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Prediction of Poisson's ratio of worsted woven fabrics considering fabric extension in various directions

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The paper aims to analyse the Poisson's ratio of woven fabrics in terms of fabric tensile behavior in different directions. In this research, measurement of the Poisson's ratio of a series of worsted woven fabrics has been carried out through uniaxial extension of the fabrics on the tensile testing machine and tracing the dimensional changes of them during the load application. By the use of the Matlab curve fitting toolbox, the best equation for representing the relationship between the Poisson's ratio and the tensile load exerted to the fabric is derived. The mentioned function can be utilized for the prediction of the Poisson's ratio at various levels of load. Due to the non-isotropic behaviour of the woven fabrics, the differences of the Poisson's ratio obtained in the two main fabric directions (warp and weft) are investigated. Finally, the influence of weave structure and weft density on the Poisson's ratio of the fabrics is studied. Analysis of the results reveals that the value of the Poisson's ratio in terms of tensile load follows a similar trend for all the fabrics in both warp and weft directions. The mentioned trend is fitted reliably by a trigonometric function with the correlation factor (R^2) of more than 92%. The result of investigating the Poisson's ratio in two perpendicular directions is found in agreement with the structural changes of the fabric in different directions. Statistical analysis of results confirms that the effect of weave structure and weft density on the Poisson's ratio is significant at the 95% confidence level.

Keywords: Fabric extension, Fabric direction, Image processing, Poisson's ratio, Polyester/wool fabric, Woven fabric

1 Introduction

One of the most prominent concepts in textile mechanics is the Poisson's ratio, which indicates the relation between the fabric strains in its two perpendicular directions. Poisson's ratio and different methods for measuring this property has been the subject of many previous research workers due to its significant influence on fabric deformability, drape, shear, etc.

Leaf[1], through analyzing the mechanical behavior of plain woven fabrics, presented a relationship between shear modulus and Poisson's ratio in the warp and weft directions. Bao *et al*.[2] studied the error sources of measuring the Poisson's ratio of textile fabrics during uniaxial tensile tests. Basset *et al*.[3] stated that it is hard to precisely measure the Poisson's ratio of fabrics due to lack of reliable experimental techniques. Giroud[4] investigated the Poisson's ratio of textile sheets used in nonwoven geomembranes and geotextiles. In this study, theoretical equations for calculating the Poisson's ratio as a function of strain were found. Sun *et al*.[5] using the fabric geometry, established theoretical equations for estimating the Poisson's ratio in the warp and weft directions. It was concluded that the Poisson's effect in a woven fabric is affected by the interaction between warp and weft yarns and can be expressed in terms of mechanical and structural parameters of system. Hursa *et al*.[6] concluded that the value of the Poisson's ratio depends on the weave type and the number of yarns in the fabric. Jinyun *et al*.[7] demonstrated that there is a significant Poisson effect for knitted fabrics under tensile deformation. In this research, a method for testing the elastic knitted fabric Poisson ratio and modulus was proposed based on orthotropic theory and strip biaxial tensile test. Ezazshahabi *et al*.[8] investigated the effect of weight reduction treatment on Poisson's ratio of microfiber polyester woven fabric. Statistical analysis of results showed that weight reduction at percentages lower than 25%, does not affect the Poisson's ratio of the fabric. Perumalsamy *et al*.[9] during the prediction of the deformation behavior of single jersey cotton knitted fabrics, revealed that the Young's modulus, Poisson's ratio and shear modulus of fabrics are reduced by increasing the loop length which leads to a rise in the deformability of the fabrics. Chen[10] evaluated the deformation of coated fabrics used for airship envelope

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considering the Poisson's ratio variation. It was concluded that the Poisson ratio variation is necessary to be considered for precise deformation prediction of large flexible airship and the significant deformation variation is found from only the change in the Poisson's ratio.

In this paper a more accurate measurement of the Poisson's ratio of worsted woven fabrics, considering the deformation behavior of the fabrics at various stages of extension has been investigated and the Poisson's ratio function in the terms of extensibility is presented. Besides, by quantifying the Poisson's ratio in two perpendicular directions (warp and weft direction), a comparison between the dimensional changes of the fabrics in the stated directions is carried out.

2 Materials and Methods

2.1 Materials

Weave structure, warp and weft densities (threads/cm), are the basic structural parameters of a woven fabric which affect the mechanical properties such as Poisson's ratio. So, in this study, nine various groups of worsted fabrics consisting of 3 different weave structures and 3 weft densities were utilized. The fabrics were made of 55% polyester and 45% wool. Other properties such as the yarn count (40/2 Nm) and the warp density remained constant for the fabrics investigated. The main characteristics of the fabric samples are listed in Table 1.

2.2 Test Procedure

Considering the fact that dimensional changes of fabric, especially at low extensions, are quite small, the special consideration in measurement including high accuracy and precision is required; otherwise results are prone to immense error. To meet this requirement, extra care in preparation and mounting of samples on the tensile testing machine and at different stages of experiments was taken. Additionally, a more accurate method of measurement was employed.

In order to measure the Poisson's ratio of the fabrics, digital recording of the fabric deformation during extension was carried out using the Instron tensile tester 5566. After the tracing of the lateral contraction of samples at different stages of extension via image processing techniques and by the utilization of graphical and CAD software, the Poisson's ratio was calculated using the following equation:

$$P = -\frac{\varepsilon_x}{\varepsilon_y} \quad \ldots (1)$$

where ε_x and ε_y are the lateral contraction and the extension strains respectively; and P, the Poisson's ratio.

The samples were extended only up to 12 % as after this extension point they were likely to buckle in the middle and also twisted at both edges, which causes an error in the results. For each fabric type, five samples with the dimension of 35cm × 5cm were tested in both warp and weft directions, on tensile testing machine with the gauge length of 20cm. Finally, the average Poisson's ratio values of five specimens were reported.

3 Results and Discussion

It is a known fact that a woven fabric is a non-isotropic material and its mechanical properties in different directions are dissimilar. Since most of the times fabrics experience tensile loads in the warp and weft directions, their behaviour in these two directions is considered more important. In this study, it is tried to observe the fabric tensile behaviour during extension in warp and weft directions and the variations in Poisson's ratio in these directions are calculated as a measure of fabric deformability during extension.

Table 1 — Fabric properties

Weave structure	Twill 3/1			Twill 2/2			Hopsack 2/2		
Density, cm^{-1}									
Warp		28			28			28	
Weft	19	21	23	19	21	23	19	21	23
Crimp, %									
Warp	6.5	5.2	4.9	5.2	4.8	4.3	4.2	3.6	3.2
Weft	6.6	7	7.4	6.8	6.9	7.3	7.4	7.5	8.2
Breaking load, N									
Warp	946	1018	1038	958	956	1042	945	1018	1038
Weft	725	762	832	663	726	816	665	747	816
Areal weight, g/m^2	251.3	257.2	270.2	245.4	263.2	269.7	244.4	260.5	271

The Poisson's ratio obtained for different sample groups for various levels of extension in both warp and weft directions are listed in Table 2.

3.1 Relationship between Tensile Load and Poisson's Ratio

During the extension of fabric on the Instron tensile tester, the dimensional changes of fabric in the direction of the exerted load and in the perpendicular direction to the loading are traced. Moreover, the value of the tensile load at different stages of the extension is recorded.

Variations in fabric Poisson's ratio in relation to the tensile load, which is applied to the fabric for different groups of fabrics in the warp and weft directions has been investigated. As an example, the diagrams of the variation in Poisson's ratio against the tensile load in two perpendicular directions (warp and weft), for 3/1 twill with the weft density of 21, are shown in Fig. 1. Similar trend is observed for all sample groups both in warp and weft directions.

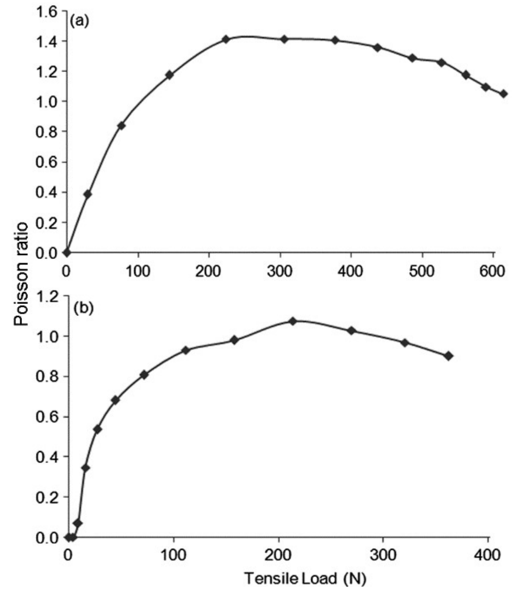

Fig. 1 — Poisson's ratio in relation to the exerted load for twill 3/1 with weft density of 21/cm [(a) warp-wise, and (b) weft-wise samples]

Table 2 — Poisson's ratio of warp-wise and weft-wise samples

Extension, %	19 cm^{-1}			21 cm^{-1}			23 cm^{-1}		
	Twill 2/2	Twill 3/1	Hopsack 2/2	Twill 2/2	Twill 3/1	Hopsack 2/2	Twill 2/2	Twill 3/1	Hopsack 2/2
Warp-wise									
1	0.32	0.43	0.78	0.63	0.39	0.10	0.47	0.05	0.00
2	0.82	1.04	1.53	1.06	0.84	1.04	0.76	0.79	0.82
3	1.04	1.36	1.80	1.27	1.18	1.55	1.25	1.02	1.29
4	1.28	1.48	1.85	1.39	1.42	1.71	1.31	1.30	1.56
5	1.43	1.54	1.90	1.46	1.42	1.63	1.43	1.34	1.53
6	1.38	1.50	1.84	1.40	1.41	1.62	1.43	1.39	1.48
7	1.40	1.48	1.69	1.39	1.36	1.55	1.35	1.35	1.40
8	1.38	1.42	1.55	1.34	1.29	1.40	1.32	1.31	1.34
9	1.31	1.30	1.45	1.24	1.26	1.35	1.22	1.22	1.25
10	1.24	1.24	1.36	1.12	1.18	1.25	1.19	1.17	1.16
11	1.14	1.17	1.28	1.06	1.10	1.16	1.12	1.11	1.07
12	1.08	1.09	1.20	0.97	1.05	1.07	1.04	1.02	1.00
Weft-wise									
1	0.18	0.05	0.04	0.08	0.00	0.00	0.00	0.00	0.00
2	0.26	0.14	0.08	0.26	0.07	0.12	0.21	0.15	0.13
3	0.39	0.35	0.22	0.37	0.35	0.29	0.34	0.37	0.34
4	0.58	0.49	0.31	0.51	0.54	0.36	0.54	0.58	0.40
5	0.73	0.62	0.46	0.72	0.68	0.57	0.71	0.70	0.53
6	0.85	0.78	0.59	0.81	0.81	0.70	0.82	0.89	0.67
7	0.93	0.87	0.68	0.95	0.93	0.75	0.98	0.97	0.81
8	0.98	0.91	0.71	1.04	0.98	0.84	1.07	1.07	0.96
9	0.94	0.93	0.75	1.10	1.08	0.89	1.15	1.15	0.97
10	0.91	0.92	0.74	1.11	1.03	0.85	1.16	1.13	0.99
11	0.87	0.88	0.73	1.06	0.97	0.85	1.15	1.09	0.96
12	0.82	0.86	0.70	1.01	0.90	0.82	1.09	1.06	0.91

In both warp- and weft-wise samples, the graph of Poisson's ratio shows a similar trend at different load values. It starts from a small value, followed by a gradual rise and after reaching the peak, decreases gently.

Considering Eq. (1), it can be explained that the Poisson's ratio of a fabric is the ratio of fabric dimensional changes in lateral direction to the direction of load application. In the first stages of the extension, the lateral contraction of the fabric in contrast to the extension is small, so the value of the Poisson's ratio is below 1. By continuing the extension and applying greater tensile loads, the rate of lateral contraction compared to the extension of the fabric increases, which leads to a rise in the value of the Poisson's ratio. In case the proportion of the contraction and the extension becomes the same, the Poisson's ratio of the fabric reaches the value 1. Due to the structural parameters of the fabric, such as the weave structure and the yarn density, the rate of horizontal contraction of the fabric can exceed the extension rate and in this situation the value of the Poisson's ratio becomes more than 1.

It should be noted that the crimp interchange of the fabric in this phase of the tensile test has a dominant role in the Poisson's effect of the fabric. By carrying on the tensile test, after complete de-crimping of the extended yarns, and also by gradual onset of the jamming condition, the rate of the dimensional change in the lateral direction decreases which reduces the value of the Poisson's ratio to below 1. After this stage, by extending the fabric, due to the locking of the yarns in the fabric construction, the strain in the width direction remains constant (ε_x = cte) and no further contraction occurs, while the longitudinal strain (ε_y) keeps rising. Thus, at large extensions the value of Poisson's ratio is expected to decrease steadily.

From the explanations given above, it is clear that the Poisson's ratio is a factor which demonstrates the dimensional changes of the fabric in two perpendicular directions during the application of tensile load. Thus, the total deformation of the fabric can be estimated through the calculation of the Poisson's ratio. As a result, it can be stated that the prediction of the Poisson's ratio in the fabric extension is important for determining the fabric tensile behaviour for various applications, such as the clothing, technical and industrial textiles. In this regard, by considering the variation of the Poisson's ratio at different load levels (Fig. 1), it is clear that the mentioned trend can be defined as a function of tensile load, as shown below:

$$P=P\,(L) \qquad \text{... (2)}$$

where P is the Poisson's ratio; and L, the tensile load.

It is proposed that Poisson's ratio variation as a function of load can be a kind of some trigonometric function. By application of the curve-fitting toolbox of MATLAB software, it is found that the Poisson's ratio variation could be expressed as:

$$P\,(L) = \sum a_i \times \sin(b_i \times L + c_i) \qquad \text{... (3)}$$

where a_i, b_i and c_i are the constant values, which depend on fabric properties.

The results of curve fitting for Poisson's ratio variation in terms of tensile load for twill 2/2 with the weft density of 19 cm^{-1} in both warp and weft directions are evident in Fig. 2. It is observed that for the case i=2, a good correlation for Poisson's ratio values can be obtained. The values of constants are summarized in Table 3 for warp and weft directions. According to Table 3, there is high correlation (> 92%) between experimental data and curve fitting results at 95% confidence level.

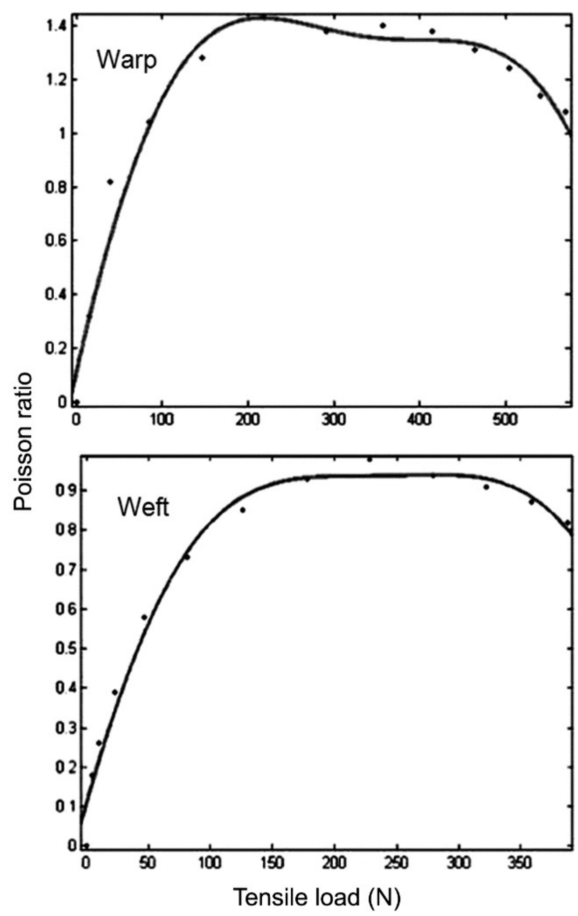

Fig. 2 — Results of curve fitting for Poisson's ratio as a function of tensile load (T2/2-19)

It should be emphasized that the Poisson's ratio is a determinant factor in the evaluation of fabric dimensional instability while tolerating tensile loads, which affects garment appearance and the efficiency of fabrics in various end uses. Thus, by the use of the Poisson's ratio functions in terms of exerted load [Eq. (3)], it is possible to evaluate fabric performance for a variety of loading conditions.

3.2 Comparison of Poisson's Ratio of Warp-wise and Weft-wise Samples

In order to compare the obtained Poisson's ratio in two perpendicular directions, the calculated Poisson's ratio is plotted for different stages of extension for both warp-wise and weft-wise samples (Fig. 3).

Generally, for the fabrics tested for each sample group, it is observed that the values of Poisson's ratio calculated for the specimens elongated in the warp direction are higher than weft-wise specimens, for all stages of extension. In addition, the Poisson's ratio of warp-wise specimen increases dramatically at small extensions, reaches the peak at around 5% extension and then gently reduces. On the other hand, the Poisson's ratio in weft-wise fabric tests increases at a gradual rate at small extensions and reaches its maximum at higher extension than in warp-wise samples (around 8%).

It should be noted that when a particular fabric (e.g. 2/2 twill with the weft density of 19) is tested in both warp and weft directions, the only factor changes in these two mentioned tests is the number of loaded yarns. In the investigated fabrics, the warp density is always higher than the weft density. So, when a fabric is extended in the warp direction, the number of yarns which are elongated by tensile tester

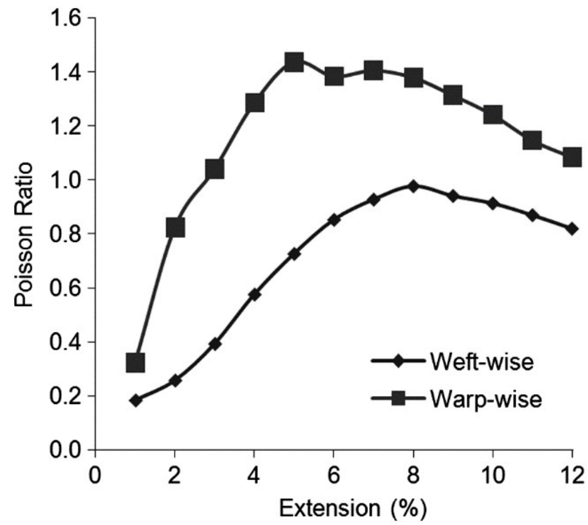

Fig. 3 — Comparison of the Poisson's ratio of warp-wise and weft-wise fabric samples (twill 2/2 with weft density of 19/cm)

Table 3 — Values of constants for Poisson ratio curve fitting for both warp-wise and weft-wise samples

Weave structure	Weft density, cm^{-1}	a_1	b_1	c_1	a_2	b_2	c_2	R^2
				Warp-wise				
Twill 2/2		6.022	0.006881	-0.7409	4.664	0.007941	2.033	0.9707
Twill 3/1	19	5.228	0.006036	-0.7072	3.74	0.007187	1.98	0.9904
Hopsack 2/2		10.89	0.006313	-0.7906	9.087	0.006944	2.093	0.9682
Twill 2/2		6.497	0.006316	-0.7233	5.107	0.007204	2.085	0.9615
Twill 3/1	21	3.773	0.005778	-0.6289	2.387	0.007256	1.91	0.9971
Hopsack 2/2		1.919	0.004355	-0.05448	0.2978	0.01144	0.029	0.9825
Twill 2/2		3.308	0.005298	-0.5371	1.909	0.006782	1.988	0.9881
Twill 3/1	23	2.557	0.005382	-0.5163	1.197	0.007659	1.709	0.9743
Hopsack 2/2		1.661	0.003994	0.01543	0.1779	0.01262	-0.7912	0.9808
				Weft-wise				
Twill 2/2		2.933	0.008996	-0.5914	1.996	0.01095	2.084	0.9835
Twill 3/1	19	1.012	0.005962	0.2028	0.1022	0.04361	-1.122	0.9395
Hopsack 2/2		0.7975	0.005617	0.1752	0.06468	0.0425	-1.13	0.9561
Twill 2/2		1.183	0.005481	0.2041	0.1133	0.04136	-0.9887	0.9525
Twill 3/1	21	1.152	0.00623	0.1781	0.1373	0.0428	-1.115	0.9379
Hopsack 2/2		0.9531	0.005859	0.2358	0.1537	0.04387	-1.009	0.9381
Twill 2/2		1.252	0.005572	0.179	0.1268	0.04195	-1.095	0.9498
Twill 3/1	23	1.25	0.00593	0.1924	0.1517	0.04247	-1.159	0.9422
Hopsack 2/2		1.091	0.005933	0.1909	0.1016	0.0422	-1.014	0.9279

is more, so the influence of them on weft yarns movement increases. This situation leads to a rise in the lateral contraction and apparently an increase in the value of the Poisson's ratio.

Taking into account the fabric properties (Table 1) it is found that the warp crimp is always lower than weft crimp, so the de-crimping phenomenon ends earlier in the warp direction, and as a result the Poisson's ratio of warp-wise samples attains the maximum point at lower extensions. Moreover, since the warp density is always higher than the weft density, the occurrence of the jamming condition for the warp-wise samples is at lower extensions compared to that for weft-wise samples, so after reaching the maximum Poisson's ratio, the reduction in the value of this property is more dramatic. The results obtained for the tested fabrics (Fig. 3) are the testimony for this observation. These variations in both directions can be a good guide for making use of the fabric in the correct direction for specific applications.

3.3 Effect of Fabric Structural Parameters on Poisson's Ratio

In order to investigate the effect of weave structure on the Poisson's ratio of fabrics, in both warp and weft directions, the values of the Poisson's ratio for a specific density group are compared. For the weft-wise samples (Table 2) in all density groups (19, 21 and 23 cm^{-1}) twill 2/2 and hopsack 2/2 had the highest and lowest Poisson's ratio respectively. On the other hand, for the warp-wise samples (Table 2), the maximum value of the Poisson's ratio belongs to the hopsack 2/2, followed by the twills 3/1 and 2/2.

Also, the influence of weft density on the Poisson's ratio of fabrics in two perpendicular directions is analyzed. It is observed that for the samples elongated in the warp direction, having all weave structures (twill 2/2, twill 3/1 and hopsack 2/2), fabrics with the weft density (/cm) of 19 showed the highest value of Poisson's ratio compared to the other density groups (21 and 23 cm^{-1}). On the other hand, for the weft-wise samples the density group of 19 has the lowest Poisson's ratio and the maximum Poisson's value is achieved for the fabric with the weft density of 23.

The above effects are attributed to the firmness of the fabric structure, the number of interlacing and the pressure points, which are affected by the weave pattern and the number of yarns in fabric construction (density). Statistical analysis of the results reveals that at the 95% confidence level, the effect of weave structure and weft density on the Poisson's ratio of woven fabrics is significant.

4 Conclusion

In the current study, a thorough investigation into the variations in Poisson's ratio of the woven fabrics in two prominent directions (warp and weft direction) during the tensile loading has been carried out. Poisson's ratio is an indicator of the fabric deformation and it is affected by the applied load. In this study, by defining the variation function of the Poisson's ratio in terms of the exerted load, it is made possible to predict the fabric performance during fabric extension.

Since woven fabric is a non-isotropic material, the value of Poisson's ratio varies in the two perpendicular directions, and it is necessary to individually estimate this property in the two mentioned directions. Thus, after the calculation of Poisson's ratio for the warp and weft directions, a comparison is carried out between these results. Analysis of results reveals that the values of Poisson's ratio calculated for samples experimented in the warp direction are always higher than the weft-wise samples. Considering the trend of Poisson's ratio in both directions (warp and weft) in various extensions, it is shown that the maximum value of Poisson's ratio in the warp direction happens at lower values of extension compared to the weft direction. These variations in both directions can be helpful for making use of fabric in the correct direction for a specific purpose. Fabric structural parameters such as the yarn density and the weave structure have a significant effect on the Poisson's ratio at 95% confidence level.

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