A Review on the Poisson’s Ratio of Fabrics

Nazanin Ezazshahabi* and S. Mohammad Hosseini Varkiyani

Abstract- **The Poisson’s ratio is one of the fundamental properties of any engineering material and presents an essential mechanical aspect of them. The mechanical properties of fabrics as the most common type fibrous materials, especially the Poisson’s ratio, needs to be thoroughly studied. Sometimes the value of Poisson’s ratio obtained for fabrics differs significantly from the other engineering materials, which results in the unique performance of fabrics when subjected to the tensile deformations. Besides, due to the nature and exclusive structure of fabrics compared to the other sheet materials, the measurement methods of Poisson’s ratio and accuracy of the results have been always a matter that required special consideration. A detailed review of different measurement methods of the Poisson’s ratio of fabrics and also the relationship between this property and other physical and mechanical characteristics can be useful for the continuation of researches in this field.**

Keywords: **Poisson’s ratio, woven fabric, nonwoven, knitted fabric, mechanical properties**

I. INTRODUCTION

Woven and knitted fabrics and also the nonwovens fulfill a wide range of needs and requirements and are the main source of the textile materials in sheet form. The physical and mechanical properties of these materials define the choice of their end use in a variety of needs and applications. Hence, it is vital to have a better understanding of the parameters that influence the behavior of these materials.

Poisson’s ratio and different methods for measuring this property have been the subject of many previous research studies due to their significant influence on fabric performance.

Bearing in mind the flexible nature and the nonlinear behavior of fabrics during extension, the experimental procedure for the measurement of this property should have enough care and reliability in order to eliminate the source of errors and reach more precise results.

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A. Definition of Poisson’s Ratio

From experiments, it is known that in addition to the deformation of materials in the direction of the applied normal stress, another remarkable change can be observed in all solid materials, specifically, at right angles to the applied stress that a certain amount of lateral (transverse) expansion or contraction takes place.

If a solid body is subjected to axial tension, it contracts laterally. On the other hand, if it is compressed, the material “squash out” sidewise. With this in mind, directions of lateral deformations are easily determined, depending on the sense of the applied normal stress.

For a general theory, it is necessary to refer to these lateral deformations based on deformation per unit of length of the transverse dimension, i.e., on the basis of lateral linear strains. The ratio of the absolute value of the strain in the lateral direction to the strain in the axial direction is Poisson’s ratio:

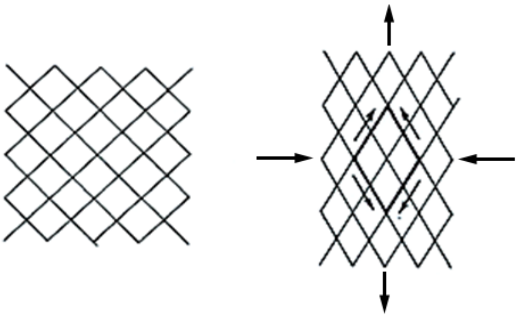
$$\nu=-\frac{\varepsilon_x}{\varepsilon_y}=-\frac{\text{lateral strain}}{\text{axial strain}} \tag{1}$$

The negative sign accounts for the contraction of materials in the direction perpendicular to the applied stress.

As it was stated by Bais-Singh, Anandjiwala, and Goswami (1996) [1], Poisson’s ratio is the most commonly used ratio, which relates the strains in two perpendicular directions. Poisson’s ratio was mainly defined for the linear elastic materials, but in textile mechanics, this property is used for relating the longitudinal and transverse strain in the nonlinear deformation zone.

B. Importance of Poisson’s Ratio

The use of fabrics in special exceptional cases and also



(a) (b)

Fig. 1. Lattice model: (a) Unstrained and (b) identical strain when is subjected to either tensile, compressive, or shear forces [3].

their industrial usage have encouraged researchers to predict and determine their behavior and mechanical properties. According to the considerable complexity of the fabric behavior from different mechanical aspects, interpreting and predicting their behavior are difficult. Various mathematical models for analyzing the fabric characteristics have been established. One of the parameters in characterizing the fabric properties is Poisson's ratio. For the application mentioned above, it is necessary to measure Poisson's ratio corresponding to the tensile modulus and its variation with the increase of strain (Lloyd and Hearle, 1977) [2].

In analyzing the shear properties of fabrics, there is a tendency to think of solid material, with very low Poisson's ratio, where the area under uniaxial tensile stress increases, so additional compressive tensions will be needed to have simple shear deformation with the constant area. The lattice model is constructed of rods, jointed together, as shown in Fig. 1.

This model deforms under a uniaxial tension, which gives a shear at a constant length of the sides and the area reduces with a high Poisson's ratio. When the rods are perpendicular to each other, there is no change in the area for small deformations and Poisson's ratio is 1. However, as the rods are bent with an acuter angle, Poisson's ratio increases, and the area decreases (Hearle *et al.*, 1969) [3].

While analyzing the mechanical behavior of plain woven fabric and estimating their initial modulus, Leaf (2001) stated that Kilby [4] has established a Trellis model for a woven fabric in 1963 and has illustrated its planar stress-strain behavior, based on the continuum mechanics for an anisotropic elastic lamina. They finally presented this relationship between the shear modulus and Poisson's ratio in the warp and weft directions:

$$\frac{1}{G}=\frac{4}{E_{45}}-\frac{(1-\sigma_2)}{E_1}-\frac{(1-\sigma_1)}{E_2} \qquad (2)$$

In this equation, σ_1 and σ_2 are the Poisson's ratios in the warp and weft directions, respectively, E_1 and E_2 are the tensile moduli in these directions, G is the shear modulus and E_{45} is the tensile modulus in a direction making a 45º angle with the warp threads.

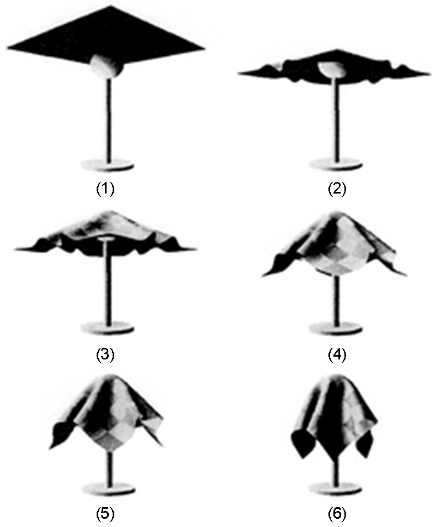


Fig. 2. Animation of cloth falling on a sphere [8].

In a research done by Nhan (1985) [5], a mathematical model for the buckling of woven fabric under a combination of tensile and shear forces is presented. This model takes into account the anisotropic properties of the fabric, in terms of flexural rigidity in the warp and weft directions, Poisson's ratio, shear modulus and the ratio of width to height of a rectangular specimen.

Moreover, during the simulation of fabric drape, the properties of the fabric, such as Poisson's ratio, shear modulus, and tensile modulus are fed to a fabric simulator (Fig. 2) to obtain the results of fabric drape, and the effect of these parameters on the drape is studied (Collier *et al.*, 1991 [6]; Chen and Govindaraj, 1995 [7]; and Yuen, 2003 [8]).

C. Investigation of Poisson's Ratio

C.1. Theoretical Approach

In the field of theoretical analysis of Poisson's ratio and its relationship with the mechanical properties of the fabric, different researches have been carried out.

Some theoretical discussions were expressed by Lloyd and Hearle (1977) [2]. In this study, the linear elastic theory at small strains has been used for continuous sheets concerning the initial elastic properties of fabrics. In the case of an initially flat fabric in which there is no elastic coupling between in-plane strains and bending strains, and also for a symetric structure (for example the warp and weft direction in a non-skew woven fabric), the relation for in-plane stress-strain can be expressed as below:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_{12} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_1} & \frac{-\nu_2}{E_2} & 0 \\ \frac{-\nu_1}{E_1} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_{12} \end{bmatrix} \tag{3}$$

In this equation, ε_1 and ε_2 are the strains in two perpendicular directions (for instance warp and weft), E_1 and E_2 are the tensile moduli, ν_1 and ν_2 are the Poisson's ratios in two directions, T_1 and T_2 are the tensile stresses and ε_{12} and T_{12} are the shear strain and stress, respectively and also G is the shear modulus.

Similar theoretical considerations were also presented by Lioyd and Hearle (1977) [9] in determining the Poisson's ratio of nonwoven fabrics. In this research, it was assumed that the nonwoven fabrics are elastic and have orthotropic behavior, and corresponding equations are as follows:

$$\begin{aligned} T_2 &= \left((\frac{\nu_{12}E_1}{1-\nu_{12}\nu_{21}}) \right).\varepsilon_1 + \left((\frac{E_2}{1-\nu_{12}\nu_{21}}) \right).\varepsilon_2 \\ T_1 &= \left((\frac{E_1}{1-\nu_{12}\nu_{21}}) \right).\varepsilon_1 + \left((\frac{\nu_{12}E_1}{1-\nu_{12}\nu_{21}}) \right).\varepsilon_2 \end{aligned} \tag{4}$$

Where, ε_1 and ε_2 are the strains in the orthotropic directions (machine direction and cross direction), E_1 and E_2 are the tensile moduli, ν_1 and ν_2 are the Poisson's ratios and T_1 and T_2 are the tensile stresses. From symmetry:

$$\nu_2 E_1 = \nu_1 E_2 \tag{5}$$

In the condition that ε_1 and T_1 are the known and shear stresses are zero, $1/E_1$ can be determined, which is necessarily related to a uniaxial tensile test, where the sample can be contracted freely in the cross direction. On the other hand, if the specimen is constrained to constant width (ε_2 and shear strains are zero) and if T_1 and ε_1 are known, $E_1/(1-\nu_1\nu_2)$ can be possibly calculated. This situation is related to biaxial tensile tests, and previous equations can be expressed as below.
Where $\varepsilon_2 = 0$:

$$\begin{aligned} T_2 &= \left((\frac{\nu_{12}E_1}{1-\nu_{12}\nu_{21}}) \right).\varepsilon_1 \\ T_1 &= \left((\frac{E_1}{1-\nu_{12}\nu_{21}}) \right).\varepsilon_1 \end{aligned} \tag{6}$$

And also in the case of $\varepsilon_1 = 0$:

$$\begin{aligned} T_2 &= \left((\frac{E_2}{1-\nu_{12}\nu_{21}}) \right).\varepsilon_2 \\ T_1 &= \left((\frac{\nu_{12}E_1}{1-\nu_{12}\nu_{21}}) \right).\varepsilon_2 \end{aligned} \tag{7}$$

By determining E_1, E_2, $E_1/(1-\nu_1\nu_2)$, $E_2/(1-\nu_1\nu_2)$ and Eq. (5), it is possible to calculate Poisson's ratio in each of the conditions mentioned before.

In the same year (1977), a general analysis of fabric mechanics using the optimal control theory, for deformation of woven fabric structure was presented by De Jong and Postle [10]. By using this method, the values of Poisson's ratio were found to be below 1. This behavior of poison's ratio can be explained by the fact that when a fabric is extended, the gap between the yarns increases. This occurrence can be observed during the extension of woven fabric in a thickness tester of fabric, and the increase in the thickness of the fabric is noticeable. The yarns employed in a woven fabric are significantly flat, and during load exertion to the fabric, their cross section becomes round, so the distance between yarns, increases. For relatively low-twist yarns, there is less tendency to deform and $\nu < 1$.

Analysis of the initial load-extension behavior of plain woven fabric was carried out by Leaf and Kandil (1980) [11]. By assuming that the yarns are incompressible and inextensible, the initial Poisson's ratio can be calculated from this equation:

$$\nu_1 = -\frac{\varepsilon_1}{\varepsilon_2} = \frac{p_2.\tan\theta_2}{p_1.\tan\theta_1} \tag{8}$$

The parameters used in this equation were p_1, the distance between warp yarns, p_2 is the distance between weft yarns, Θ_1 and Θ_2, which were the warp and weft weave angle, respectively.

Technical discussions in the illustration of Poisson's ratio of nonwoven fabrics under biaxial tensile stresses were expressed by Vigo *et al.* (1984) [12].

Analysis of the Poisson's ratio of textile sheets used in nonwoven geomembranes and geotextiles was performed by Giroud (2004) [13].

It is known that the incompressible materials have a Poisson's ratio of 0.5. This assumption is only valid during small strains. In this paper, Giroud established an equation for the Poisson's ratio of unreinforced geotextiles and geomembranes subjected to large strains, which have a Poisson's ratio below 0.5 for all strains.

The Poisson's ratio is defined as the ratio of strain in the direction perpendicular to the load exerted and the strain in the direction of load, within a uniaxial tensile test:

$$\varepsilon_1 = \varepsilon_2 = -\nu.\varepsilon \tag{9}$$

Where, ε is the strain in the direction of stress in a uniaxial tensile test and ε_1 and ε_2 are the strains, in two perpendicular directions to the applied stress and ν is the Poisson's ratio of the material used in the tensile test [13].

C.2. Variation in Volume During a Tensile Test

The relative changes of volume during a uniaxial tensile test are achieved from Eq. (10), where V_0 is the volume of the specimen at the beginning of the test and V is the volume of the specimen due to the strain in the direction of exerted load.

$$\frac{V}{V_0}=(1+\varepsilon).(1+\varepsilon_1).(1+\varepsilon_2) \tag{10}$$

By combining Eqs. (9) and (10):

$$\frac{V}{V_0}=(1+\varepsilon).(1-\nu\varepsilon)^2 \tag{11}$$

$$\frac{V}{V_0}=1+(1-2\nu).\varepsilon+\nu.(\nu-2).\varepsilon^2+\nu^2.\varepsilon^3 \tag{12}$$

When ε is too small, Eq. (12) is converted to:

$$\frac{V}{V_0}\approx 1+(1-2\nu_0).\varepsilon \tag{13}$$

Where ν_0 is the value of ν for ε = 0 [13].

C.3. Incompressible materials

In the condition of incompressible materials, there is no change in the volume and $V=V_0$, so Eqs. (11) and (13) are converted to Eqs. (14) and (15):

$$1=(1+\varepsilon).(1-\nu\varepsilon)^2 \tag{14}$$

$$1=1+(1-2\nu_0).\varepsilon \tag{15}$$

Eq. (15) is derived from Eq. (13) and is only valid for small strains and states that the Poisson's ratio of incompressible materials for small strains is $\nu=\nu_0$.

Eq. (14) is valid for all strains, and for incompressible materials, it is converted to Eq. (16):

$$\nu=\frac{1}{\varepsilon}\left(1-\frac{1}{\sqrt{1+\varepsilon}}\right) \tag{16}$$

As it is evident from Eq. (16), the Poisson's ratio of an incompressible material decreases during the increase of strain [13].

C.4. Compressible Materials

In this condition, it is assumed that the ratio of V/V_0 changes as a linear function of ε (strain). By combining Eqs. (11) and (13):

$$(1+\varepsilon).(1-\nu\varepsilon)^2=1+(1-2\nu_0).\varepsilon \tag{17}$$

So, in the end, Eq. (18) is derived:

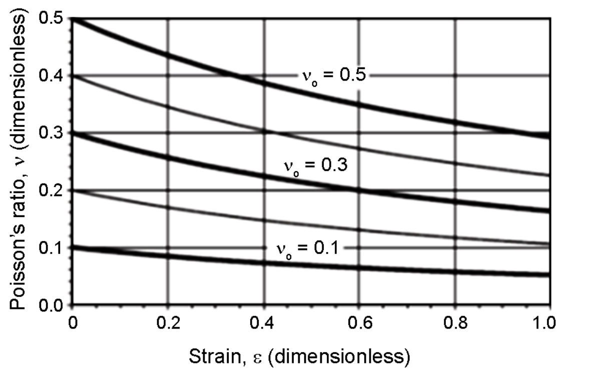


Fig. 3. Poisson's ratio as a function of strain in the direction of the applied load for compressible materials (ν_0 = 0 - 0.5), in the strain range of 0% to 100% [13].

$$\nu=\frac{1}{\varepsilon}\left(1-\sqrt{\frac{1+\varepsilon(1-2\nu_0)}{1+\varepsilon}}\right) \tag{18}$$

From Eq. (18), the value of Poisson's ratio is obtained as a function of ε for a material with an initial Poisson's ratio of ν_0 for ε = 0. The values computed from Eq. (18) are plotted against strain in Fig. 3 [13].

Theoretical equations by the use of fabric geometry, for representing the Poisson's ratio (in the warp and weft directions) were established by Sun *et al.* (2005) [14]. By analyzing the resulting equations, they concluded that Poisson's effect in a woven fabric is affected by the interaction between the warp and weft yarns and can be expressed in terms of mechanical and structural parameters of the system. It was also declared that according to the equations, it is evident that Poisson's ratio for a woven fabric is dependent on yarn properties and the geometrical structure of the fabric.

As it is evident from this diagram, with increasing Young's modulus ratio and also the ratio of warp to weft yarns diameter, Poisson's ratio increases but the influence of diameter ratio between warp and weft yarns is more significant. It was also concluded that the increase of pick spacing leads to a significant rise in the value of Poisson's ratio (even more than 2).

During the analysis of the Poisson's ratio of the needle-punched nonwoven fabrics it was stated by Hosseini Varkiyani (2005) [15] that in the case of small elongations (around 0.1%), the strain is calculated as below:

$$\varepsilon=\int_{x_0}^{x}\frac{dx}{x_0}=\frac{\Delta x}{x_0} \tag{19}$$

This strain is shown by ε, and it is called nominal strain. In this equation, x_0 is related to the initial length, and Δx represents the change in length in accordance to the exerted load.

In the case of large elongations, the strain is:

$$\bar{\varepsilon} = \int_{x_0}^{x} \frac{dx}{x} = \ln\left(\frac{x}{x_0}\right) = \ln\,(1+\varepsilon) \qquad (20)$$

In this equation, ε is called true strain.

If Eq. (20) is extended, it can be written:

$$\int_{x_0}^{x} \frac{dx}{x} = \ln\left(\frac{x}{x_0}\right) = \ln\left(1+\frac{\Delta x}{x_0}\right) \qquad (21)$$

$$\varepsilon = \ln\left(1+\frac{\Delta x}{x_0}\right) = \frac{\Delta x}{x_0} - \frac{1}{2}\left(\frac{\Delta x}{x_0}\right)^2 + \frac{1}{3}\left(\frac{\Delta x}{x_0}\right)^3 \qquad (22)$$

The Poisson's ratio for large strains is calculated as below:

$$\nu = -\frac{\varepsilon_x}{\varepsilon_y} = -\frac{\ln\left(\frac{x}{x_0}\right)}{\ln\left(\frac{y}{y_0}\right)} \qquad (23)$$

This equation is true for linear situations and here ε_x and ε_y represent strains and x_0 and y_0 show the initial length, respectively in x and y directions.

For materials with linear behavior, Poisson's ratio is constant and is not related to the strain. On the other hand, the Poisson's ratio for the materials with non-linear behavior is calculated by Eq. (24):

$$\nu = -\frac{d\varepsilon_x}{d\varepsilon_y} = -\frac{d\left(\ln\left(\frac{x}{x_0}\right)\right)}{d\left(\ln\left(\frac{y}{y_0}\right)\right)} \qquad (24)$$

Here the Poisson's ratio is called the coefficient of transverse coupling. Since the polymeric and textile materials have large relative elongations, to obtain the values of strain and Poisson's ratio, Eq. (24) can be used for having exact results.

A geometrical model for the evaluation of the Poisson's ratio of two-guide-bar warp-knitted fabrics was presented by Dabiryan and Jeddi (2012) [16]. In order to propose the mentioned model, some simplifying assumptions have been applied including: cross-section of yarns is circle, yarns are inextensible and incompressible, and the tensile behavior of fabrics is linear. As can be seen in Fig. 4, both reduction in course spacing (Δc) and extension in wale spacing (ΔW) occur due to force exertion, simultaneously. Concerning the definition of Poisson's ratio, it can be written:

$$\nu = -\frac{\Delta c / c}{\Delta w / w} \qquad (25)$$

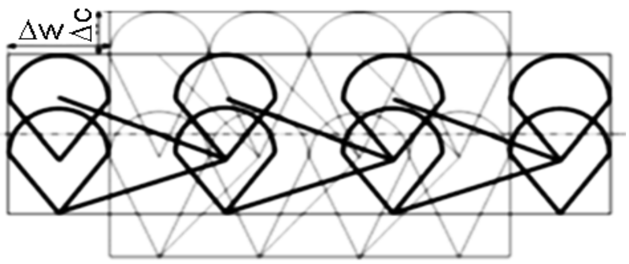


Fig. 4. Dimensional variations of warp-knitted structures under uni-axial tension [16].

II. EXPERIMENTAL APPROACH

In this section, the research works that analyzed the tensile tests and measured Poisson's ratio experimentally are concluded.

In the experiments for the measurement of the fabric Poisson's ratio, by the use of a high-quality camera during a uniaxial tensile test, some pictures are taken to cover the entire process of deformation. With this experiment, a numerical value for Poisson's ratio using the existing tensile machines can be obtained and also a better understanding of fabric lateral contraction behavior and its dependence on the other various factors can be achieved. However, sometimes, the resolution of the images is low, which leads to lower precision of the analysis. Some other problems, due to the curling of the specimen at edges, may result in overestimation of Poisson's ratio. Slippage of the fabrics at the jaws may be another source of error in the estimation of the fabric's Poisson's ratio.

An explanation of the experiments done to measure the tensile behavior of nonwovens in a range of test angles related to the principal directions was given by Petterson and Backer (1963) [17]. All of the experiments were held on an Instron tensile tester with the constant rate of elongation. During the load exertion in the experiments, some wrinkles were seen on the sample. In order to achieve accurate measurements in the lateral direction, during tensile stresses (and thus to determine the lateral contraction) the effect of wrinkling has to be reduced as much as possible. To ensure that the sample is subjected to pure uniaxial tensile stress, the specimen has to be long enough in order to eliminate the jaw effects in the strain zone. Poisson's ratio is defined as the proportion of lateral contraction in the x-direction to the extension in the y-direction and is stated according to the strain in the y-direction. Thus, when the lateral contraction (lateral strain) εx is plotted against the extension in the longitudinal direction of the specimen, the slope of the diagram is the value of Poisson's ratio, νxy. Such a diagram for νLT (when the strain is in the longitudinal direction) is shown in Fig. 5.

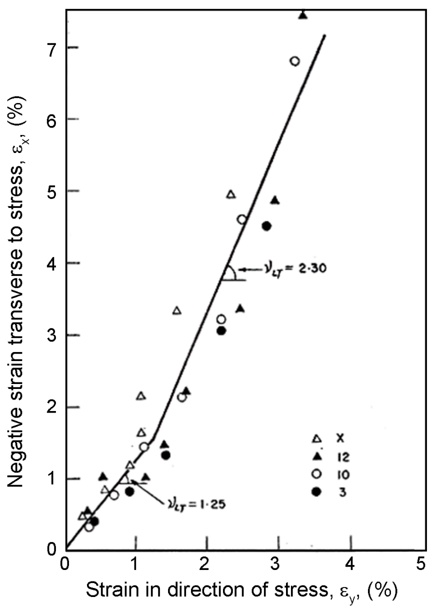


Fig. 5. Fabric's Poisson's ratio [17].

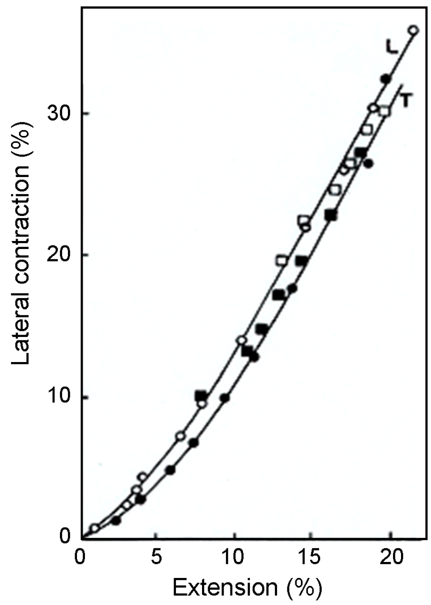


Fig. 6. Lateral contraction for longitudinal (L) and transverse (T) directions of extension for a cross-laid fabric, (O) extension increasing and (□) extension [18].

Measurement of the dimensional changes and lateral contraction in the plane of a sheet (Poisson's ratio) was carried out by Thirwell and Treloar (1965) [18]. This property is used in the definition of geometrical strain in theoretical studies and in the change in the thickness of the nonwoven fabrics during deformation. From these two measurements, the variation in the sample volume was calculated.

As it is evident from Fig. 6, the lateral contraction diagrams of cross-laid nonwoven fabrics for elongation in the machine and cross machine directions are similar. The ratio of lateral contraction to elongation in the longitudinal direction of the fabric increases continuously within the increase of strain, and the values of Poisson's ratio are not constant and reach high values such as 2 in the highest strain.

The obtained results give a better understanding of the geometry of the strain of the nonwoven structure. If the materials were isotropic in a plane normal to the direction of the applied tensile strain, there would be equal contractions in the lateral direction in the plane of the sheet and the thickness direction. For such materials, in the condition of low strains, the value of Poisson's ratio is more than 0.5 and represents the reduction in the volume during elongation.

In order to illustrate Poisson's ratio of woven fabrics, Lloyd and Hearle (1977) [2] established an experimental test such that the positioning of the clamps was as those shown in Fig. 7. The jaws were made of mild-steel bars with finished dimensions 24×3×1.2 cm^3. The surfaces of the clamps were covered with fine emery to prevent slippage. The specimen had 20 cm wide, and the distance between the clamps was 1 cm. These dimensions were selected due to the dimensions of the tester and the need to reduce the ratio of length to width of the specimen as much as possible. The movement speed of the cross-head was 0.1 cm/min, and the maximum extension was small (about 3-4 mm to failure). It was concluded that this method is appropriate for extensible fabrics with an open weave. The main target for the application of a wide sample with small length is to obtain a condition of the tensile test, in which the width of the specimen remains constant. However, this method is not accurate enough, due to its high sensitivity to errors during the measurement of the distance between jaws (because of slippage) and also the assumption of zero

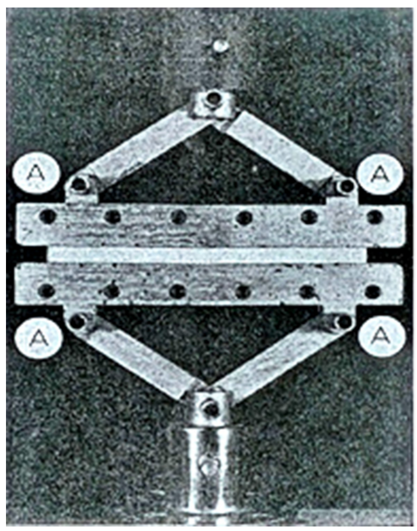


Fig. 7. The positioning of the clamps [2].

lateral contraction in a uniaxial tensile test which is not acceptable.

Several tests on narrow strips (20 cm long and 2 cm wide) of finished fabrics were carried out by De Jong and Postle (1977) [10]. For most of the specimens, the value of Poisson's ratio was more than one, but only for the fabrics constructed of low-twist multifilament yarns, Poisson's ratio in both directions (warp or weft) was less than one.

In another research performed by Hearle and ozsanlav (1979) [19], the Poisson's ratio of adhesive-bonded nonwovens was measured. Five random specimens with dimensions of 3×30 cm have been cut from three known directions of the fabric (0, 45, and 90°). Since the restrictive conditions caused by the jaws of the tensile tester were eliminated in a specific distance from the jaws, measurement of strains had to be done near the center of the specimen. During initial experiments, the researchers declared that the sample which is positioned in the tester did not seem to be flat and moreover, when the extension of the sample continued, the long edges of the specimen tended to curl. Under this circumstance, the changes in the width of the specimen, considering the applied strain could not be measured accurately. In order to keep the samples straight, a smooth plate was positioned behind the sample on the Instron tester and as a conclusion, the center of the specimen.

Fig. 8 shows the diagrams of lateral strain against longitudinal strain in three directions. First, the rate of lateral contraction is low, but between 5% to 10% elongation, it increases. For the fabrics with higher breaking elongation, this rate tends to decrease again.

The thermo-bonded nonwoven fabrics and the binder film were examined by Vigo *et al.* (1984) [12]. Both of these materials were tested uniaxially on the Instron tester in the machine direction and cross-machine directions. The dimensions of the samples were 6×6 cm, and the rate of

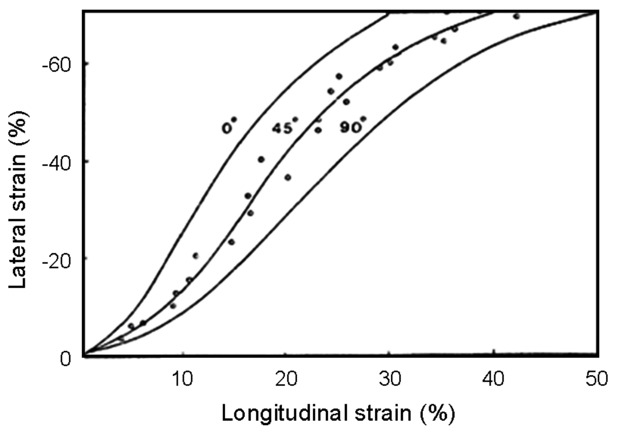


Fig. 8. Lateral contraction changes against elongation in different angles from the principal direction [19].

elongation was 50 and 200% per minute. With the use of longitudinal strain values ε_1 and ε_2, and the values of lateral contraction in both experiments, the values of ν_{12} and ν_{21} were calculated. The reported values of Poisson's ratio were related to the point of maximum recorded stress in the stress-strain curve (for estimation of E_1 and E_2). Then, in order to analyze the Poisson's ratio of the thermo-bonded nonwovens and the binder film, a biaxial test was done on a 6×6 cm sample.

In the biaxial test, in one situation, the dimensions normal to the tensile direction remain constant. Poisson's ratios ν_{12} and ν_{21} (machine and cross machine directions) can be determined by the process below.

With the use of biaxial test information, the values of maximum stresses were measured (according to the stress-strain curves of the nonwoven fabrics used in this research). The rigidity values, $E_1/(1-\nu_{12}\nu_{21})$ and $E_2/(1-\nu_{12}\nu_{21})$ were obtained from biaxial tests. The values of E_1 and E_2 were known (from the uniaxial tests), and Eqs. (4) and (5) were used to calculate ν_{12} and ν_{21}.

In this research, the accuracy and efficiency of uniaxial and biaxial tensile tests, for determining the Poisson's ratio of thermo-bonded nonwoven fabrics were compared, and it was concluded that the uniaxial test does not yield good results compared to biaxial tests. On the other hand, the biaxial test is more time-consuming in comparison to the uniaxial test but leads to more accurate values for Poisson's ratio.

Anadjiwala and Leaf (1991) [20] stated that the load-extension and recovery behavior of fabrics could readily be obtained by using the Instron tensile testing machine. In order to ensure that the specimens were neither loose nor pretension between the jaws, enough caution and accuracy were held while positioning the samples in the tester. The values of Poisson's ratio for both warp and weft directions were obtained in the range of 0 to 0.9, for different extension percentages.

Prediction of the tensile behavior of the spun-bonded nonwoven fabrics was done by Bais-Singh and Goswami (1995) [21]. They indicated that the measurement of Poisson's ratio could be carried out by measuring continuous axial elongation and lateral contraction in a fabric sample under uniaxial tensions.

During the test, the specimens were illuminated by using halogen lamps. A higher resolution camera was used to record the deformation at the center portion of the specimens, continuously. The recorded photographs are then fed to an image processing system for further illustrations. The percentage of lateral contraction in the center of the specimen during uniaxial load exertion for two fabric samples (in the machine and cross machine

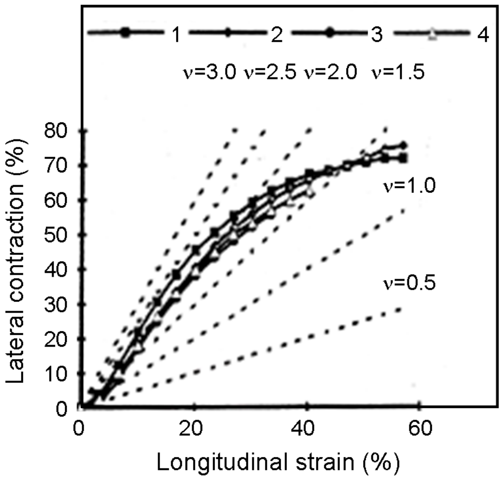


Fig. 9. The measured lateral contraction for two fabric samples A and B, (1) fabric A in the machine direction, (2) fabric A in the cross-machine direction, (3) fabric B in the machine direction, and (4) fabric B in the cross-machine direction [21].

direction) against the longitudinal strain is shown in Fig. 9.

Bais-Singh, Anandjiwala, and Goswami (1996) [22] used a similar method for measuring the Poisson's ratio of polyester spun-bonded nonwoven fabrics. The experimental set-up is shown in Fig. 10.

Ezazshahabi *et al.* (2012) [23] investigated the effect of weight reduction treatment on Poisson's ratio of the microfiber polyester woven fabric. In the mentioned research, a microfiber polyester fabric had been treated with different sodium hydroxide concentrations at four weight reduction percentages. Then, the Poisson's ratio of original and treated fabrics was measured using an Instron tensile tester and a particular method for calculation of Poisson's ratio. Results showed that the Poisson's ratio of the fabric increased from 1% up to about 5% non-linearly, and after that, it started to reduce in a linear trend. Regarding the effect of weight reduction treatment of the fabric on the Poisson's ratio, statistical analysis showed that weight reduction at a percentage lower than 25% did not have a considerable effect on the Poisson's ratio of the microfiber polyester fabric. It was found that there was a considerable variation in the results at lower extensions, and as the fabric extension continued, this variation reduced. It was found that in the extension range of 6–10%, there was a high non-linear correlation between the weft crimp and the Poisson's ratio. Also, there was a high non-linear correlation between Poisson's ratio and the fabric cover factor.

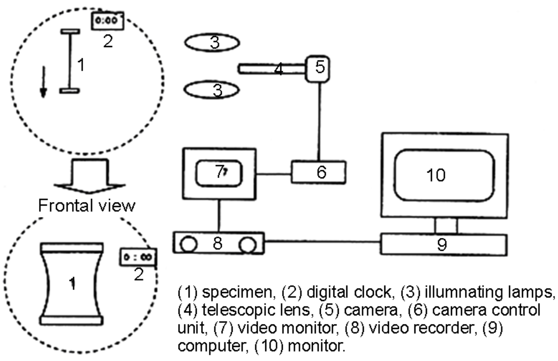


Fig. 10. Schematic of the experimental set-up for measuring Poisson's ratio [22].

In another work by Ezazshahabi *et al.* (2013) [24], the influences of weave structures and weft density on the Poisson's ratio of worsted fabric under uniaxial extension were analyzed. In this study, nine groups of worsted fabrics comprised of three weave structures (twill 2/2, twill 3/1, and hopsack 2/2), each produced in three different weft densities were examined. Samples were extended in weft direction uniaxially, and the Poisson's ratio of the fabric in various extensions was measured. The analysis showed that the effects of both weft density and weave structure are significant, with no combination effect on the Poisson's ratio. It was found that there is an exponential correlation between warp and weft crimp during fabric extension. It was also concluded that for the fabrics with the same condition but the only difference in structures, this ratio is related to the structural firmness of the fabric. For the worsted fabrics used in this research, in all three fabric structures, fabrics with higher weft yarn density have a higher value of Poisson's ratio. In all three fabric structures, the value of the Poisson's ratio followed the same pattern of twill 2/2, twill 3/1, and hopsack 2/2 from the highest to lowest value. It was revealed that there is a high linear correlation between the crimp interchange ratio and Poisson's ratio.

Evaluation of the deformation of coated fabrics used for airship envelope considering Poisson's ratio variation was performed by Y. Chen and W.Chen (2014) [25]. It was concluded that the Poisson's ratio variation is necessary to be considered for precise deformation prediction of a large flexible airship, and the significant deformation variation is found from only the change in Poisson's ratio.

In research by Ezazshahabi *et al.* (2016) [26], prediction of Poisson's ratio of worsted woven fabrics considering fabric extension in various directions was carried out. The paper aims to analyze Poisson's ratio of woven fabrics in terms of fabric tensile behavior in different directions. In this research, measurement of Poisson's ratio of a series of worsted woven fabrics was carried out through uniaxial extension of the fabrics on the tensile testing machine and tracing their dimensional changes during the load application. By the use of the Matlab curve fitting toolbox, the best equation for representing the relationship between Poisson's ratio and the tensile load exerted to the fabric was found. The mentioned function can be utilized for the

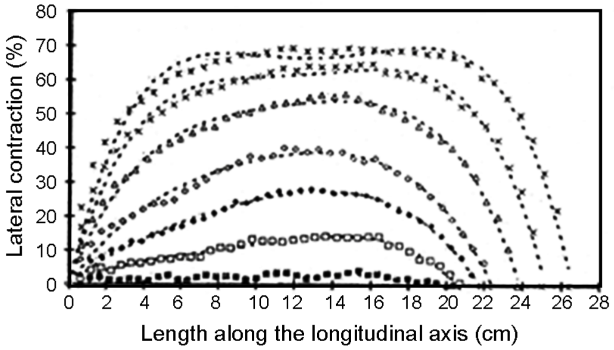


Fig. 11. Lateral contraction trend in a sample [22].

prediction of Poisson's ratio at various levels of load. Due to the non-isotropic behavior of the woven fabrics, the differences in Poisson's ratio obtained in the two main fabric directions (warp and weft) were investigated. Finally, the influence of weave structure and weft density on Poisson's ratio of the fabrics was studied. Analysis of the results revealed that the value of Poisson's ratio in terms of tensile load follows a similar trend for all fabrics, in both warp and weft directions. The mentioned trend was fitted reliably by a trigonometric function with the correlation factor (R2) of more than 92%. The result of investigating Poisson's ratio in two perpendicular directions was in agreement with the structural changes of the fabric in different directions. Statistical analysis of results confirmed that the effect of weave structure and weft density on Poisson's ratio is significant at the 95% confidence level.

A. Effect of Specimen Dimensions on the Measurement of Poisson's Ratio

The suitable dimension and geometry of specimens for measurement of the fabric's Poisson's ratio have been a crucial issue in many research works.

Analysis of the effect of specimen dimensions on Poisson's ratio was done by Bais-singh *et al.* (1996) [22]. It was expressed that with the use of very long, narrow specimens, the restrictive influence of jaws can be reduced and an even strain zone in the region of measurement can be obtained. The applied diagrams of lateral contraction percentage against the specimen's length have been shown in Fig. 11 for spun-bonded nonwoven fabrics. This figure also shows the effect of gauge length and specimen's width on the lateral contraction. According to the effect of necking during fabric elongation, specimens show the lowest lateral contractions near the jaws and the most lateral contraction in the central part of the specimen. As the elongation proceeds, the percentage of lateral contraction in each point on the length of the specimen increases alternatively. First, there is a significant increase, but by continuing the deformation, it decreases.

Fig. 12 shows the rate of increase in the lateral contraction in the center of specimens with different dimensions. In the range of low longitudinal strains (2-20%), the high proportion of increase indicates the least restrictions in the lateral contraction. However, in the range of higher strains, a much lower rate of increase in the lateral contraction can be observed, due to the occurrence of jamming in the structure.

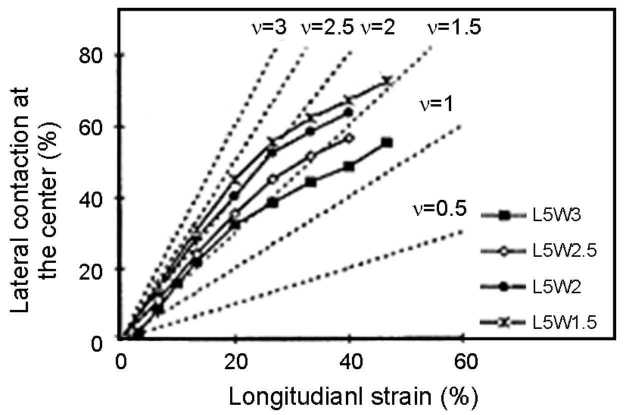
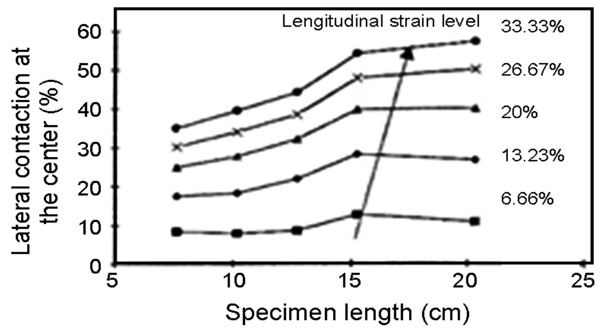
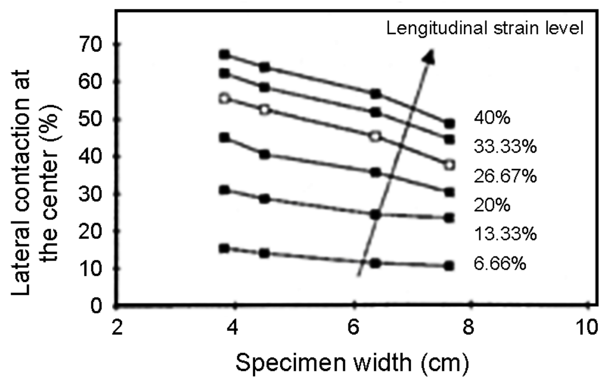


Fig. 12. Effect of sample dimensions on the lateral contraction at the center [22].



(a)



(b)

Fig. 13. Effect of: (a) length and (b) width of the specimen on the lateral contraction at the center [22].

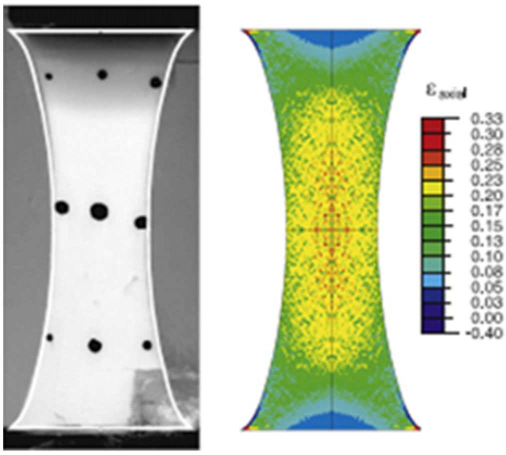


Fig. 14. Tensile deformation of the electrospun nonwoven mats [28].

It is evident from Fig. 12 that the dynamic response of Poisson's effect is substantially related to specimen dimensions. The value of this effect increases with the increase of longitudinal strains, and for higher longitudinal strains, the value of Poisson's ratio is larger for all of the samples. By the increase of gauge length, the lateral contraction in the center of the specimen in all ranges of longitudinal strains increases. Moreover, by the reduction of sample width, the lateral contraction at the center of the specimen increases. This fact can be observed in Fig. 13. If the gauge length increases significantly, the effect of jaws at the center of the specimen should become negligible.

Besides, it can be expressed that the measured values of lateral contraction are affected by curling of the edges and lead to errors in the measurement of this property and by reduction of specimen width, the amount of curling increases.

Jinyun *et al.* (2010) [27] revealed that there are linear elastic behaviors and significant Poisson effects in the elastic knitted fabric due to its unique stitch structure. It is an important parameter for practical pattern design, numerical simulation of garment pressure distribution, and garment dressing system.

Silberstein *et al.* (2012) [28] studied the elastic-plastic behavior of the nonwoven fibrous mats. In this research, mats electrospun from amorphous polyamide were used as a model system. The elastic-plastic behavior of single fibers was obtained in tensile tests.

Experimental mechanical characterization of random mats electrospun from the same polymer solution revealed an elastic-plastic stress-strain behavior with significant post-yield hardening for these mats. At small strains, the initial Poisson's ratio is near zero implying an initial structural rigidity opposing fiber alignment. This resistance is then overcome, and there is a significant transverse contraction with axial straining, with a transverse to axial strain ratio near -1. Under cyclic loading, the mats are seen to unload and reload in a nearly linear manner and exhibit an elastic modulus that increases significantly with strain.

III. CONCLUSION

To sum up, Poisson's ratio is one of the fundamental properties of any engineering material and can be used to express the mechanical behavior of fabrics. This parameter has an important role in many engineering systems, in which the fabric is one of the main parts. Poisson's ratio is an indicator of the fabric deformation, and it is influenced by the value of the applied load, loading direction, fabric structure, and yarn properties. Determination of Poisson's ratio for fabric is not easy, and different values of Poisson's ratio for different fabrics have been reported. As it is presented in this review, the evaluation of Poisson's ratio of fabrics needs special equipment, care and preciseness in order to obtain reliable results. Thus, many works had been carried out to choose the best method of measurement from various points of view, such as the specimen dimension, tensile loading (uniaxial and biaxial), marking on the specimens, image processing techniques and different approaches for the elimination of errors through quantification. Mainly, the sources of error are affected by the flexible nature of the fabric, curling and the formation of micro-bucklings during axial deformation and also the slippage of the fabric in jaws. Moreover, uneven strains that are distributed in the fabric specimen are important and should be included for predicting the precise tensile response of the fabric. Besides, in the case of knitted fabrics, since the curling of the fabrics at the edges becomes critical, it is harder to measure the Poisson's ratio of this category of fabrics. Thus in previous researches, it was tried to find and propose other indexes which can be calculated and applied for evaluation of the dimensional changes of fabrics during loading.

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