure thermo-physiological comfort [1-3]. It was confirmed in [4] that seersucker woven fabrics are characterised by a low value of thermal absorptivity (< 200 $Wm^{-2} s^{1/2} K^{-1}$) in a wet state, which means that the fabrics are good from the point of view of moisture management [4].

Surface properties of seersucker woven fabrics are important from the point of view of sensorial comfort. The stiff and rough surface of the fabrics gives a massaging effect during clothing usage. Matusiak et al. patented a seersucker woven fabric (***Figure 1***) with a micro-massage function [6].

The authors utilised the following properties of the seersucker woven fabrics developed:
- great stiffness,
- great surface roughness,
- great thermal resistance.

Both the great stiffness and rough surface of seersucker woven fabric ensures the micro-massaging effect. The thermal resistance of the fabric, much higher than that of standard cotton fabric, ensures the so-called "thermal effect", consisting in hindering human body heat outflow [6].

Seersucker woven fabrics have been known and applied for centuries. However, their structure and properties are not fully recognised. Matusiak et al. investigated the tensile properties of seersucker woven fabrics of different structure [7]. They stated that both the tensile strength and elongation at break depend on the kind of weft yarns applied in the fabric and on the variant of pattern of the seersucker effect. Moreover, the investigations performed showed that in the case of such patterned fabrics as seersucker woven fabrics, the repeat of the puckered strips is a very important factor from the point of view of the mechanical properties of such fabrics. It was stated that the way of testing the sample preparation, especially the place of cutting it, significantly influences the results of the breaking force and elongation at break in the warp direction [7]. Measurements of the thermal-insulation properties of seersucker woven fabrics also confirmed that the share of the area of the puckered strips in the total area of the seersucker woven fabric influences the results [8-10]. Taking this into consideration, it was assumed that the structure of seersucker woven fabrics, especially their surface geometry, also influences the results of measurement of bending stiffens.

Bending stiffness is defined as the resistance of textile against bending by its specific weight and external force [11]. It is an important property of fabrics both for clothing manufacturing and for technical applications. In the case of apparel fabrics, their stiffness is strongly connected with the ability of fabrics to drape [12]. The bending properties of fabrics are determined by yarn bending behaviour, the weave of the fabric, and the way of finishing. There are also interactions between the factors mentioned [13].

The aim of work presented was to investigate the bending stiffness of seersucker woven fabrics of different structure. On the basis of the results, the influence of the repeat of the seersucker effect and linear density of weft yarns on the bending stiffness was analysed. Additionally, the problem of sample preparation for measurement was discussed. Results showed that in the case of such a kind of patterned fabric as seersucker, it is important to determine precisely the place of cutting of test specimens.

Materials and methods

Measurement was performed for seersucker woven fabrics made of cotton. In total, 9 variants of seersucker woven fabrics were the objects of the investigation. The fabric variants differed from each other in the aspect of the repeat of the seersucker effect and in the kind of weft yarn. In the experimental set of fabrics, 3 kinds of repeat of the seersucker pattern and 3 kinds of weft yarns were applied. 20 tex x 2 yarn was applied as both warps: basic and puckering. In the weft the following yarns were used: 20 tex x 2, 25 tex x 2 and 30 tex x 2.

The variants of the seersucker effect differed from each other in the range of the width of puckered strips and in the distance between them as follows:

- variant 1: width of puckered strips – 5 mm, distance – 8 mm,
- variant 2: width of puckered strips – 9 mm, distance – 18 mm,
- variant 3: width of puckered strips – 11 mm, distance – 41 mm.

Measurements of circular bending rigidity and bending stiffness were performed by means of a Digital Pneumatic Stiffness Tester and Cantilever Stiffness Tester.

Circular bending rigidity was measured using the Digital Pneumatic Stiffness Tester. In the test that gives the fabric stiffness in all directions, a plunger forces a flat, folded swatch of fabric through an orifice in a platform (***Figure 2***). The diameter of the orifice is 38 mm, whereas that of the plunger is 25.4 mm. The maximum force required to push the fabric through the orifice is an indication of the fabric stiffness (resistance to bending). Measurement is performed according to the ASTM D 4032 – 08 standard [14]. For each fabric variant 5 testing samples were prepared in the form of a rectangle with dimensions of 102 mm by 204 mm. The short side of the specimen must be parallel to the machine (length) direction of the fabric. Next, the sample is folded to form a square 102 mm by 102 mm.

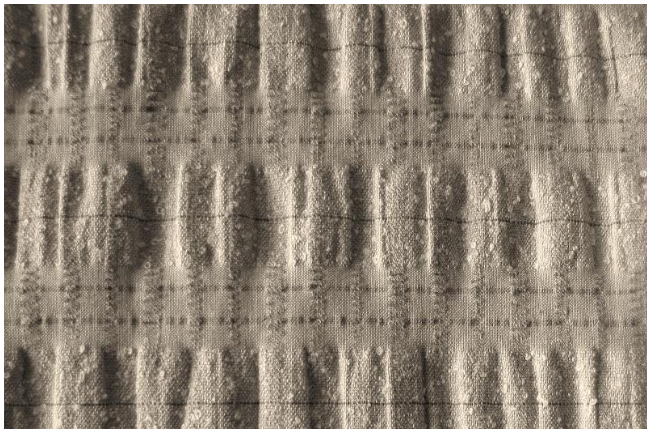

Figure 1. *Seersucker woven fabric with a therapeutic function [5, 6].*

In the test by means of the Cantilever Stiffness Tester, a horizontal strip of fabric is slid at a specified rate in a direction parallel to its long dimension, until its leading edge projects from the edge of the horizontal surface (***Figure 3***).

The length of the overhang *L* is measured when the tip of the specimen is depressed under its own mass to the point where the line joining the top to the edge of the platform makes a 41.5° angle with the horizontal. It is known as the bending length, and from this measured length, the bending stiffness is calculated using ***Equation (1)*** given below [15]:

$$B = m_p c^3 g \text{, Nm} \qquad (1)$$

Where:
m_p – mass per square metre, kg/m^2,
c – bending length [m], where: $c = L/2$
g – gravitational acceleration 9.81, m/s^2.

Bending stiffness is determined separately for both the warp and weft directions. Next, the total bending stiffness is calculated according to ***Equation (2)***:

$$B_{Tot} = \sqrt{B^2_{warp} \times B^2_{weft}} \text{, Nm} \qquad (2)$$

This method is commonly used all over the world for the assessment of the bending stiffness of textile materials. However, the cantilever method is not suitable for fabrics that are too limp or show a marked tendency to curl or twist at a cut edge.

The investigations presented showed that the measurement of seersucker woven fabrics creates some problems related to testing a sample preparation. Measurement was performed for test samples in the form of a rectangle with dimensions 300 mm x 30 mm. Samples were cut in the warp and weft directions, 5 samples for each direction. The test samples should be cut in randomly chosen places of the fabric. However, in the case

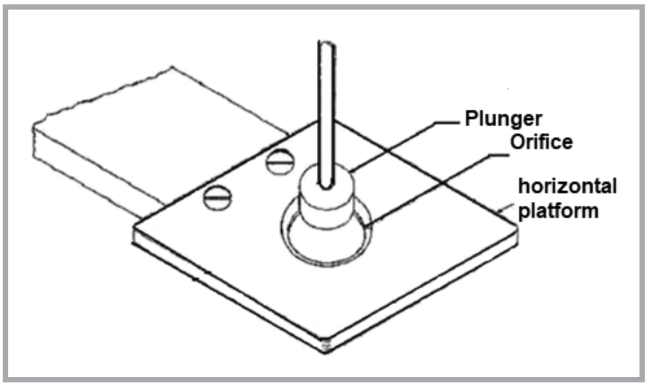

Figure 2. *Measuring unit of the Circular Pneumatic Stiffness Tester [14].*

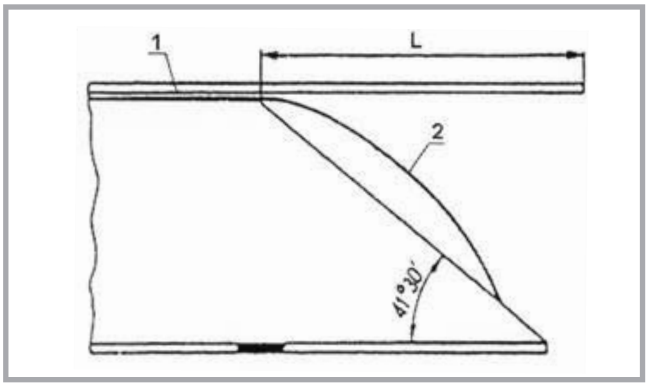

Figure 3. *Scheme of measurement by the Cantilever Stiffness Tester: L – length of overhang, 1 – gauge, 2 – fabric sample.*

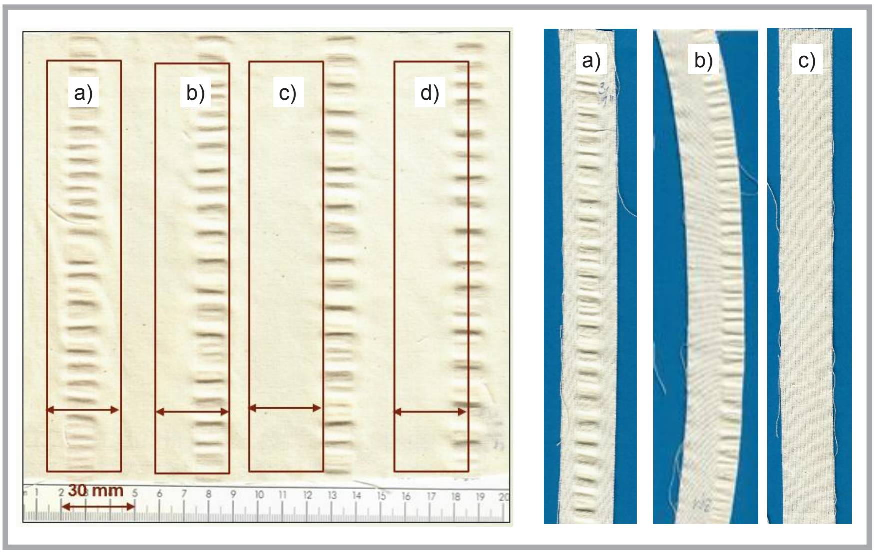

Figure 4. *Possible placements of test specimen on the fabric representing the MM 3 repeat of the seersucker effect.*

of seersucker woven fabrics, cutting the samples in the warp direction in random places of the fabric causes that each test sample can have a different structure.

Figure 4 presents an example of the seersucker woven fabric investigated. It is a seersucker fabric representing the MM 3 variant of the seersucker effect, i.e. the variant with the widest puckered strips and biggest distance between them. The test samples for bending stiffness measurement were of 30 mm width. It is clearly seen that in the warp direction there are almost 4 possible placements of test sample cutting in the fabric area. Each specimen is characterised by a different share of the puckered area in the total area of the test specimen. Additionally, specimens *b* and *d* have a tendency to curl or twist at the cut edge (***Figure 4.b*** and ***4.d***). Due to this fact they are not appropriate to be measured using the cantilever method. It was decided to measure the bending stiffness of the seersucker woven fabrics investigated with test specimens having a puckered strip in the middle (***Figure 4.a***).

However, cutting in such a way causes that the share of the puckered area in the total area of the test specimen is different than that of puckered strips in the total area of the fabrics measured. Especially, it concerns seersucker woven fabrics representing the MM 3 variant of the repeat of the seersucker effect. In the test specimen of the MM 3 variant, the share of the puckered area in the total specimen area is ca. 37 % (11 mm/30 mm), whereas in the whole fabric it is 21% (11 mm/52 mm). Thus, the results for the test specimens of the MM3 fabric variants having a puckered strip in the middle may not reflect the results for the whole fabric. Thus, for comparison, measurement of a test specimen without a puckered strip (***Figure 4.c***) was performed for fabrics of the MM 3 variant of the repeat of the seersucker effect.

In order to analyse the results, statistical analysis was performed using Multi-Factor ANOVA (Analysis of Variance). In general, the purpose of ANOVA is to test for significant differences between means. The statistical analysis was performed using TIBC STATISTICA 7 software version 13.3. The analysis was based on the individual measurement of particular samples. According to the software applied, the analysis was based on a comparison of the variance due to between-group variability (called *Mean Square Effect*, or MS_{effect}) with the within-group variability (called *Mean Square Error*, or Ms_{error}). The STATISTICA compared those two estimates of variance via the *F* test, which tested whether the ratio of the two variance estimates is significantly greater than 1.

Results and discussion

Circular bending rigidity

Results from the Digital Pneumatic Stiffness Tester are presented in ***Figure 5***. It is clearly seen that the bending force increases with an increase in the linear density of weft yarn. Statistical analysis using ANOVA confirmed that the influence of the linear density of weft yarn on the maximum bending force is statistically significant at the significance level 0.05. The influence of the repeat of the seersucker effect and the interaction between the repeat and linear density of weft yarn are statistically insignificant. It should be mentioned here that during the measurement using the Digital Pneumatic Stiffness Tester, friction between the specimen measured and the edge of the orifice in the horizontal platform (***Figure 2***) occurred and influenced the results – the maximum

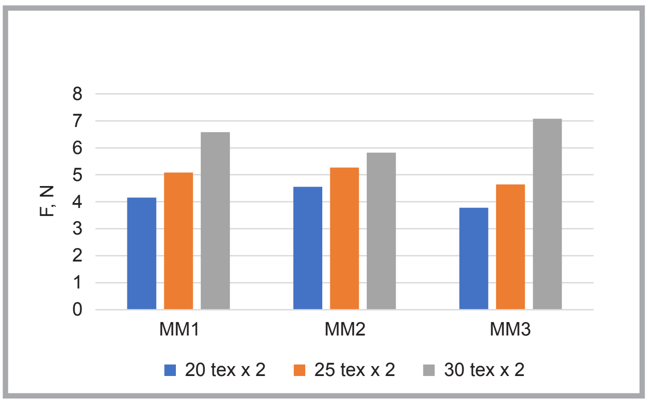

Figure 5. *Results from the Digital Pneumatic Stiffness Tester.*

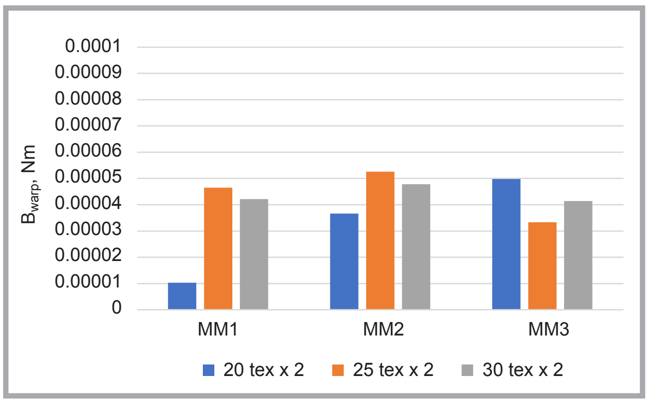

Figure 6. *Bending stiffness of the seersucker woven fabrics in the warp direction.*

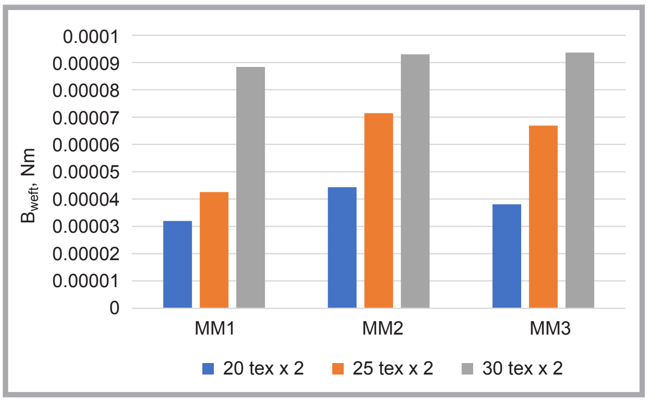

Figure 7. *Bending stiffness of the seersucker woven fabrics in the weft direction.*

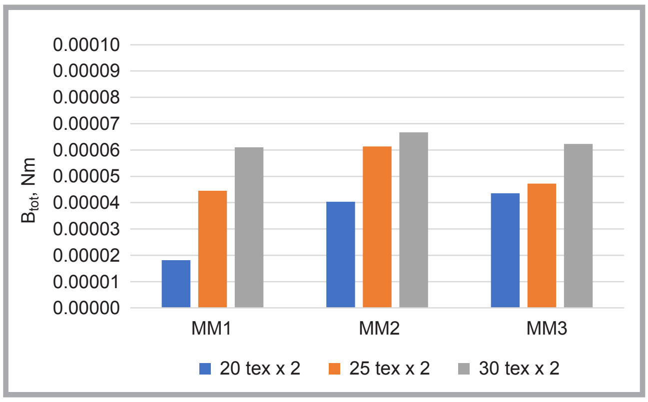

Figure 8. *Total bending stiffness of the seersucker woven fabrics.*

force required to push the fabric through the orifice. In the case of seersucker woven fabrics, the puckered strips can disturb the movement of the test specimen through the orifice. It can also increase the force necessary to push the fabric. It is impossible to separate the impact on the measurement results of these three factors mentioned: fabric stiffness, friction resistance, and distortion of sample movement on the surface of the puckered strips.

Bending stiffness

Figure 6 presents the results of measurement of the specimens having a puckered strip in the middle by means of the Cantilever Stiffness Tester.

In the warp direction it is difficult to state any clear tendency. Only in the case of the fabrics with 20 tex x 2 weft yarn (blue columns) did the bending stiffness in the warp direction increase, from the MM 1 repeat variant to the MM 3 variant. In the weft direction (***Figure 7***), there is a clear relationship between the bending stiffness and linear density of weft yarn. Bending stiffness increases with an increase in the linear density of weft yarn. The tendency is according to expectations.

The same tendency occurred for the total bending stiffness (***Figure 8***). It is due to the fact that the bending stiffness of the seersucker woven fabrics investigated is significantly higher in the weft direction than in the warp direction. Therefore, the bending stiffness in the weft direction dominated the total bending stiffness of the fabrics tested.

For the fabrics representing the MM 3 variant of the seersucker effect, measurement in the warp direction was performed for test specimens without a puckered strip (***Figure 4.c***). A comparison of bending stiffness in the warp direction for test specimens with and without puckered strips is presented in ***Figure 9***. It can be seen that the results for both kinds of test specimens are different. For the fabric with 20 tex x 2 weft yarn, the bending stiffness for the test specimen with a puckered strip is higher than for the flat test specimen; while for fabrics with 25 tex x 2 and 30 tex x 2 weft yarns the relation is opposite.

It should be mentioned here that the mass per square metre is one of the factors taken for calculation in ***Equation (1)*** – describing the bending stiffness. The results presented above were calculated on the basis of the mass per square metre of the fabrics presented in ***Table 1***. This mass was determined by the full-width method. In this method the mass per square metre is determined on the basis of a rectangular specimen of the following dimensions: the width equal to the entire width of the fabric and length of 500 mm. The specimen is weighted. Additionally, the width of the fabric is measured in three places. The mass of square metre is calculated on the basis of the mass of the specimen and its dimension. This method in standardised. Test specimens for measurement by means of the Cantilever Stiffness Tester, depending on the place of cutting, are characterised by different shares of the puckered area in the total area of the specimen. Due to this fact the mass per square metre of test specimens may be different from that of the fabric investigated. It is owing to the fact that the take-up of the warp creating the puckered strips is significantly higher than that of the warp creating the flat strips (***Table 1***). The mass per square metre of the test specimen influences the length of overhanging and, at the same time, the bending length.

Table 1. *Basic structural properties of fabrics investigated.*

	Unit	Value								
Weave – warp I	–	plain								
Weave – warp II	–	rep 2/2								
Repeat variant	–	MM 1			MM 2			MM 3		
Weft yarn	–	20 tex x 2	25 tex x 2	30 tex x 2	20 tex x 2	25 tex x 2	30 tex x 2	20 tex x 2	25 tex x 2	30 tex x 2
Symbol	–	MM 1/1	MM 1/2	MM 1/3	MM 2/1	MM 2/2	MM 2/3	MM 3/1	MM 3/2	MM 3/3
Warp density	cm^{-1}	12.7	11.9	12.8	12.6	12.5	12.3	11.4	11.8	11.6
Weft density	cm^{-1}	11.4	11.1	10.4	11.5	11.0	10.4	11.4	11.1	11.4
Mass per square metre	$g\ m^{-2}$	212.9	233.0	253.0	207.8	226.1	245.6	192.8	212.5	230.0
Take up – warp I	%	8.3	7.3	7.9	6.0	6.3	8.2	5.2	6.6	11.1
Take up – warp II	%	49.8	56.0	60.2	48.8	50.4	49.6	49.7	46.3	47.2
Take up – weft	%	7.1	8.6	8.7	6.4	6.4	6.2	8.2	5.0	6.7

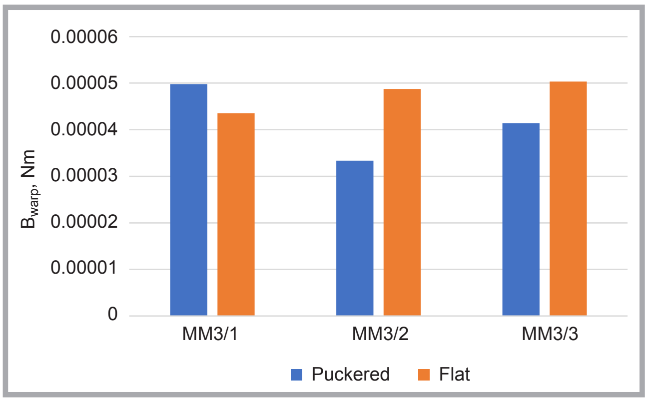

Figure 9. *Bending stiffness in the warp direction of the seersucker woven fabrics measured on the basis of test specimens with and without a puckered strip.*

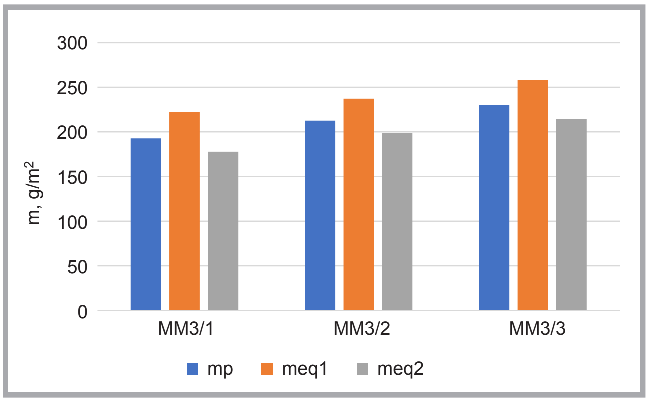

Figure 10. *Mass per square metre of the seersucker woven fabrics investigated: m_p – weighted for full-width sample, m_{eq1} – equivalent calculated on the basis of the weight of the test specimen with a puckered strip in the middle, m_{eq2} – equivalent calculated on the basis of the weight of the test specimen without a puckered strip.*

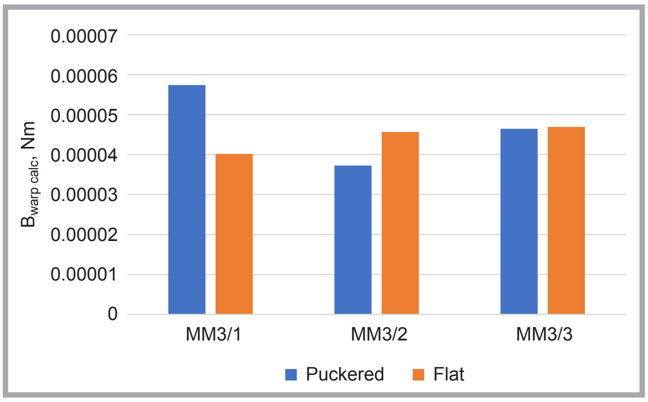

Figure 11. *Bending stiffness in warp direction for test specimens with and without a puckered strip calculated on the basis of the equivalent mass per square metre.*

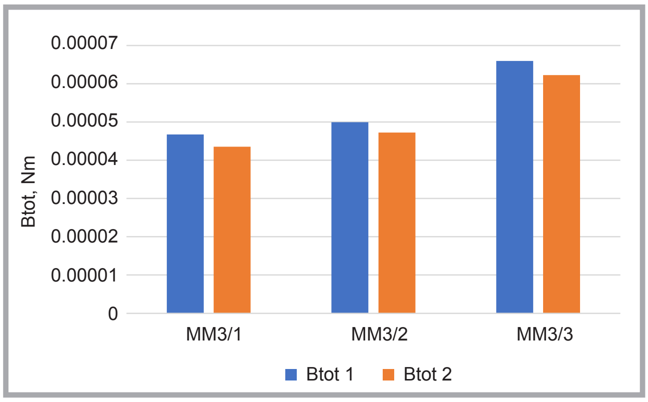

Figure 12. *Total bending stiffness calculated on the basis of results for testing specimens having a puckered strip in the middle: B_{tot} 1 – calculated on the basis of the mass per square metre determined using the full-width method, B_{tot} 2 – calculated on the basis of the equivalent mass per square metre.*

In order to analyse this problem, the test specimens were weighted. Next, the weight of the specimen was compared with that calculated on the basis of the mass per square metre of fabric (from ***Table 1***) and dimensions of the test specimen, according to ***Equation (3)***:

$$m_s = m_p \times 0.3 \ \times 0.03 \qquad (3)$$

Where:
m_p – mass per square metre of fabric, kg/m^2,
m_s – mass of test specimen of dimensions 0.30 m x 0.03 m, kg.

In all cases the real weight of test specimens was different that that calculated by means of ***Equation (3)***. For the test specimens having a puckered strip in the middle, the real weight was higher, and for the test specimens the real weight was lower than the calculated one. Due to the fact that the real weight of the test specimen causes its bending during measurement of the bending stiffness, it was assumed to recalculate the bending stiffness in the warp direction of the seersucker woven fabrics. In order to do it first, the equivalent mass per square metre was calculated according to ***Equation (4)***:

$$m_{eq} = \frac{m_s}{A_s}, \text{kg/m}^2 \qquad (4)$$

Where:
m_{eq} – equivalent mass per square metre,
m_s – mass of test specimen of dimensions 0.30 m x 0.03 m, kg,
A_s – area of test specimen (0.30 m x 0.03 m), m^2.

A comparison of the mass per square metre of MM 3 fabric variants determined using the full-width sample method and equivalent – calculated on the basis of the weight of test specimens using ***Equation (4)***, is presented in ***Figure 10***.

The equivalent mass per square metre proposed reflects a weight which causes the bending of the test specimen while using the Cantilever Stiffness Tester in a better way than that determined using the full-width method. Thus, the values of the equivalent mass per square metre calculated were introduced into ***Equation (1)*** and the bending stiffness of the fabrics in the warp direction recalculated.

Figure 11 presents a comparison of the bending stiffness in the warp direction of seersucker woven fabrics representing the MM3 variant of the repeat of the seersucker effect calculated on the basis of the equivalent mass per square metre according to ***Equation (4)***.

It is clearly seen that the values of bending stiffness in the warp direction of the seersucker woven fabrics is different for test specimens having a puckered strip in the middle and for the flat specimen without a puckered strip. The values presented are different from those determined on the basis of the mass per square metre measured using the full-width method (***Figure 9***). It is difficult to assess which one reflects the real bending stiffness of the seersucker woven fabrics investigated. The question is how should the bending stiffness be measured in the case of seersucker woven fabrics or other fabrics of developed geometrical structure. Which results from those presented above reflect the real bending stiffness of the seersucker woven fabrics?

Figure 12 presents a comparison of the total bending stiffness of the seersucker woven fabrics determined on the basis of the results for test specimens having a puckered strip in the middle. $B_{tot}1$ means the bending stiffness calculated using the mass per square metre determined by the full-width method, while $B_{tot}2$ is the total bending stiffness based on the recalculated bending stiffness in the warp direction. In the analysis it was assumed that the influence of the pattern of the seersucker effect on the bending stiffness of the seersucker woven fabrics in the weft direction can be neglected.

Summing up

The investigation presented confirmed that the linear density of weft yarn influences the bending stiffness of the fabrics investigated, both the circular bending stiffness, determined using the Digital Pneumatic Stiffness Tester, and the bending stiffness in the warp direction, determined using the Cantilever Stiffness Tester.

An increase of the linear density of weft yarn causes an increase in the circular bending stiffness. This relationship is statistically significant at the probability level 0.05. The repeat of the seersucker effect also influences the bending stiffness of the seersucker woven fabrics. However, there is no clear relationship between the repeat of the seersucker woven fabrics and their bending stiffness.

In measurement of the bending stiffness by means of the Cantilever Stiffness Tester, test samples cut in different places of the seersucker woven fabrics in the warp direction are characterised by a different share of the puckered area in the total area of the test specimen and, in the same way, a different mass per square metre. It influences the results from the Cantilever Stiffness Tester. This was shown in the example of fabrics representing the MM 3 variant of the repeat of the seersucker effect, which should be taken into consideration while preparing test specimens for measurement. The problem can also concern other patterned woven fabrics, depending on the kind of pattern. In the case of seersucker woven fabrics, it is necessary to take into account the relationships between the puckered strip repeat and the width of the test specimen in the warp direction.

At this point it is difficult to state clearly how test specimens should be prepared for measurement of the bending stiffness in the warp direction of seersucker woven fabrics to get representative results for the whole fabric. However, it is necessary to describe the way of test sample preparation in the report on measurement.

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