ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
ID: TG-20170816142553

Original scientific paper

INFLUENCE KINDS OF MATERIALS ON THE POISSON'S RATIO OF WOVEN FABRICS

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Abstract: Poisson's ratio is one of the fundamental properties of any structural material including woven fabrics and textile materials. This coefficient determines important mechanical characteristics of fabrics in many applications, including a variety of composite systems containing textiles as a structural element. Due to the anisotropy of woven fabrics, Poisson's ratio changes over the fabric sample stretching. In this paper, the practical application of the uniaxial testing of woven fabrics for determining its breaking properties and Poisson's ratio is presented. Experimental testing was carried out on two different fabrics of a different raw material composition (cotton, wool) and of the same weave (plain weave). Samples were stretched with tensile force in the weft and warp direction, and based on the different measured values of the fabric stretching, warp and weft, Poisson's ratio is calculated. The influence of the raw material composition on the values of Poisson's ratio was examined.

Keywords: anisotropy; elongation at break; Poisson's ratio; warp; weft; woven fabric

1 INTRODUCTION

Nowadays, the use of textile materials in different industrial branches is on the rise. Anisotropy is a characteristic of most materials, especially woven fabrics. The impact of the direction of action of the external load (tensile force) on the properties of the fabric is enormous, and is frequently examined [1]. The mechanical properties of fabrics under the influence of the tensile load began to be studied in 1937 [2]. Kilby defined the Poisson's ratio and measured the tensile properties of fabrics in an arbitrary direction of the tensile force. He noted that there is a connection between the Poisson's ratio, shear modulus and modulus of the elasticity of the fabric [3]. The Poisson's ratio affects certain mechanical properties of the fabric such as the draping and shear. The researchers determined Poisson's ratio in the warp and weft based on the geometric model of fabric and without the impact of the Poisson's ratio of the yarn. The Poisson's ratio in fabrics comes out of the interaction between the warp and weft, and can be expressed in terms of structural and mechanical system parameters [4]. Due to the woven fabric anisotropy, the analysis of the impact of the physical parameters of fabric on the value of the Poisson's ratio is useful and provides a better explanation for certain woven fabric behavior. Because of the inherent nature of textile, an accurate and reliable measurement of the Poisson's ratio is a difficult task. This engineering property is studied by many scientists.

Bao and colleagues [5] were examining why in the measurements of the Poisson's ratio, when uniaxial tensile load is put on the fabric, errors occur. The previously measured experimental values were compared with the theoretical results. He also studied the influence of the yarn and fabric structural parameters of the Poisson's ratio. An accurate measurement of the Poisson's ratio of woven fabric is quite difficult to obtain due to the lack of reliable experimental techniques [6]. Uniaxial testing is most commonly performed in woven fabrics by using either the commercial or custom designed instruments [7] and analyzing the physical and mechanical properties of textile products [8]. The Poisson's ratio of textile materials used in the non-woven geotextile was analyzed by Giroud [9]. He set the theoretical equation to calculate the Poisson coefficient, as a function of strain.

Experiments on the extension of the woven fabric sample under the static load will are discussed in this paper. The influence of the raw material composition on the values of the Poisson's ratio has been researched, too.

2 THEORETICAL OVERVIEW

The Poisson's ratio, which expresses the change in the volume of a solid undergoing deformation, is an important characteristic, along with the initial modulus of elasticity and shear, of the behavior of a material under a tension load; and can be used in the calculations of the true stresses (from the actual cross-sectional area) coming into being in the textile fibers and yarns subjected to the extension, and can serve, moreover, as an indirect characteristic of the structure of the material and of the mechanism of its deformation. It is well known that when a solid having the shape of a rectangular parallelepiped, Fig. 1a, is subjected to tension forces in the direction of its axes x, y and z, the change in its volume equals:

$$\frac{\mathrm{d}V}{V} = \frac{y \cdot z \cdot d_x + x \cdot z \cdot d_y + x \cdot y \cdot d_z}{x \cdot y \cdot z} = \frac{d_x}{x} + \frac{d_y}{y} + \frac{d_z}{z} = \varepsilon_x + \varepsilon_y + \varepsilon_z \tag{1}$$

where ε_x, ε_y and ε_z are the relative tensile deformations in the direction of the x, y and z axes of the parallelepiped.

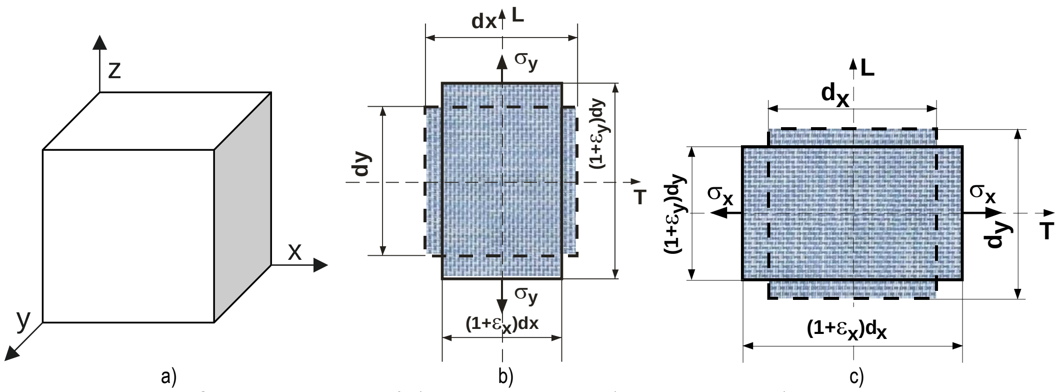


Figure 1 Schematic presentation of: a) solid volume element, b) Poisson's ratio ν_{xy}, c) Poisson's ratio ν_{yx}

In the tensile deformation in the direction of the *x* axis, the solid will be subjected to compression in the direction of the *y* and *z* axes (i.e, laterally to the *x* axis):

$$\frac{\mathrm{d}V}{V}=\varepsilon_x-2\cdot\varepsilon=\varepsilon_x\cdot\left(1-2\cdot\frac{\varepsilon}{\varepsilon_x}\right)=\varepsilon_x\cdot(1-2\cdot\nu) \tag{2}$$

where ε is the relative compressive deformation and ν is the Poisson's ratio.

It is obvious that for ν = 0.5 the volume of a material subjected to tensile forces will not change (dV = 0), for ν < 0.5 the volume will increase (dV > 0), while for ν > 0.5 it will decrease (dV < 0).

When a fabric is stretched in one direction, it tends to contract in the direction perpendicular to the direction of the stretch, Fig. 1b, 1c. The yarns in the direction of the tensile force are flattened out (extended), and in the orthogonal or non-loading direction, the yarns have a longer geometrical path to 'curve around'. Because there is no limiting force, the waviness (amplitude) of the yarn in the vertical direction of the force increases. The consequence to this is the dimension reduction of the fabric width. This phenomenon is called the Poisson effect. The Poisson's ratio, a measure of the Poisson effect, is the ratio of the relative contraction strain *s* to the related extension strain ε in the direction of the applied load. To determine the Poisson's ratio of fabrics, devices for measuring the tensile strength are used, and the coefficient is determined in the linear part of the diagram of the Hooke's law [10]. During the testing of the fabric to stretch, the initial length of the tested sample l_0 is increased for Δl, and a final sample length of fabric is l. The initial width of the fabric sample b_0 is decreased for Δb and the final sample width is b. The physical meaning of the Poisson's ratio ν is shown by the Eq. (3). The Relative contraction and extension strains have an opposite sign.

$$\nu=\left|\frac{s}{\varepsilon}\right|=\left|\frac{l_0}{b_0}\cdot\frac{b-b_0}{l-l_0}\right|,\quad s=-\nu\cdot\varepsilon\,. \tag{3}$$

The relative longitudinal strain (relative extension strain) ε and transverse strain (relative contraction strain) *s* is defined in the Eq. (4).

$$\begin{aligned}\varepsilon&=\frac{\Delta l}{l_0}\cdot 100\%=\left(\frac{l}{l_0}-1\right)\cdot 100\%\\ s&=\frac{\Delta b}{b_0}\cdot 100\%=\left(\frac{b}{b_0}-1\right)\cdot 100\%\end{aligned}\,. \tag{4}$$

Due to the anisotropy of the fabric, the Poisson's ratio is being changed in the process of the extension of the fabric sample.

3 EXPERIMENTAL TESTING

The experimental study was carried out by measuring the extension of woven fabrics samples under the action of the tensile force till rupture [11]. The tensile force acts on the samples that are cut at warp and weft direction. The values of the tensile force in relation to the relative extension were measured. For the extensions and tensile forces which act in the warp and weft direction, the corresponding contraction strains of woven fabrics were scanned. The Poisson's ratio of woven fabrics was calculated by using the testing results. Two different fabrics of a different raw material composition (cotton, wool) and of the same weave (plain weave) were available. The raw material and the structural properties of the tested fabrics are shown in Tab. 1.

Table 1 Structural characteristics of the tested samples

	Warp direction			Weft direction				
Fabric structure	Fiber composition	Yarn count (tex)	Linera density (cm^{-1})	Fiber composition	Yarn count (tex)	Linera density (cm^{-1})	Mass per unit area ($\mathrm{g/m}^2$)	Thickness, *t* (mm)
Plain	Cotton	32	22	Cotton	30	22	150.34	0.318
Plain	Wool	50.6	26	Wool	47	18	234.75	0.568

The yarn count was determined by the gravimetric method according to the standard ISO 2060:1994. The number of threads per unit length was tested according to the standard ISO 7211-2:1984. The standard ISO 5084:1996 describes a method for the determination of the thickness of the fabric. Before testing all samples were conditioned under the conditions of the standard atmosphere (relative air humidity 65 ± 2 %, at a temperature of 20 ± 2 °C). Standard samples with the dimensions of 300 × 50 mm were cut and clamped in clamps of the tensile tester at a distance of l_0=200 mm and subjected to a uniaxial tensile load till rupture. The pulling speed of clamps is 100 mm/min. The samples were cut in the weft direction (φ =0°) and warp direction (φ = 90°). Three tests were done on the tensile tester for each mentioned cutting direction of the sample. The tensile properties of all samples were tested in accordance with the standard ISO ISO13934-1:2008 by using the strip method for measuring the fabric strength on the tensile strength tester Textechno Statimat M. This tensile tester is an automatic, microprocessor-controlled instrument operating on the principle of constant deformation speed, Fig. 2.

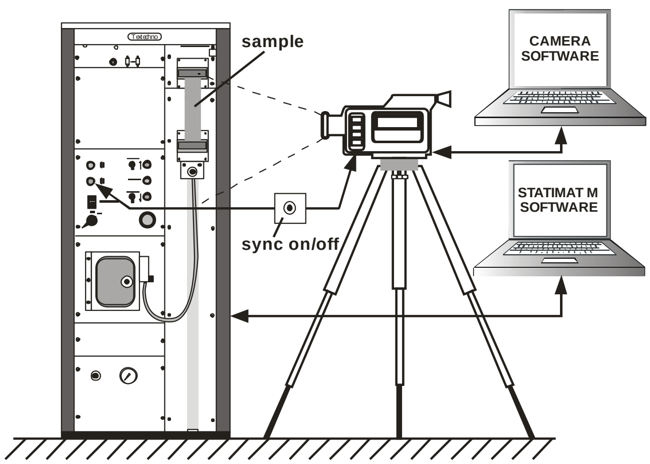


Figure 2 Schematic view of the experiment

For an accurate recording and measurement of the spatial deformation of fabric, a 1x1 grid pattern was mounted on the tensile tester immediately behind the test specimen; the whole process of drawing the specimen till rupture was recorded by the Panasonic NV-GS500 Digital Video Camera placed on a tripod in front of the device. The digital video camera had the resolution of 720 × 576 pixels, and a recording speed of N_{sl}=25 frames/s, and was connected to the computer via an IEEE 1394 (FireWire) interface. The horizontal distance between the camera and the sample was such that 1 mm on the grid amounted to 10 pixels on the picture. Two sources of white light which mutually closed the angle of 90° were used for measuring. The number of images N at a certain extension is:

$$N = \frac{\varepsilon \cdot l_0}{100} \cdot \frac{60}{\mathrm{v}} \cdot N_{\mathrm{sl}} \,. \tag{5}$$

The tensile tester and the camera were connected to a special assembly with a simultaneous on/off which fully ensured the exactness of the video recording of the entire process of stretching the fabric to rupture. The width of each sample was measured in three spots (1/4, 2/4 and 3/4 of the length and width of the sample). The transverse strain was obtained after all samples were recorded by camera, and the mentioned grid pattern enabled a fast and accurate editing of the footage processed by the software package Adobe Premiere created for this purpose which specified the spatial deformation of samples on the basis of shifting in the direction of the x- and y-axis.

3.1 Overview of testing results

The diagrams (F-ε) of mean values of the test results of the action of the tensile force F and the corresponding longitudinal strain (extension) ε for the samples that are cut in the weft and warp direction are shown in Fig. 3.

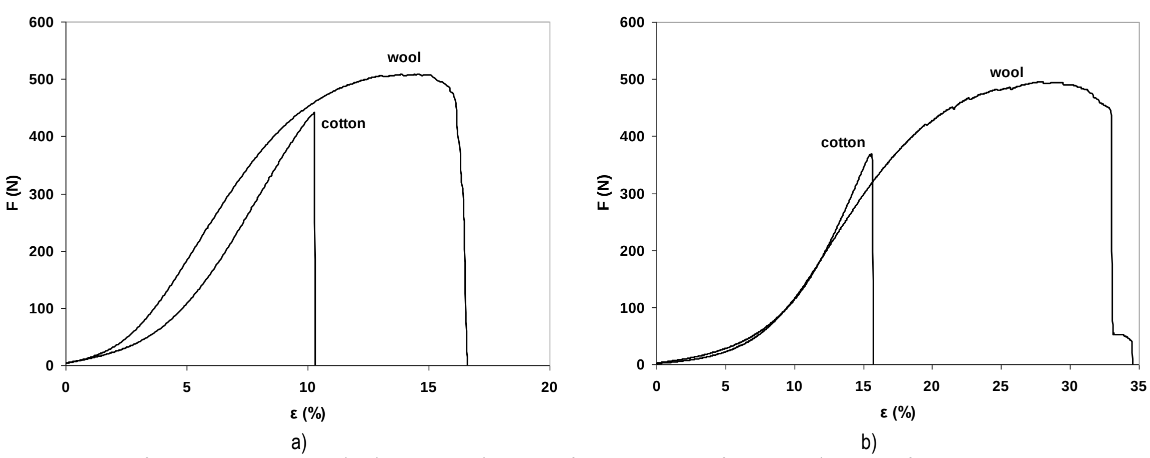
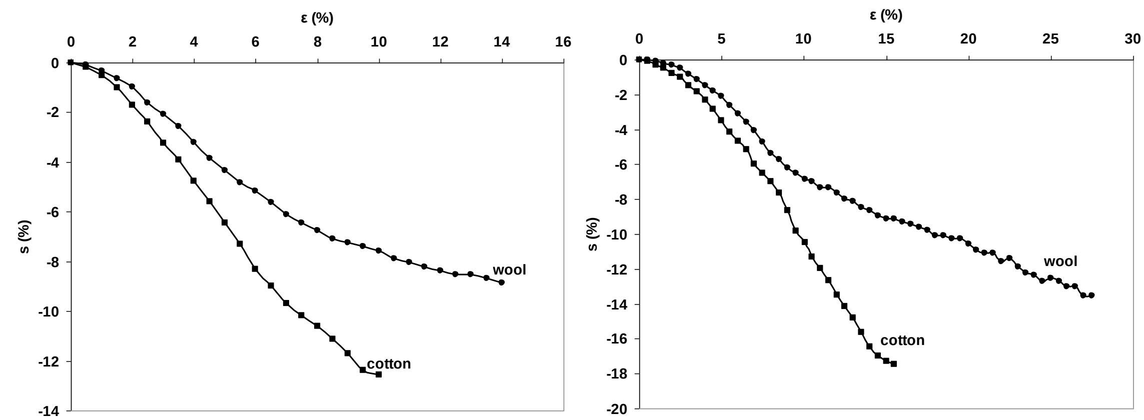


Figure 3 Tensile force-elongation diagram (F-ε) till rupture: a) when the force acts in the weft direction, b) when the force acts in the warp direction

3.2 Determination of Poisson's ratio

The fabric sample width is b_0 = 500 pixels, which is equivalent to b_0 = 50 mm. When reading the value of the fabric width, after the effect of the force, the relative transverse strain is calculated by using the Eq. (4). The contraction of fabric occurs in the transverse direction, i.e. in the direction which is perpendicular to the direction of stretching. Due to this phenomenon, there is a loss of the rectangular shape of the sample, i.e. there is a contraction of the fabric sample. The relation between the continuous change of the relative contraction s (%) of the sample and its relative extension ε (%) when a force acts on the samples that are cut in the weft direction is shown in Fig. 4a by a characteristic curve. Fig. 4b shows a characteristic curve of the relative contraction of the sample in relation to its relative extension when the force acts on samples that are cut in the warp direction. When a force acts on samples that are cut in the weft and warp direction, at the same relative extension ε, cotton fabric has a higher relative contraction s than wool fabric, Fig. 4. When the force acts in the weft direction, at a relative extension ε = 10%, the lateral contraction for the cotton fabric is s = 12.56% and for wool fabric s = 7.57 %. The lateral contraction of cotton fabric is 66% higher than the contraction of wool fabrics for ε = 10%. When force acts in the warp direction, at a relative extension ε = 15.5%, the lateral contraction for cotton fabric is s = 17.47% and for wool fabric s = 9.12%. The lateral contraction of cotton fabric is 92% higher than the contraction of wool fabric for ε = 15.5%. Both fabrics have a bigger extension and contraction when the force acts in the warp direction.

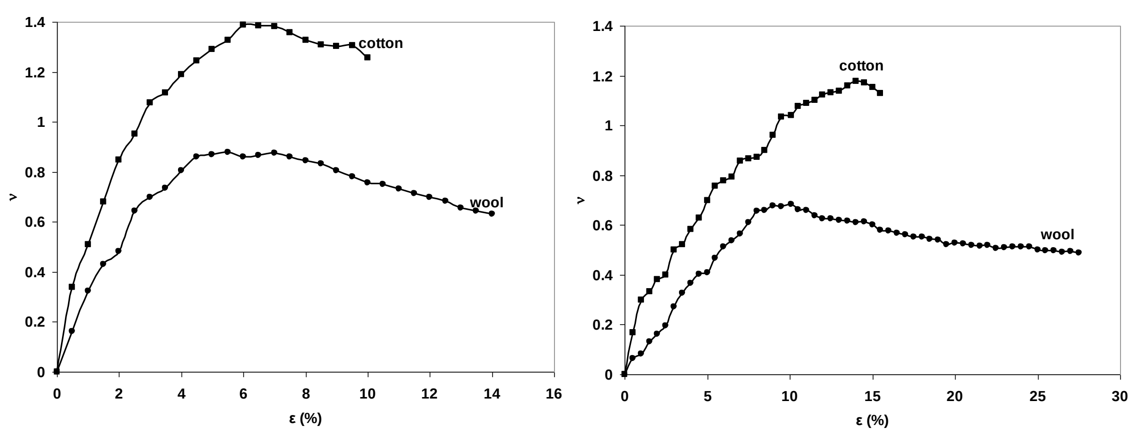


a) b)

Figure 4 Diagram of the relative contraction of the fabric s (%): a) when the force acts in the weft direction, b) when the force acts in the warp direction

From the diagrams in Fig. 4 it is evident that fabric contractions are small at the beginning of stretching. After that, with the increase of stretching, the values of fabric contractions also increase.

According to the Eq. (3) and based on the experimental values of the relative contraction s and relative extension ε from Fig. 4, the values of the Poisson's ratio v are calculated when the force acts on the samples that are cut in the weft and warp direction. Fig. 5a shows a curve of the values of the Poisson's ratio v in relation to its relative extension when the force acts on the samples that are cut in the weft direction and Fig. 5b shows the values in the warp direction.



a) b)

Figure 5 Poisson's ratio v of the fabric: a) when the force acts in the weft direction, b) when the force acts in the warp direction

The shape of the Poisson's ratio curve of the woven fabric is the result of the internal interactions in the fabric. The shape of the Poisson's ratio (Fig. 5) affected by the changes in the value of the relative contraction of the fabric are shown in Fig. 4. The Poisson's ratio curve consists of two zones. The first zone includes the area from the beginning to the highest peak of the curve. When a force acts in the weft direction, the highest value of the Poisson's ratio for the cotton fabric ν = 1.39 is where the relative extension ε is between 6 and 6.5%, and for wool fabric ν = 0.88 is where ε is between 5.5 and 6%, Fig. 5a. When a force acts in the warp direction, the highest value of the Poisson's ratio for the cotton fabric ν = 1.18 is where the relative extension ε is between 14 and 14.5%, and for wool fabric ν = 0.68 is where ε is between 9.5 and 10%, Fig. 5b. Both fabrics have a higher value of the Poisson's ratio when the force acts in the weft direction.

Cotton fabric has a higher value of the Poisson's ratio than wool fabric for each value of the extension. When the force acts in the weft direction, at a relative extension ε = 6 %, the value of the Poisson's ratio for cotton fabric is 62% higher than the Poisson's ratio for wool fabrics. When the force acts in the warp direction, at a relative extension ε = 6 %, the value of Poisson's ratio for cotton fabric is 52% higher than the Poisson's ratio for wool fabrics.

The second zone is from the highest peak of the curve to the end of stretching, i.e. it is interrupted. In this zone, the curve of the Poisson's ratio decreases and it represents the end of the lateral contraction despite the stretching of the fabric sample.

After considering the equation of the Poisson's ratio, the relative contraction becomes a constant when the lateral contraction of the woven fabric is completed. Furthermore, the sample is still stretching for the value ε. Therefore, the equation of the Poisson's ratio takes on a new form, which is the general form of the reciprocal function. Mathematically, the limit of this equation is zero. In practice, due to the break of the sample, this condition never occurs. However, taking into account the significance of the Poisson's ratio that represents the ratio between the transverse and longitudinal deformation of the material, if the transverse deformation does not take place in this ratio, the Poisson's ratio has no practical significance.

The ending of the lateral contraction of a woven fabric can occur for two reasons. Firstly, due to the termination of the flattening crimp of yarn in the direction of the stretching fabric and secondly, because of the structure of the fabric. If there is a possibility of a further contraction of fabric, it can not continue taking place because there is no continued existence of space between the neighboring threads in the fabric, so there can be no contraction of the fabric.

Note: This research was presented at the International Conference MATRIB 2017 (29 June - 2 July 2017, Vela Luka, Croatia).

4 CONCLUSION

Due to the anisotropy of woven fabrics, the Poisson's ratio is not constant, but varies with each fabric extension. The behavior and shape of the Poisson's ratio curve of the coated fabric that is subjected to the tensile force mostly depends on its behavior in a direction perpendicular to the extension. The Poisson's ratio values depend on the number of coatings applied to the raw fabric. The shape of the Poisson's ratio curve for woven fabrics is a result of the internal interactions in the coated and raw fabrics. A change in the values of the relative contraction of coated fabrics affects the shape of the Poisson's ratio curve. When the force acts on samples that are cut in the weft direction, the Poisson's ratio assumes the maximum value at a relative extension of cotton fabrics between 6 and 6.5%, and for wool fabrics between 5 and 5.5%. When the force acts on the samples that are cut in the warp direction, the Poisson's ratio assumes the maximum value at a relative extension of cotton fabrics between 14 and 14.5%, and between 9.5 and 10% for wool fabrics. In the weft and warp direction, the values of the Poisson's ratio of cotton fabrics are higher than the Poisson's ratio of wool fabrics at the same relative extension.

Because of the anisotropy of fabrics, the Poisson's ratio is not constant. It is changing with each elongation of the woven fabric. The behavior and form of the curve of the Poisson's ratio of the woven fabric which is exposed to tensile force, i.e. elongation, mainly depends on the behavior of the fabric in a direction perpendicular to the elongation. First, the Poisson's ratio increases nonlinearly and after having reached the peak value, it decreases. These two zones represent two different processes in the deformation of the fabric. The first zone represents the way of the lateral contraction because of the longitudinal stretching. The second zone shows the termination of the lateral contraction of the woven fabric and the fabric is stretching without any further contractions.

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