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The Impact of Fabric Weave and Anisotropy on the Poisson's Ratio in Technical Fabrics

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Abstract: Poisson's ratio changes during the tensile stress of technical fabric samples due to the anisotropy of technical fabrics. This paper examines the effects of the type of weave and the anisotropic characteristics of the technical fabric on maximum tensile force, corresponding elongation, work-to-maximum force, elasticity modulus, and Poisson's ratio when axial tensile forces are applied to samples cut at various angles in the direction of the weft yarns of the technical fabric. In the lab, 3 cotton fabric samples of constant warp and weft density with different structural weave types (plain weave, twill weave, atlas weave) were subjected to the tensile force until they broke at the following angles: 0°, 15°, 30°, 45°, 60°, 75°, 90°. Based on the different measured values of technical fabric stretching in the longitudinal direction and lateral narrowing, Poisson's ratio is calculated. The Poisson's ratio was calculated up to a relative elongation of the fabric of 8%, as the buckling of the fabric occurs according to this elongation value. According to the results presented in this paper, the type of weave of the fabric, the direction of tensile force, and the relative narrowing of the technical fabrics all play important roles in the Poisson's ratio value. The Poisson's ratio curve of a technical fabric under tensile stress (i.e. elongation) is primarily determined by its behaviour in the opposite direction of the elongation. The change in the value of the Poisson's ratio is represented by a graph that first increases nonlinearly and then decreases after reaching its maximum value.

Key words: Warp, weft, technical fabric, weave type, Poisson's ratio, tensile force.

1. Introduction

Woven fabrics (technical fabrics, nonwovens) are inhomogeneous, anisotropic and discontinuous products. In today's world, new technologies are being developed in various sectors to create new products that are then used to create quality textiles. Chemical fibres, which have amazing mechanical properties, were first commercially available in the middle of the 20th century. Fabrics are manufactured using the most up-to-date manufacturing techniques, which are also applicable to the construction industry. The durability of fabrics is enhanced by the addition of various polymers to them. They are able to withstand extreme environmental conditions such as sunlight, temperature variations, biological effects, wind and rain and snow. They are also better able to withstand high levels of water, are stronger and better able to withstand extreme temperatures, are slower to age and are easier to care for [1, 2]. High-rise building planners can benefit from technological textiles due to the rapid development of technology, multi-disciplinary research, and industrial-scientific partnerships [3, 4]. Technical textiles offer superior physical characteristics and resistance to a wide range of environmental factors, while also adhering to stringent environmental regulations. Unfortunately, there is an insufficient amount of testing of experimental buildings to demonstrate the practicality of technical textiles. Appropriate standards are needed to demonstrate the suitability of materials for specific building types.

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The anisotropy of fabrics has a significant influence on their physical and mechanical properties and determines the extent of their final application. Therefore, it is important to better understand the parameters that influence the behavior of these materials [5, 6].

Fabric mechanical characteristics under tension stress have been researched since 1937 [7]. Kilby [8] starts from the standard elasticity theory and supposes that the fabric is orthotropic, i.e., anisotropic, because it has two planes of symmetry. He examined the relationship between stress and strain in the plane using a basic mesh model for fabrics. He determined the Poisson ratio and examined the tensile properties of the fabric in all directions of the tensile force. He found that there is a correlation between Poisson's ratio, shear modulus, and elastic modulus of the fabric. Poisson's ratio has been extensively discussed in the literature [9-11] in relation to the specific mechanical properties of fabrics, including drape and shear.

The researchers determined the Poisson's ratio in warp and weft direction based on the geometric model of the fabric. In this way, they concluded that Poisson's ratio in fabrics arises from the interaction of warp and weft threads and can be expressed by the structural and mechanical parameters of the system [12]. This is due to the anisotropic nature of the fabric, and the analysis of the effect of the physical parameters on the Poisson's ratio can be helpful in elucidating certain behaviour of the fabrics. Due to the characteristics of textiles, the accuracy and reliability of the measurement of Poisson's ratio is challenging. Many scientists have researched this technical property.

In their study, Bao et al. [13, 14] looked at the reasons why measurement errors occur in Poisson's ratio measurements when applying a uniform tensile force to the fabric. The theoretical findings were cross-referenced with experimental data previously collected. Measuring Poisson's ratio of fabrics is challenging due to a lack of reliable experimental methods [15, 16].

Giroud [17] investigated the Poisson ratio of textile materials used in geotextile nonwovens. In the context of this study, he developed theoretical equations for the calculation of the Poisson's ratio as a product of deformation. Hearle et al. [18, 19] proposed a method to determine Poisson's ratio under uniaxial tensile load. They calculated the Poisson's ratio of bonded nonwovens and discovered that the degree of lateral contraction is minimal for low elongations but rises between 5% and 10% elongation.

The aim of this paper is to investigate the effect of weave type and anisotropy on the Poisson's ratio, maximum force and corresponding elongation, modulus of elasticity, and work done up to maximum force when the fabric is stretched to break under the action of a uniaxial tensile load. Tests will be performed to stretch the fabric sample under static loading when the force acts in different directions relative to the weft of the fabric sample. The Poisson's ratio is displayed until the length of the fabric reaches the point where it no longer buckles.

2. Poisson's Ratio of Technical Fabrics

The study of the mechanical properties of fabrics is a fundamental field of research in textile science [20]. The study of mechanical properties of fabrics is conducted primarily in the domain of elasticity, i.e. under low load conditions [21-23]. The measurement system should be operated in such a way that it does not affect the test specimen. Therefore, optical methods, such as measurements by the processing of recorded video data, are currently employed [24]. Poisson's ratio is a fundamental mechanical property of materials. It affects the behavior of the material and contributes to the understanding of textile behaviour in practice and is important to consider when developing computer models of fabrics and clothing. Warp and weft are involved in the formation of Poisson's ratio, which may be reflected in the structural and mechanical systems characteristics of fabrics [25].

In order to find the Poisson's ratio on fabrics, various devices are used to measure the breaking force. When the fabric is tested for elongation, the initial length of the tested sample l_0 is increased by Δl, giving the final length of the fabric sample l, and the initial width of the fabric sample b_0 is decreased by Δb, giving the final width of sample b:

- absolute longitudinal deformation (absolute elongation):

$$\Delta l = l - l_0 \tag{1}$$

- absolute transverse deformation (absolute narrowing):

$$\Delta b = b - b_0 \tag{2}$$

The transverse deformation is negative during stretching (the fabric narrows), hence the longitudinal deformation Δl and the transverse deformation Δb always have the opposite sign. The definition of relative longitudinal deformation is as follows:

$$\varepsilon = \frac{\Delta l}{l_0} \cdot 100\% = \left(\frac{l}{l_0} - 1 \right) \cdot 100\% \tag{3}$$

and the relative transverse deformation (relative narrowing) is defined by:

$$s = \frac{\Delta b}{b_0} \cdot 100\% = \left(\frac{b}{b_0} - 1 \right) \cdot 100\% \tag{4}$$

Experiments have shown that there is a relationship between the relative transverse deformation (perpendicular to the force direction) and the relative longitudinal deformation (axial) under the influence of a uniaxial force, the absolute value of which is called Poisson's ratio v. Its physical meaning is shown in Eq. (5).

$$v = \left| \frac{s}{\varepsilon} \right| = \left| \frac{l_0}{b_0} \cdot \frac{b - b_0}{l - l_0} \right| \quad , \quad s = -v \cdot \varepsilon \tag{5}$$

Poisson's ratio ranges from 0 to 0.5 for isotropic, homogenous materials. These values are different from the conventional technical material values and fall outside of the range defined for fabrics [26].

The Poisson's ratio is affected by the stretching of the sample due to the anisotropic nature of the fabrics. Fig. 1 shows a graph illustrating the Poisson's ratio of the characteristic curve for fabrics [1].

Fig. 1 Graph of the Poisson's ratio of a fabric.

The shape of the curve is determined by the internal structure of the fabric and the displayed curve is split into two regions. Each region represents the result of two different physical processes taking place within the fabric. The first region is the area from the beginning of the curve to the highest peak (maximum value). The second region extends from the top of the curve to the end.

3. Experimental Part

In the experimental phase of this paper, technical fabric samples were stretched until they broke under static loads. The highest tensile forces and related elongations (extensions) were determined in this test, as well as data on breaking forces, breaking elongations, and work at maximum force. In addition to the elongation, the corresponding transverse narrowing of the fabric was also read. Traditional methods and tools for evaluating the tensile characteristics of fabrics were used for this purpose. The Poisson ratio was calculated as a function of the direction of the tensile force on the samples of the technical fabrics. The samples were cut in the weft direction (φ = 0°), in the warp direction (φ = 90°), and at angles of 15°, 30°, 45°, 60°, 75°. The purpose of this experiment is to evaluate the effect of the weave type and the tensile force direction on the Poisson's ratio for technical fabrics.

3.1 Test Samples

As indicated in Table 1, samples of three cotton fabrics with constant warp density and constant weft density were woven in three different weave types for the test: plain weave, twill weave, and satin weave.

Table 1 Parameters of test fabrics.

Weave type	Density (yarns/cm)		Yarn count (tex)		Take-up (%)		Mass per unit area	Fabric thickness
	warp g_o	weft g_p	warp Tt_o	weft Tt_p	warp U_o	weft U_p	m (g/m^2)	d (mm)
Plain weave	24	24	32.52	29.35	3.85	3.29	149.94	0.48
Twill weave	24	24	31.75	30.77	2.72	2.68	154.77	0.54
Satin weave	24	24	30.48	30.44	2.34	2.54	144.44	0.71

The yarn count of the woven fabric will be determined by the gravimetric method according to ISO 2060:1994. The density of the woven fabric was tested according to ISO 7211-2:1984. Determination of fabric thickness is defined by ISO 5084:1996. Determination of the density of warp and weft yarns were performed using a computer-controlled (stereo) microscope DinoLite. A yarn strength tester was used to determine the crimp of warp and weft yarns in the fabric according to ASTM D 3883. Each yarn system is measured five times.

Using the mean values of the measurement results of tensile force F and associated elongation ε for the warp and weft yarns, the take-up u_i in the initial state for the warp yarns and the weft yarns was calculated. The mass per unit area of the fabric was measured according to ISO 7211-5:2021.

3.2 Method for Measuring Elongation and Lateral Narrowing of Fabric until Breaking

To determine the tensile characteristics of the material, standard samples (350 × 50 mm) were cut, fixed in the device clamps at a distance l_0 = 200 mm, and subjected to a uniform tensile load. The clamps of the strength tester travel at a constant velocity v = 100 mm/min until the sample is broken. The fabric samples were cut in seven different directions: in the weft direction (φ = 0°), in the warp direction (φ = 90°) and at angles of 15°, 30°, 45°, 60°, 75° to the weft (Fig. 2). The tensile force is always in the same direction during the experiment. For each direction of the tensile force specified on the materials, five tests were conducted. The tensile strength qualities of all samples were examined using the test strip method on a textile strength measurement instrument in accordance with the ISO 13934-1:2013 standard. The strength tester used for testing was Textechno, which records data in graphical form.

The Statimat M tensile strength tester, as previously indicated, is a fully automated, microprocessor-controlled static strength tester that operates on the concept of constant rate of deformation. For a variety of cutting angles in the sample, the correlation of the tensile forces with the elongation at break was calculated experimentally. The tests were carried out in a controlled environment with a temperature of 20 ± 2 ℃ and a relative humidity of 65% ± 2%. Before testing, the yarn was kept for 24 h under normal circumstances to create a balanced humidity.

For the purpose of accurately recording and measuring the spatial deformations of the fabric applied to the device for the purpose of the breaking strength testing (tensile strength tester), a template was affixed to the material with a 1 × 1 mm grid on paper at the location of the sample being tested. The entire stretching process of the sample until the breaking

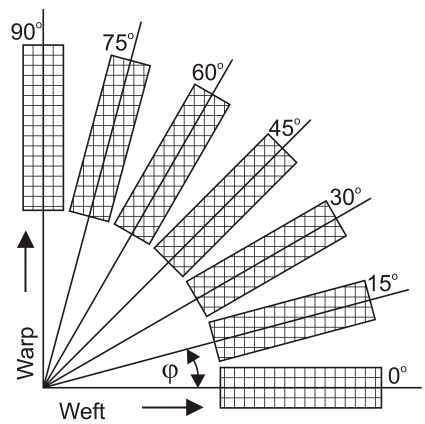

Fig. 2 Schematic representation of cutting directions (angles) of samples.

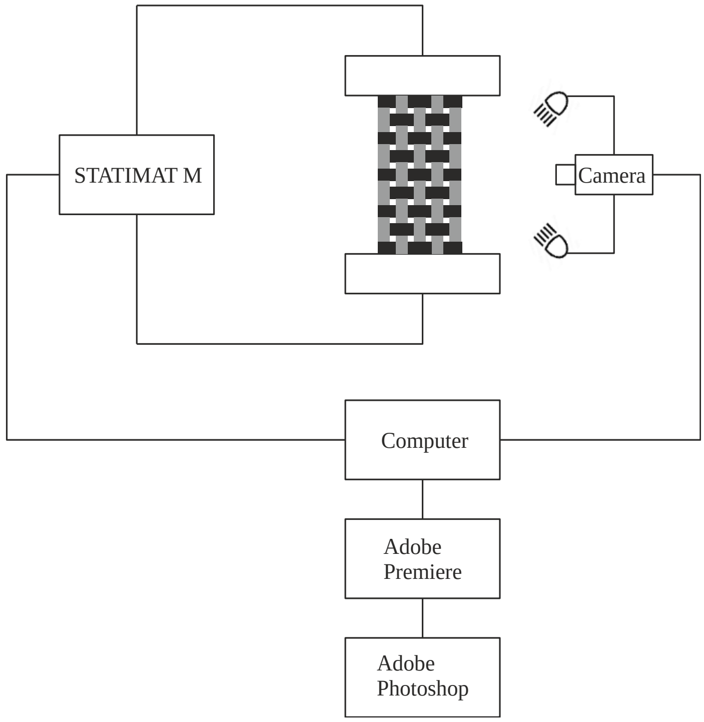

Fig. 3 Schematic representation of the determination of the longitudinal and transverse deformation of the fabric up to the breaking point.

point was documented with the help of the digital video camera (Sony HDR-CX240E) mounted on a tripod facing the device, as depicted in Fig. 3. A digital video camera with a resolution of 1,920 × 1,080 pixels and a recording rate of N_{sl} = 25 frames/s was used, which was connected to a computer via a High-Definition Multimedia Interface (HDMI) interface. The horizontal distance between the camera and the fabric sample is chosen so that 1 mm on the grid corresponds to 10 pixels on the image. For the measurement, two white light sources were placed at an angle of 90° to one another. Eq. (6) represents the number of images N at a particular stretching:

$$N = \frac{\varepsilon \cdot l_0}{100} \cdot \frac{60}{\mathrm{v}} \cdot N_{sl} \tag{6}$$

All recordings are stored on the hard drive of the computer in the format MPEG-4. The width of each sample was measured at three points (1/4, 2/4 and 3/4 of the length and width of the sample) to ensure the greatest possible accuracy of the measured transverse and longitudinal deformations. A separate circuit links the strength tester to the camera, allowing it to turn on and off simultaneously, ensuring complete coverage of the entire fabric stretching process until it breaks.

The transverse deformation was measured after all samples had been recorded with a camera and the above-mentioned grid template enabled quick and accurate video editing with the programme Adobe Premiere. Each raster image was processed in Adobe Photoshop (Fig. 3). The dimensions of the fabric were measured in pixels, and the change in dimensions was determined using the Microsoft Excel program.

4. Test Results and Discussion

The Microsoft Excel software was used for statistical analysis of data at $p < 0.05$ for five measurements. When applying a tensile force F, the resulting elongation ε is determined. The average values of the measured tensile force F, as well as the resulting elongation ε, are presented in the F-ε diagrams, which are illustrated in Fig. 4 (for plain weave), Fig. 5 (for twill weave) and Fig. 6 (for satin weave) for fabric samples that have been cut at the following angles: 0°, 15°, 30°, 45°, 60°, 75° and 90° towards the weft direction.

Tensile force values in the elastic linear region are used which are presented in the graphs in Figs. 4-6. The initial modulus of elasticity E is derived from the first linear region of the stress-strain curve (F-ε), which is observed from the regression control chart (i.e., the regression line) of the experimental data [27]. There is a linear relationship of force, that is, stress and strain, in that region. The slope of the stress-strain curve in the linear region of elastic deformations where Hooke's law is valid for the uniaxial state of stress is defined as the initial modulus of elasticity E:

$$E = tg\alpha = \frac{\sigma}{\varepsilon} = \frac{F}{\varepsilon \cdot b \cdot d}\left[Pa\right] \quad (7)$$

where b represents sample width (mm).

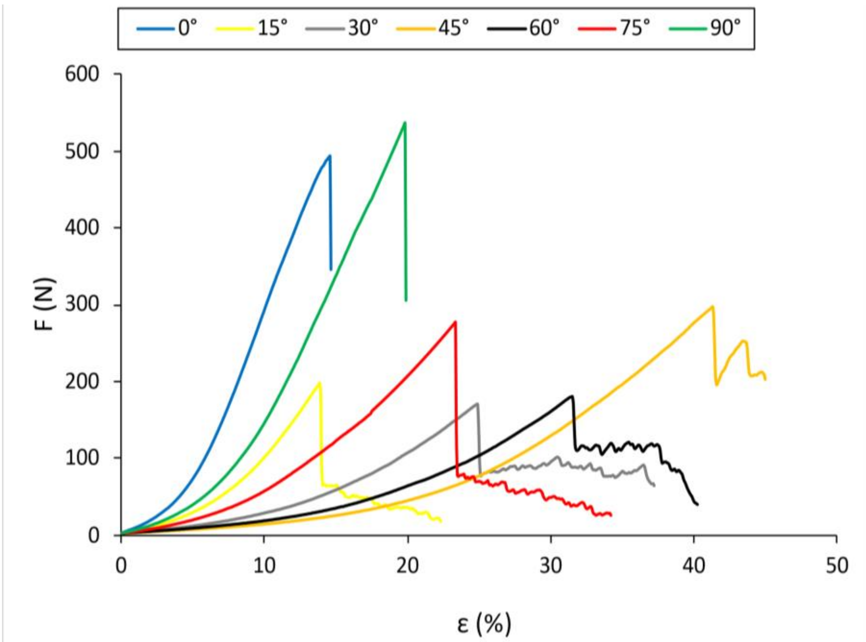

Fig. 4 Stress-strain curve (F-ε) for plain weave fabric.

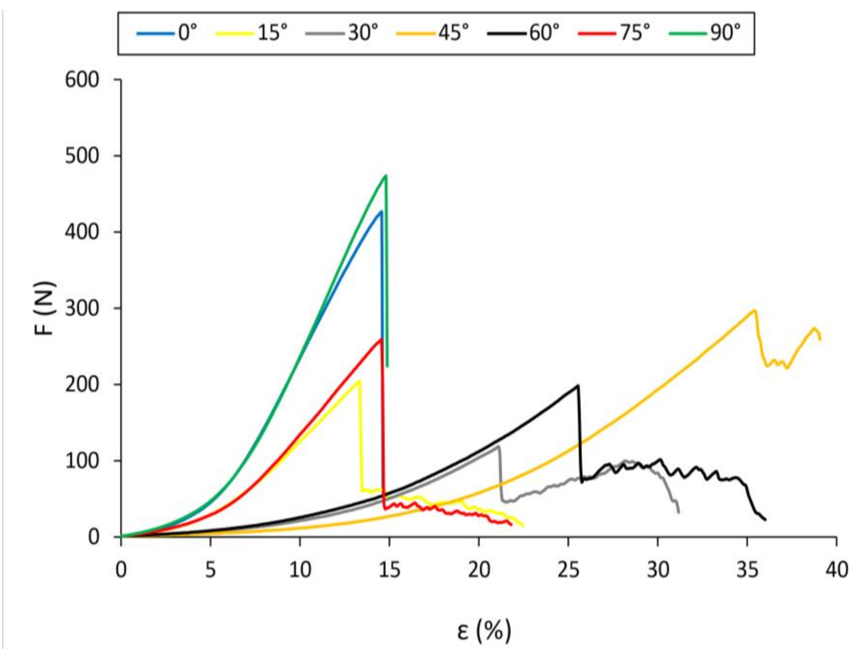

Fig. 5 Stress-strain curve (F-ε) for twill fabric.

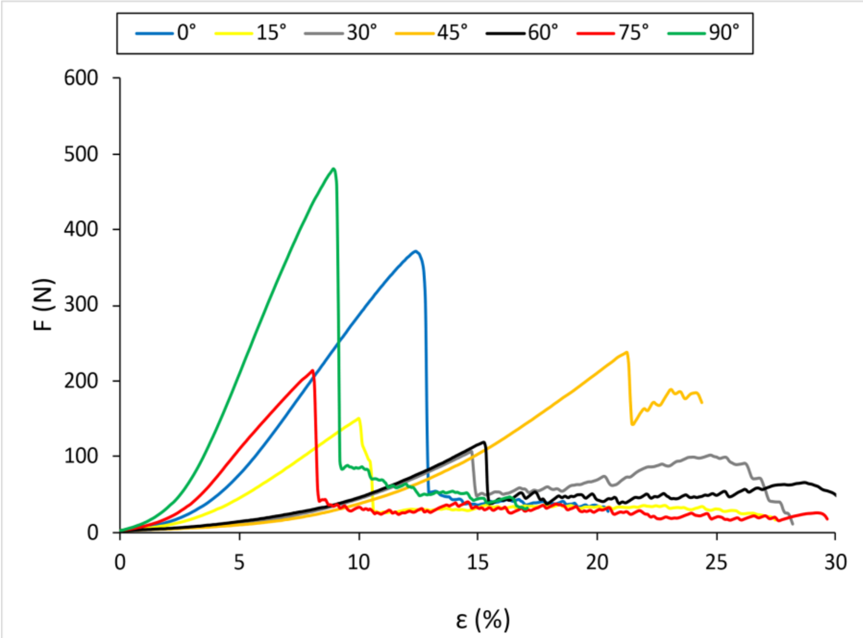

Fig. 6 Stress-strain curve (*F*-*ε*) for satin weave fabric.

Table 2 Average values of the maximum force F_{max}, maximum elongation ε_{max}, work done at the maximum force W_{max} and initial modulus (*E*) of elasticity *E* of plain weave fabrics.

Angle (°)	0 °	15 °	30 °	45 °	60 °	75 °	90 °
ε_{max} (%)	14.60	13.87	24.87	41.27	31.47	23.33	19.87
F_{max} (N)	494.5	198.2	170.8	296.8	181.0	277.4	535.8
W_{max} (N mm)	3,439	1,557	1,702	4,191	2,150	1,704	3,214
E (N/mm^2)	251.0	131.1	51.4	26.2	40.1	77.9	152.2

Table 3 Average values of the maximum force F_{max}, maximum elongation ε_{max}, work done at the maximum force W_{max} and initial modulus (*E*) of elasticity *E* of twill weave fabrics.

Angle (°)	0 °	15 °	30 °	45 °	60 °	75 °	90 °
ε_{max} (%)	14.53	13.33	21.07	35.33	25.53	14.53	14.80
F_{max} (N)	426.3	204.3	120.0	296.8	197.8	260.3	474.6
W_{max} (N mm)	2,726	1,176	1,232	3,431	1,897	1,614	2,979
E (N/mm^2)	127.0	84.0	30.9	17.3	35.1	74.9	133.2

Table 4 Average values of the maximum force F_{max}, maximum elongation ε_{max}, work done at the maximum force W_{max} and initial modulus (*E*) of elasticity *E* of satin weave fabrics.

Angle (°)	0 °	15 °	30 °	45 °	60 °	75 °	90 °
ε_{max} (%)	12.40	10.00	14.73	21.27	15.20	8.07	8.93
F_{max} (N)	371.7	150.1	106.4	237.1	118.8	213.9	481.1
W_{max} (N mm)	2,190	681	1,074	1,817	700	834	2,107
E (N/mm^2)	69.0	45.9	21.6	15.1	23.8	67.0	127.8

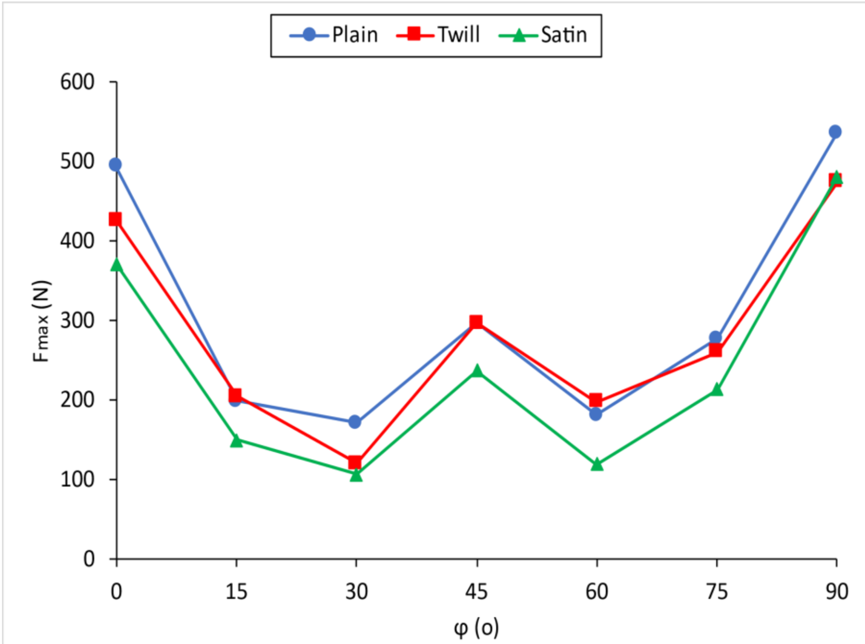

Fig. 7 Dependency of the value of maximum force F_{max} on the weave type and angle of cutting the samples.

Using the values F and ε in the elastic region and Eq. (7), the average value of the initial modulus of elasticity E is calculated with respect to any cutting direction of the fabric sample. The modulus E of elasticity is expressed as the slope of a curve, the slope of which is the direction of a straight line.

For all cutting directions of fabric samples, the corresponding mean values of maximum force F_{max}, maximum elongation ε_{max},, work done at maximum force W_{max}, and initial modulus of elasticity E are presented in Table 2 for plain weave fabrics, Table 3 for twill weave fabrics, and Table 4 for satin weave fabrics.

Fig. 7 depicts the relationship between the value of the maximum force F_{max} and the weave type and on the angle of cutting the samples with regard to the direction of the weft for all examined samples.

Plain weave fabrics give maximum force values regardless of the cutting angle of the samples. Satin weave fabrics give the lowest maximum force values. The warp and weft yarns cross at all crossing points in plain weave, and the fabric structure can withstand more significant tensile forces. Satin weave has the fewest warp crossing points per weave repeat, whereas plain weave has the most warp crossing points per weave repeat. This results in plain weave fabric having the highest tensile strength.

When the force acts in the direction of the warp (φ = 90°), the maximum fabric force has the highest values, and somewhat lower values when the force acts in the direction of the weft (φ = 0°). This is due to the fact that warp yarns tend to stretch more than weft yarns in the course of weaving. The maximum fabric force measured when the samples are cut in the warp direction is 1.08 times greater than the maximum fabric force measured when the samples are cut in the weft direction for the plain weave fabric. In twill weave fabrics, the maximum force in the warp direction is 1.11 times higher than in the weft direction.

The maximum force of a satin weave fabric in the warp direction is 1.29 times higher than the maximum force in the weft direction. Fig. 7 shows that when the force is diagonally applied, the diagram of the maximum force is roughly symmetric around the angle of φ = 45°. This is because all the fabrics tested are the same in terms of warp and weave density. The graphic is shaped like the letter "W". The maximum forces for the tested samples cut in different directions in reference to the weft and warp are lower as the number of yarns held simultaneously in both clamps of the strength tester decreases. The maximum fabric force values gradually decrease from the weft direction (φ = 0°), have the lowest value when the force acts at an angle of φ = 30°, gradually increase to an angle of φ = 45° and gradually decrease to an angle of φ = 60°, after which the maximum fabric force values gradually increase and have the highest value when the force acts in the warp direction of φ = 90°. With an angle of 45° the breaking force increases compared to the angles 15°, 30°, 60° and 75°, because the direction of the force does not match the direction of the yarn and therefore a greater force is necessary. For plain weave fabrics, the maximum force exerted in the warp direction is calculated to be 3.14 times greater than the minimum force exerted at the maximum angle φ = 30°. The greatest force acting on the warp direction in satin weave fabric is 4.52 times greater than the least force. The results of the measurement of the maximum tensile forces show that the anisotropic properties of the fabric have a significant influence on the observed values. The maximum force is determined by the cutting angle (direction) of the samples. Fig. 8 shows the relationship between the maximum elongation of the fabric ε_{max} and the type of weave, and the angle of cutting the samples in relation to the direction of weft for all tested samples.

Plain weave fabrics provide the highest maximum elongation values regardless of the angle of cutting the sample. The maximum elongation value of satin weave fabrics is the lowest value. The maximum elongation values for all types of weaves decrease from φ = 0° to 15° where they have the lowest values, and then after this angle the values of the maximum elongation quickly increase to the maximum value at 45°. As the angle φ increases, the maximum elongation values drop towards the warp direction (φ = 90°) where they achieve a slightly greater value than in the weft direction (0°). The maximum elongation values for complimentary angles (15°, 75°) are lower than those for complementary angles (30°, 60°) due to the fact that the direction of the action of force and clamped threads are virtually parallel, resulting in threads that are drawn out almost parallel to each other.

The highest values of the maximum elongation of the fabric when the force acts in the diagonal direction φ = 45° are 2.08 times higher than in the direction of the warp φ = 90° for plain weave fabrics. For twill

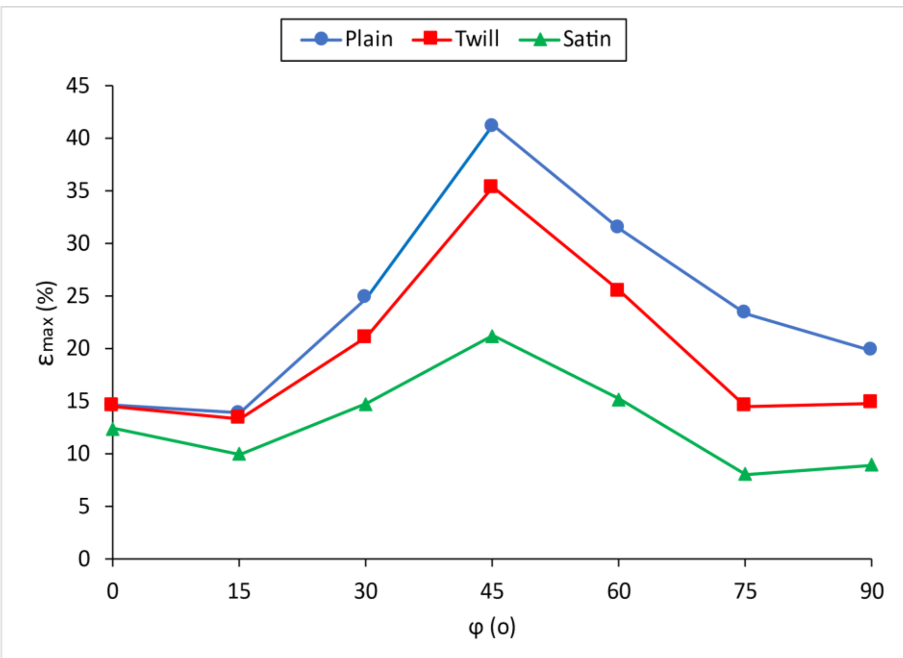

Fig. 8 Dependency graph of the maximum elongation ε_{max} on the weave type and the cutting angle of the samples.

weave fabrics, the highest values of the maximum elongation of the fabric when the force acts at an angle of φ = 45° are 2.39 times higher in relation to the direction of the warp φ = 90°, and for the satin weave, the value of the maximum elongation at φ = 45° is 2.38 times higher in relation to the angle φ = 90°. Fig. 9 depicts the dependency graph of the maximum work W_{max} of the fabric on the cutting angle of the samples.

W_{max} was determined by calculating the maximum work required to capture the properties of the fabric in the upper deformation region. Plain weave fabrics have the greatest maximum work values, regardless of the cutting angle of the sample. Satin weave fabrics tend to have the least amount of work done. For the fabric samples the values of the maximum work required to elongate the samples gradually decrease from the weft direction (φ = 0°), they have the lowest value when the samples are cut at an angle of φ = 15°, then gradually increase up to an angle of φ = 45°, where the maximum work has the highest value, and then decrease again up to the angle φ = 75°, after which the values of the maximum work increase up to the warp direction φ = 90°. The highest value of maximum work when the fabric samples are cut at an angle of 45° is 1.22 times higher compared to the weft direction φ = 0° and 1.3 times higher compared to the warp direction φ = 90° for plain weave fabrics. When cutting the fabric sample at an angle of 45°, the peak value of the maximum work is 1.26 times higher compared to the weft direction φ = 0° and 1.15 times higher compared to the warp direction φ = 90° for the twill fabric. Most of the work should be done on the elongation of fabric samples cut at an angle of φ = 45°. As a result, regardless of weave type, the cutting direction of fabric samples has a considerable impact on their tensile strength and the value of the work done. Fig. 10 illustrates a dependency graph for the initial modulus E of the fabric based on the cutting angles of the samples.

Plain weave fabrics have the greatest initial modulus of elasticity values, regardless of the angle of cutting the sample, while satin weave fabrics have the lowest values. When the samples are cut in the direction of the weft (φ = 0°), the modulus of elasticity of the plain weave is 9.58 times greater than the least value of the

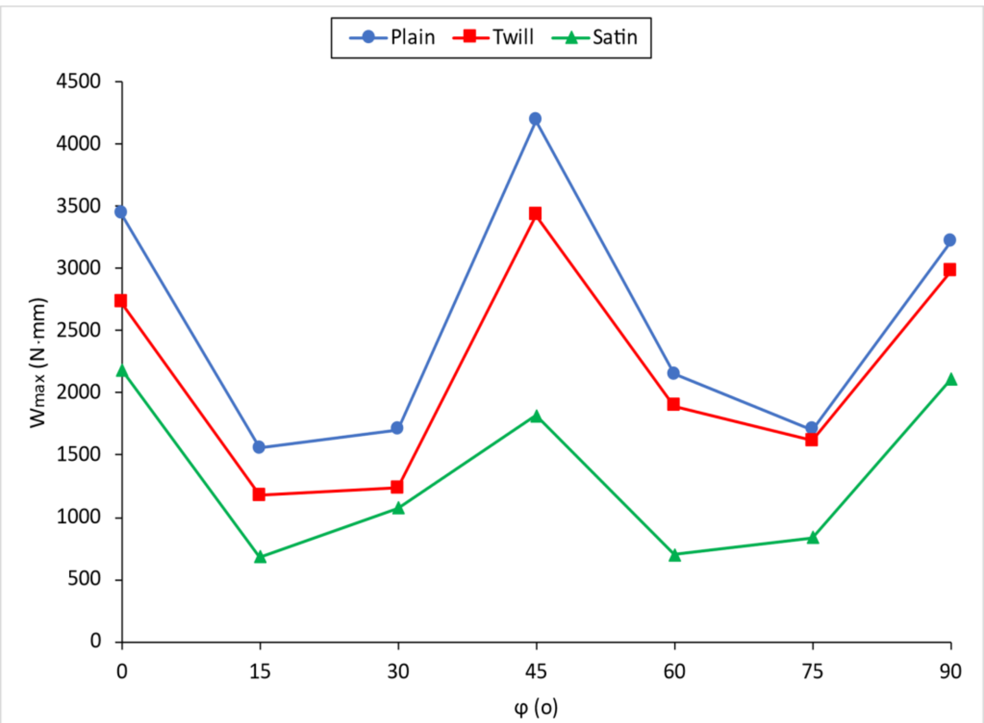

Fig. 9 Dependency of the quantity of the maximum work W_{max} on the weave type and the cutting angle of samples.

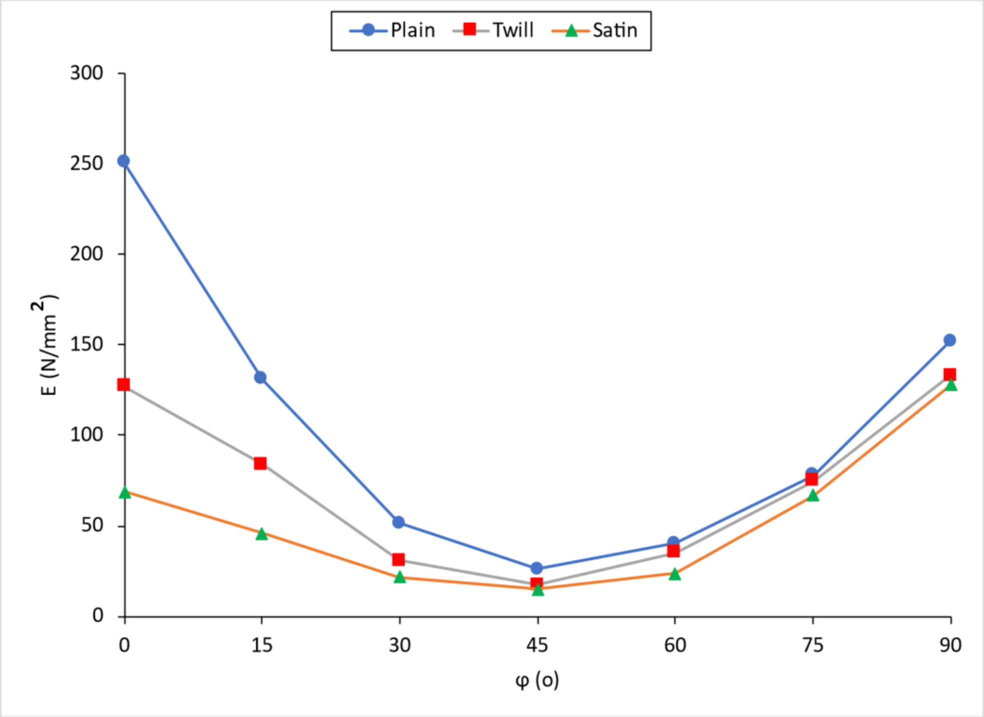

Fig. 10 Dependency of the value of the initial modulus of elasticity *E* on the weave type and cutting angle of the samples.

modulus of elasticity at an angle of 45°. The modulus of elasticity of twill and satin weave fabrics is greatest when the samples are cut in the direction of the warp (φ = 90°). As the angle φ increases, the elasticity modulus decreases rapidly. The lowest E value is obtained when the samples are cut at an angle of φ = 45° angle, taking into account the direction of weft. When the angle increases further, the elastic modulus values rapidly rise until the angle in the direction of the warp is φ = 90°.

When fabric is tested for tensile strength, the lateral narrowing of the fabric is measured to get the Poisson's ratio. Buckling occurred in the tested samples when subjected to a tensile force at a relative elongation of ε = 8%. This value represents the limit of in-plane extension, after which the sample will start to deform outside the plane. The presence of buckling leads to inaccuracies in the measurement data. As a result, Figs. 11-16 depict the sample narrowing and Poisson's ratio curves up to the value of relative elongation ε = 8% (till the start of buckling of woven fabric samples during elongation).

Fabric samples have a width of b_0 = 500 pixels, which is comparable to b_0 = 50 mm. The relative narrowing of the fabric sample (Eq. (4)) can be determined by reading the width of the sample b after the action of force. When force is applied to the weft, the take-up of the weft thread gradually decreases. Straightening the weft yarns in weaving increases the pressure of the warp yarns. This pressure causes further warp yarn deformations and supports the simultaneous and continuous interchange of weft and warp yarns, resulting in stronger warp yarn take-up. Evidence of this internal interaction is the narrowing of the fabric in the transverse direction, i.e. in the direction perpendicular to the direction of elongation. As a result of this phenomenon, the rectangular shape of the sample is lost, i.e. the fabric sample becomes narrower.

The graphs depict the characteristic curves of the continuous change of the relative narrowing s (%) of fabric samples in relation to its relative elongation ε (%) at various angles of the action of force in relation to the weft: for plain weave fabrics (Fig. 11), twill weave fabrics (Fig. 12), and satin weave fabrics (Fig. 13).

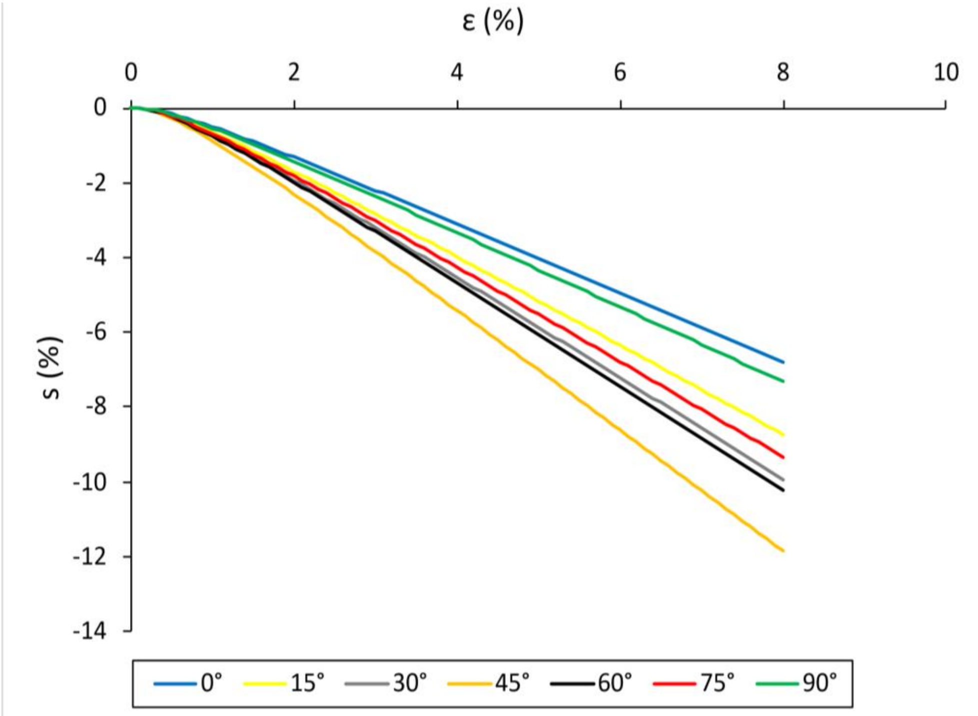

Fig. 11 Graph of the relative narrowing of the plain weave fabric *s* (%) at various angles of the action of force in reference to the weft yarn.

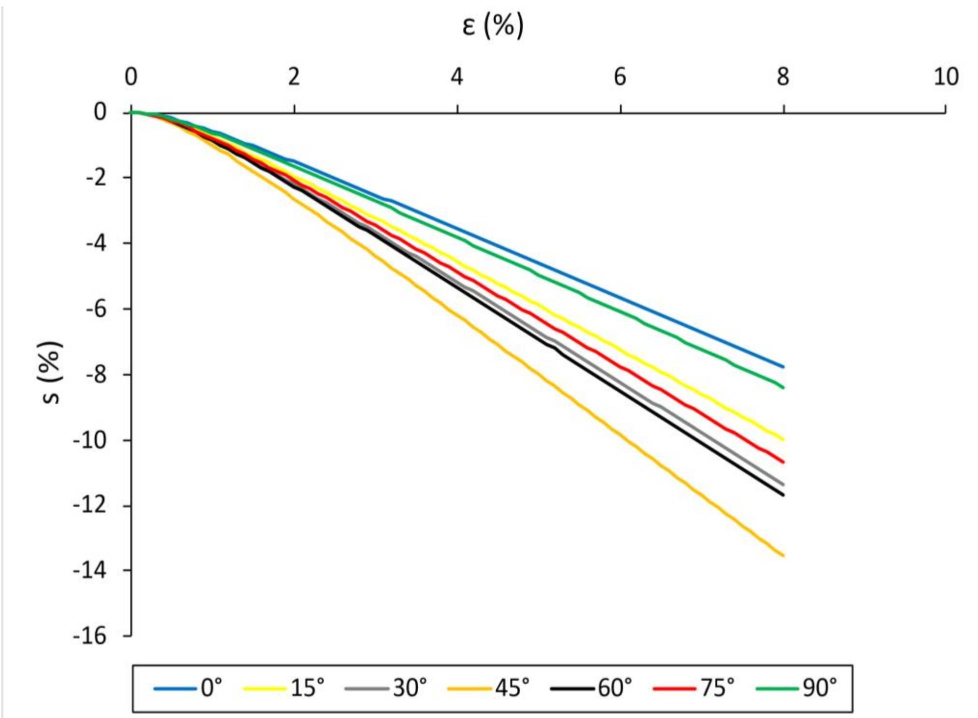

Fig. 12 Graph of the relative narrowing of the twill weave fabric *s* (%) at various angles of the action of force in reference to the weft yarn.

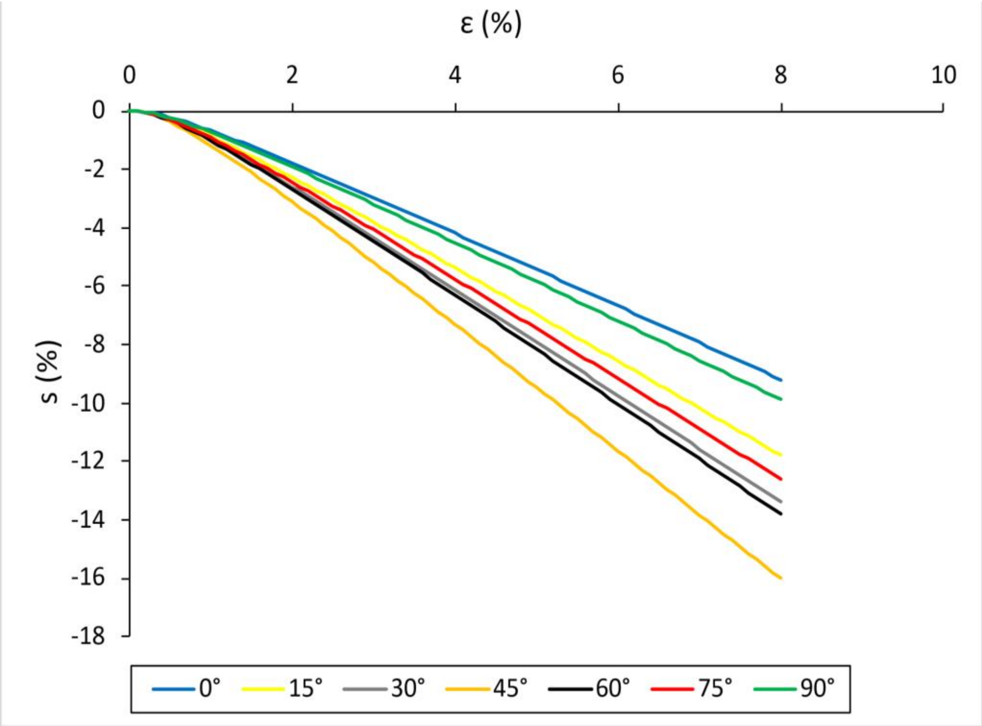

Fig. 13 Graph of the relative narrowing of the satin weave fabric *s* (%) at various angles of the action of force in reference to the weft yarn.

Table 5 Values of relative fabric narrowing *s*, and Poisson's ratio *v* for all weave types and for all cutting directions of fabric samples at *ε* = 8%.

Angle (°)	Plain weave		Twill weave		Satin weave	
	s (%)	*v*	*s* (%)	*v*	*s* (%)	*v*
0 °	-6.80	0.85	-7.77	0.97	-9.20	1.15
15 °	-8.74	1.09	-9.97	1.25	-11.79	1.47
30 °	-9.92	1.24	-11.34	1.42	-13.41	1.68
45 °	-11.86	1.48	-13.55	1.69	-16.02	2.00
60 °	-10.22	1.28	-11.69	1.46	-13.82	1.73
75 °	-9.34	1.17	-10.67	1.33	-12.61	1.58
90 °	-7.33	0.92	-8.39	1.05	-9.89	1.24

Table 5 lists the relative narrowing values of fabric *s* for all weave types and all cutting directions for the fabric samples.

The lowest values of narrowing the fabric samples are when the force operates in the direction of the warp and weft for all three weave types at the same relative elongation. The narrowing values at the complementary angles (15 ° and 75 °) and (30 ° and 60 °) are approximately equal and increase as the angle of the weft increases. Fabric samples cut at an angle of 45 ° angle have the greatest lateral narrowing. The graphs in Figs. 11-13 indicate that the fabric narrows very little at the start of the elongation. Following that, when elongation increases, the narrowing values of the fabric also increase. When the direction of the action of force changes in relation to the weft, the value of Poisson's ratio of the fabric *v* is determined using Eq. (5) using the values of relative narrowing *s* and relative elongation *ε*, which are illustrated in a graph in Figs. 11-13, and Table 5. Table 5 shows the calculated Poisson's ratio at *ε* = 8%. The graphs show the change in the value of Poisson's ratio *v* when the direction of the action of force varies in relation to the weft depending on the relative elongation of the fabric: for plain weave fabric (Fig. 14), twill weave (Fig. 15) and satin weave (Fig. 16).

The Poisson's ratio curve of the fabric is determined by internal interactions within the fabric. The shape of the Poisson's ratio curve (Figs. 14-16) is influenced by changes in the value of the relative narrowing of the fabric, as seen in Figs. 11-13. In general, the Poisson's ratio curve consists of two regions.

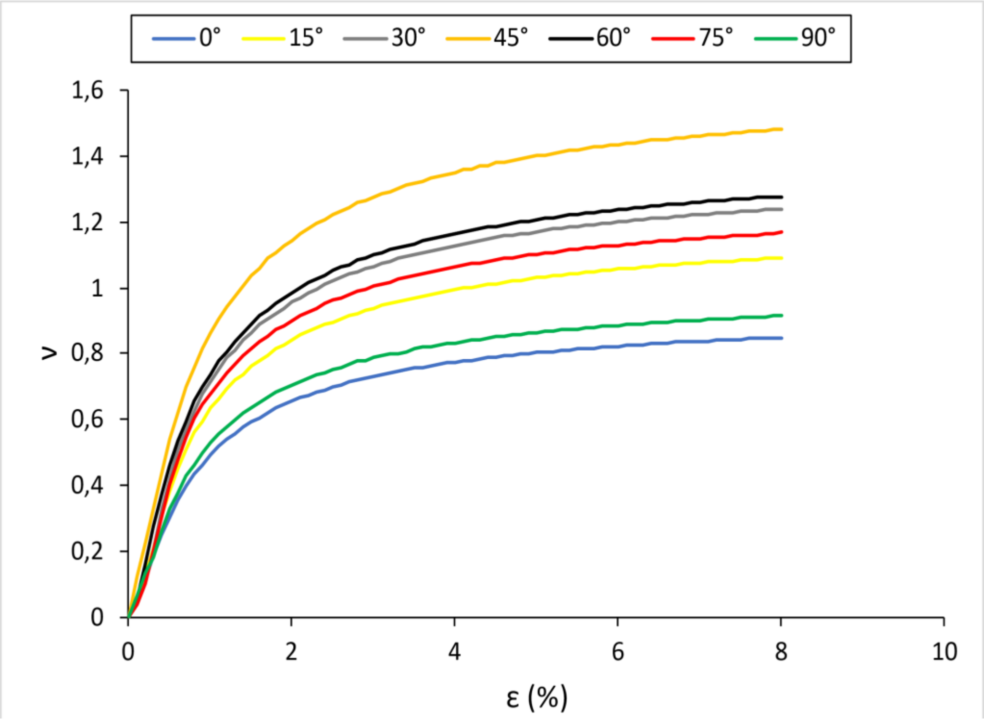

Fig. 14 Poisson's ratio *v* of the plain weave fabric.

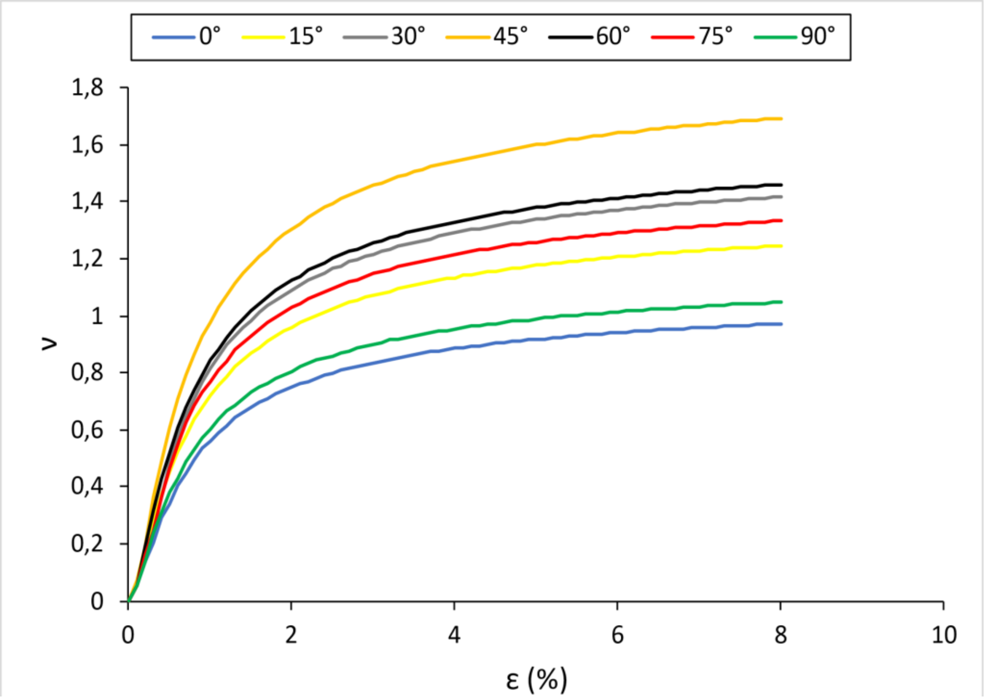

Fig. 15 Poisson's ratio *v* of the twill weave fabric.

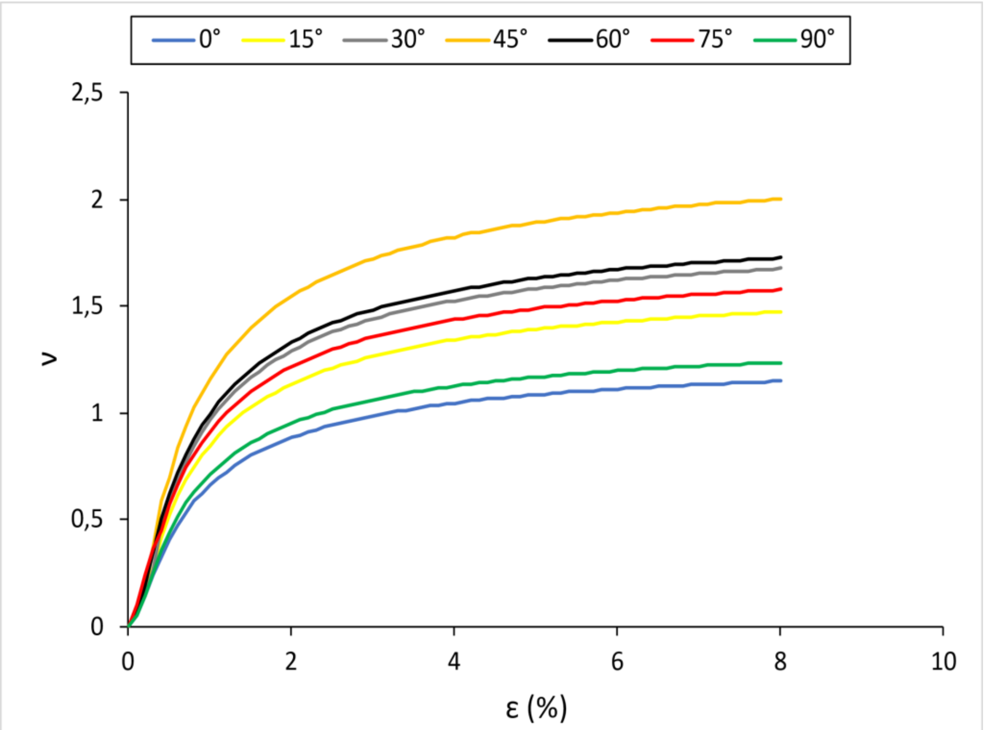

Fig. 16 Poisson's ratio *v* of the satin weave fabric.

Each region represents the result of two different physical processes taking place within the fabric. The first region is the area from the beginning of the curve to the highest peak (maximum value). The second region extends from the peak of the curve to the limit of the elongation, i.e., the break. In this region, the Poisson's ratio curve flattens out and the lateral narrowing is complete, even though the sample is elongated.

At the relative elongation of the sample ε = 8%, the Poisson's ratio for all weave types has the highest value for the direction of the action of force at an angle of 45 ° to the weft. Poisson's ratio has the smallest values when the force operates in the warp and weft directions. Satin fabrics have the greatest Poisson's ratio values, whereas plain weave fabrics have the lowest. Therefore, the type of fabric weave and the direction of tensile force significantly affect the change in Poisson's ratio.

Considering the Poisson's ratio equation, the relative narrowing is constant at the point where the lateral narrowing is completed. In addition, the length of the sample is also determined by the factor ε. The Poisson's ratio equation is therefore transformed into the general form of a reciprocal function. In mathematical terms, this equation has a value of zero. In practice, sample breakage never causes this kind of situation. When considering the importance of the ratio of transverse to longitudinal deformation of the material, it is clear that if the ratio does not exist, the ratio is of no practical significance. There are two primary reasons why the lateral narrowing of a fabric may cease. The first is related to the end of yarn straightening in the direction of fabric elongation, while the second is due to the fabric structure.

5. Conclusion

This study investigates the effect of fabric anisotropy and weave type on the Poisson's ratio, maximum force and corresponding elongation as well as the work done to the maximum force while stretching the fabric to the breaking point at uniaxial stress. Due to fabric anisotropy, Poisson's ratio does not remain constant with fabric elongation. The direction and shape of the Poisson's ratio curve of a fabric under tensile action (i.e., elongation) is largely determined by the behaviour of the fabric in the direction perpendicular to the elongation. Poisson's ratio first increases non-linearly and asymptotically approaches the maximum value.

The changes in Poisson's ratio are significantly influenced by the type of weave and tensile stress direction. Poisson's ratio has the greatest value in the direction of the force acting at an angle of 45 ° to the weft. The Poisson's ratio is the lowest when the force is in the direction of the warp and the direction of the weft. Satin has the highest Poisson's ratio while plain weave fabrics have the lowest. Twill weave fabrics have qualities that fall in between plain and satin weave fabrics. Plain weave fabrics have the highest values of maximum force, maximum elongation, and work done, whereas satin weave fabrics have the lowest values. Measurements of maximum tensile force, maximum elongation, work done and modulus of elasticity showed that the anisotropic properties of the fabric had a significant effect on the observed values. The direction (angle) of cutting the samples greatly affects the obtained values.

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