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Effect of weft yarn laying on tensile properties of weft-inserted knitted fabrics

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To investigate whether the combination of tuck and miss stitches can be used as an alternative method to produce weft-inserted fabrics, in cases where the weft knitting machine is not equipped with a weft insertion system, straight yarns with various densities and arrangements have been inserted in the course direction of rib weft knitted fabrics. The results of tensile tests in the course and wale directions denote that the use of straight yarns increases the tensile strength and tensile strain of the fabric in both directions, while the elastic modulus increases in the course direction. Furthermore, increasing the straight yarn density leads to an increase in the tensile strength and elastic modulus and a decrease in the tensile strain in both directions. Eventually, since the weft yarn arrangement has no significant effect on the fabric tensile strength and elastic modulus, this method can be used as an alternative method to produce weft-inserted fabrics.

Keywords: Double jersey fabric, Miss stitch, Polyester, Rib structure, Tensile properties, Tuck stitch, Weft insertion, Weft-knitted fabric

1 Introduction

Knitted fabrics are more flexible due to their loop structure. They exhibit reduced strength, higher elasticity, better shape retention, and recovery from bending as compared to woven fabrics[1]. Weft-inserted fabrics are knitted fabrics in which additional yarns are inserted in each course or in certain courses. These yarns are held by the loops of the fabric. The inserted yarns may be like stretch yarns to provide conformal properties or like high tenacity yarns to provide stability and good mechanical properties[2]. The presence of these yarns in the fabric structure increases the strength and compactness of the fabric[3].

The biaxial weft knitted fabrics have been widely used in industrial textiles[4,5]. Such structures with elastomeric yarns inserted are used for medical products, orthopedic stockings, and supports[3]. In weft-inserted warp knitted fabrics by inserting uncrimped yarns into the fabric, the use of these fabrics in load-carrying structural applications is allowable[1].

Up to now, woven and unidirectional reinforcements have been mainly used in industrial applications, like composite. The fibre arrangement has an important effect on mechanical properties. Complex shape piece manufacturing needs cutting and assembly operations, resulting in material waste and high production costs. This has led to the use of new reinforcement architectures, that are yarn-inserted knitted fabrics[6,7]. The yarns in the structure of biaxial weft knitted fabrics are responsible for providing the composite stiffness and strength[5].

Moreover, weft-inserted knitted fabrics are used in other industrial applications, such as geotextiles. In order to eliminate the weakness of the tensile strength of the knitted geotextile and hence to improve the tensile properties, weft inserted geotextile is used in which the flat and straight weft yarns are inserted in its structure[8]. Anand[9] modified the flat knitting machine, to produce reinforced weft knitted geotextile in the longitudinal and transverse directions by inserting natural thick fibres directly into the structure of the geotextile. The produced geotextile was more suitable for soil reinforcement due to its strength, frictional resistance, and environmental compatibility as compared to the knitted geotextile from synthetic fibre.

Balea *et al.*[10] investigated the effect of inlay yarns and fibre type (E-glass, basalt, and carbon fibers) on the mechanical behavior of plain knit reinforced composites. For this purpose, four plain knitted fabrics were produced and inlay yarns were inserted into the fabric in the course direction. Uniaxial tensile tests were performed on the fabrics in wale and course directions. The results revealed that inserting inlay yarns leads to an increase in the strength in the course direction, while it decreases the sample's

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deformation. Furthermore, the tensile behavior in the wale direction is not significantly affected by the inlays. Inlay yarns decrease the mechanical properties in 0°, whereas in 45° and 90° the properties are increased.

Xu *et al.*[2] produced co-woven-knitted (CWK) fabric and multi-layered biaxial weft-knitted (MBWK) fabric. The main difference between CWK and MBWK fabric is the ways of insertion of the warp and weft yarns. Glass filaments were used as warp and weft inserted yarns and high tenacity polyester as the knitting yarn. Tensile tests were done in the course, wale and bias directions of the composites, reinforced with these fabrics. Results showed that the tensile strength and elastic modulus of the two composites in the course and wale directions are better than those in the bias direction. Moreover, it was observed that different ways of yarns insertion lead to different buckling degrees of the warp and weft yarns of both composites. Furthermore, the buckling due to different ways of the warp and weft yarns insertion had a few influences on the tensile properties. According to the results, the use of CWK fabric has a good future in engineering applications.

Qi *et al.*[11] investigated the mechanical behavior and tensile properties of carbon/epoxy multilayer-connected biaxial weft knitted (MBWK) fabric-reinforced composite. For this purpose, samples reinforced with different multilayer-knitted structures, including three, four, and five-layer-connected biaxial weft knitted fabric were studied. Tensile tests were performed on MBWK fabrics reinforced composites in 0° (carbon fibre direction oriented along weft direction) and 90° (oriented along warp direction) directions and volume fractions of carbon fibre were different. They concluded that the increase in the number of connected layers of MBWK fabrics leads to an increase in the fibres volume fraction of composite samples. Also, volume fractions of carbon fibre have a remarkable effect on the tensile strength of MBWK composites. So, the increase in the number of connected layers of MBWK fabrics leads to improvement in the mechanical behavior and tensile properties.

Zhao *et al.*[12] investigated the mechanical properties of biaxial weft knitted fabrics (BWKF) reinforced composites. To produce these composites, they used bamboo fibres and PLA resin. Tensile and bending tests were done in two directions. Considering the characteristics of the composite's reinforcement and matrix phases as well as the biodegradable nature of bamboo fibres, they found that the natural BWKF composite has excellent tensile and flexural performance.

The purpose of this research is to consider whether the combination of tuck and miss stitches in a weft-knitted fabric can be used as an alternative method to insert straight yarns in the fabric's width, in the cases where weft knitting machine is not equipped with weft insertion system. How the fabric tensile characteristics are affected by the connecting distance of straight yarns in the fabric structure, is also studied.

2 Materials and Methods

2.1 Fabrics Production

In this research, double jersey weft knitted fabrics with rib 1×1 structure and constant loop length were produced on a 7-gauge manual flat knitting machine using 60/6 Nm polyester yarn. In order to strengthen the fabrics and to increase their dimensional stability, 110 tex high tenacity polyester yarns were inserted quasi-straight in the course direction of the fabrics using tuck and miss stitches. The yarns characteristics are presented in Table 1. In the other words, quasi-straight yarns were connected to the fabric structure using tuck stitches. Quasi-straight yarns insertion was performed with various densities and arrangements (Table 2). As illustrated in Table 2, fabrics denoted as WR1 - WR3 have the same straight yarn density (0.6 cm^{-1}) and different connecting distances of straight yarn. The connecting distance of straight yarn in WR1 to WR3 is 12, 26, and 40 needles respectively, and tuck stitches are formed on front and back needle beds alternatively. In WR fabric, the high-tenacity polyester yarns have been put completely straight in the fabric structure. Fabrics signified as $WR2_1$ to $WR2_3$ have the same connecting distance of straight yarn but different straight yarn densities as 0.4, 0.6, and 0.8 cm^{-1} respectively. Moreover, fabric with rib 1×1 structure (R) was produced as a reference fabric to compare the tensile properties of produced fabrics. After fabric

Table 1 — Yarns characteristics

Yarns	Linear density tex	Tensile strength N/tex	Tensile strain %
Polyester	16.66	0.37	25.38
High tenacity polyester	110	1.63	8.86

Table 2 — Running notation of produced knit pattern

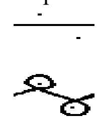
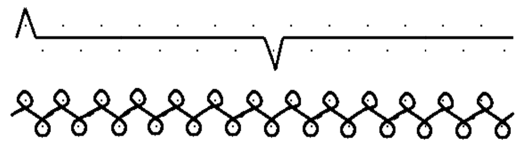
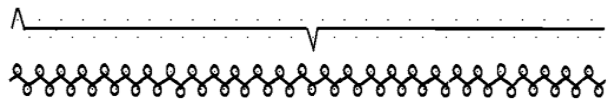
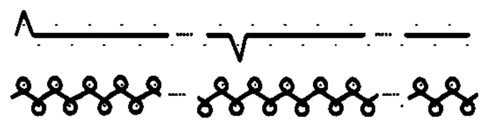
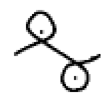
Fabric code	Straight yarn density, cm^{-1}	Knit pattern
WR	0.6	
WR1	0.6	
$WR2_1$	0.4	
$WR2_2$	0.6	
$WR2_3$	0.8	
WR3	0.6	
R	-	

Table 3 — Fabrics characteristics

Fabric code	c.p.c	w.p.c	Mass per unit area, g/m^2	Thickness mm
WR1	6	3.5	448	2.6
$WR2_2$	6	3.5	458	2.5
WR3	7	3.5	465	2.5
WR	7	4	456	2.6
R	7	4	454	2.6
$WR2_1$	6	4	442	2.6
$WR2_3$	6	4	465	2.6

production, fabrics were relaxed on a flat surface under laboratory temperature and humidity conditions of 23℃ and 56% RH for 24 h. Afterward, the fabric's structural parameters, such as course and wale densities, thickness, and areal weight, were measured according to existing standards. The results are presented in Table 3.

2.2 Uniaxial Tensile Test

Uniaxial tensile test was conducted on the fabrics using an Instron tensile tester (model 5566). From each fabric structure, five samples with the size 15×7 cm^2 were cut in the wale-wise and course-wise directions and tested using a gauge length of 5 cm at a constant speed of 300 mm/min. The samples were tested up to rupture. Load and elongation values were recorded and the average stress-strain curves were plotted. Stress was expressed as tensile force per unit width of the fabric, and the strain was defined as the relative elongation of the fabric.

2.3 Statistical Analysis

Quantitative results were statistically analyzed using one-way analysis of variance (ANOVA). Where a group of effects appeared statistically significant, Duncan's post-hoc test was used to determine whether the differences between multiple pairs are statistically significant using a statistical software package (SPSS). A statistically significant difference was reported if $p < 0.05$.

3 Results and Discussion

3.1 Effect of Weft Insertion on Tensile Behavior of Knitted Fabric

The average stress-strain curves of rib fabric (R), and weft-inserted fabrics in course-wise and wale-wise directions are illustrated in Figs 1 and 2. As can be seen, the elasticity of the rib fabric in the course direction (transverse direction) is more than in the wale direction (longitudinal direction).

As shown in Fig. 2, in the wale direction, the stress-strain curves of weft-inserted fabrics are similar to the stress-strain curve of rib fabric. However, in the course direction, the curves are different. In the stress-strain curves of weft-inserted fabrics in the course direction, two peaks are observed. The initial peak is related to the breakage of weft yarns (straight yarns)

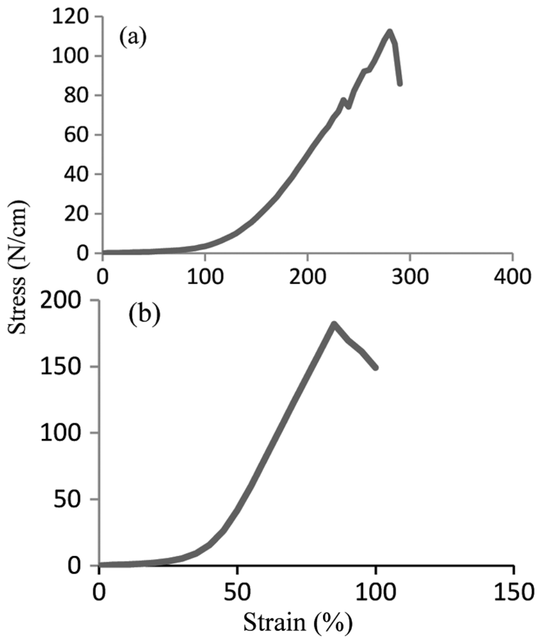


Fig. 1 — Stress-strain curves of rib fabric in (a) course direction and (b) wale direction

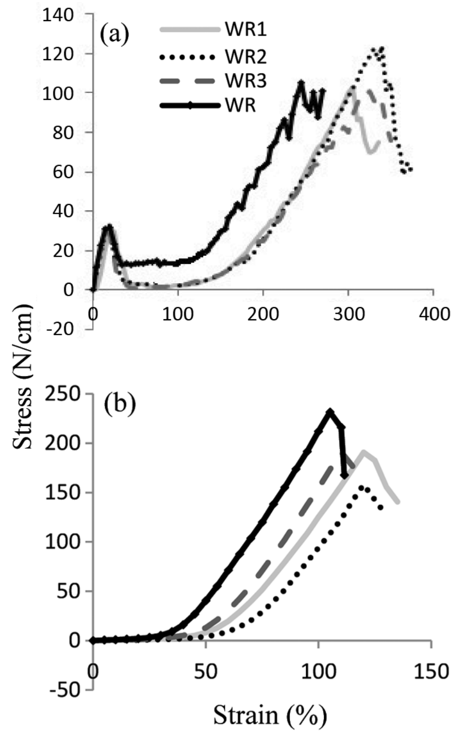


Fig. 2 — Stress-strain curves of weft inserted fabrics in (a) course direction and (b) wale direction

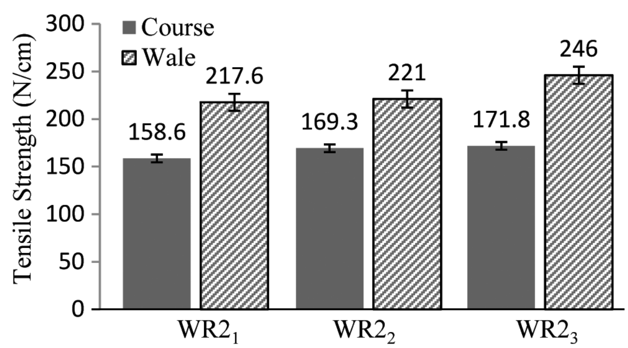


Fig. 3 — Effect of weft yarn density on tensile strength in course and wale directions

inserted in the fabric structure and the secondary peak is related to the rupture of loops in the knitted fabric structure.

3.2 Effect of Weft Yarn Density on Tensile Properties of Knitted Fabrics

In order to investigate the effect of weft yarn density on the tensile properties of weft-inserted fabrics, fabric sample denoted as WR2 is produced with three different yarn densities (0.4, 0.6, and 0.8 cm^{-1}). The effect of weft yarn density on the tensile properties of weft-inserted fabrics is discussed hereunder.

3.2.1 Effect on Tensile Strength

The tensile strength of weft-inserted fabrics includes the tensile strength of straight yarns inserted in the fabric structure and the strength of interlaced loops in the fabric structure. The mean tensile strength of weft-inserted fabrics with various weft densities in the course and wale directions are demonstrated in Fig. 3. It is obvious that by increasing the weft yarn density, the tensile strength of the fabrics increases in both directions. The increase in the strength of the fabric in the course direction is attributed to the fact, that by the increase in the weft yarn density, the number of straight yarns in the loading direction is increased.

The reason for increasing the strength of the fabric in the wale direction is that by increasing the weft yarn density, the number of contacting points between straight yarns and loops in the fabric structure increases, which subsequently enhances the friction between yarns and loops in the fabric structure. Consequently, the tensile strength of the fabric increases.

According to the statistical results, the weft yarn density has a remarkable effect on the tensile strength of the fabrics in the wale direction (p-value = 0.006), but the effect in the course direction is insignificant (p-value = 0.31).

3.2.2 Effect on Tensile Strain

Figure 4 displays the mean tensile strain of weft-inserted fabrics with various weft densities in the

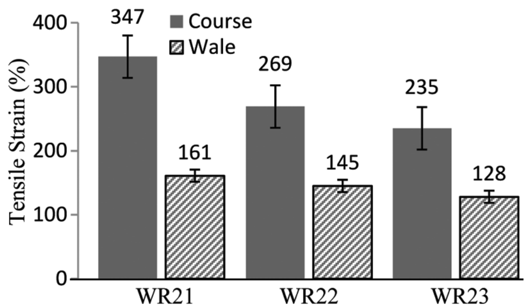


Fig. 4 — Effect of weft yarn density on tensile strain in the course and wale directions

Table 4 — Elastic modulus of fabrics in the course and wale directions

Fabric code	Elastic modulus, N/cm	
	Course direction	Wale direction
WR1	206.5	4.1
$WR2_1$	111	2.8
$WR2_2$	223.6	5.26
$WR2_3$	233	8.7
WR3	197.2	6.3
WR	211.07	9.8
R	1.55	10.6

course and wale directions. As can be seen, the increase in the weft yarn density has led to a decrease in the tensile strain of the fabrics in both directions. As mentioned formerly, by increasing the number of straight yarns in the loading direction, as well as increasing the number of contacting points between straight yarns and loops in the fabric structure, the fabrics resist more against elongation.

According to the statistical results, the effect of weft yarn density on the tensile strain of the fabrics in both directions is significant (p-value = 0.003, and 0.002 for course and wale directions respectively).

3.2.3 Effect on Elastic Modulus

The slope of the linear region in the stress-strain curves is taken as the elastic modulus of the fabrics. The elastic modulus of produced fabrics in the course and wale directions is presented in Table 4. As can be seen, by increasing the weft yarn density from sample $WR2_1$ to $WR2_3$, the elastic modulus increases in both directions. This increment is attributed to the increase in tensile strength and decrease in the tensile strain as a result of an increase in the weft yarn density.

According to the statistical results, the effect of weft yarn density on the elastic modulus of the fabrics in both directions is found significant (p-value = 0.003, and 0.00 for the course and wale directions respectively).

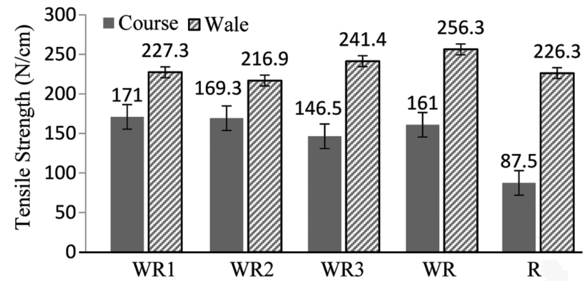


Fig. 5 — Effect of weft yarn laying on tensile strength of fabric in the course and wale directions

3.3 Effect of Weft Yarn Laying on Tensile Properties of Knitted Fabrics

In order to investigate the effect of weft yarn laying (arrangement) on the tensile properties of weft-inserted fabrics, fabric denoted as WR1 to WR3 with the same straight yarn density (0.6 cm^{-1}) and different connecting distances of straight yarn have been produced. The connecting distance of straight yarn in WR1 to WR3 is 12, 26, and 40 needles respectively, and tuck stitches are formed on front and back needle beds alternatively. Moreover, the WR fabric is produced in a way that the high-tenacity polyester yarns have been put completely straight in the fabric structure. The effect of weft yarn laying on the tensile properties of weft-inserted fabrics is discussed hereunder.

3.3.1 Effect of Weft Yarn Laying on Tensile Strength

Figure 5 demonstrates the mean tensile strength of weft-inserted fabrics with various weft yarn arrangements along with rib fabric, in the course and wale directions. It is obvious that weft-inserted fabrics exhibit higher tensile strength than rib fabric in the course direction. The reason is the presence of straight yarns in the structure of weft-inserted fabrics that reinforce the fabric structure. Taking a glance at Fig. 5, and according to the statistical result (p-value = 0.3), no significant differences are observed between various arrangements of the weft yarn in the fabric structure.

Moreover, Fig. 5 reveals that to some extent, weft-inserted fabrics display higher tensile strength than rib fabric in the wale direction, which can be due to higher friction between straight yarns and the loops of the fabric. According to the statistical results, the

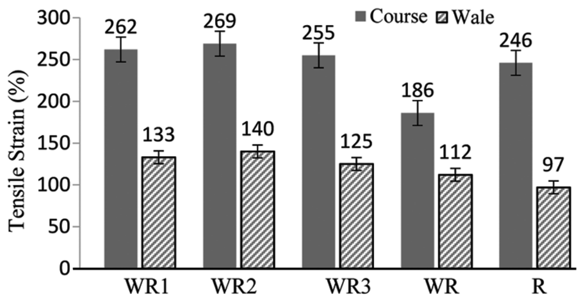


Fig. 6 — Effect of weft yarn laying on the tensile strain of fabric in the course and wale directions

effect of weft yarn laying on the tensile strength of the fabrics in wale directions is found significant (p-value = 0.019).

3.3.2 Effect on Tensile Strain

The average tensile strain of weft-inserted fabrics with various weft yarn arrangements along with rib fabric, in the course and wale directions are shown in Fig. 6. It is evident that all weft-inserted fabrics, except WR fabric, have higher tensile strain than rib fabric in the course direction. The tensile strain of weft-inserted fabrics consists of two parts. The first part is due to the elongation of quasi-straight yarns (weft yarns) in the fabric structure, and the second part is due to the elongation of the fabric as a result of slippage and movements of the loops in the fabric structure. Therefore, samples WR1 to WR3 have higher strain than rib fabric, due to the presence of quasi-straight yarns in the fabric structure. In the case of WR, the result is inversed. Since the weft yarn has been laid completely straight in this fabric structure, this yarn is crimpless and does not elongate under tensile stress, and restricts the elongation of the fabric. As a result, its strain is less than rib fabric.

Furthermore, Fig. 6 reveals that as the weft yarns are inserted more straight in the fabric structure (WR sample), the tensile strain of the fabric decreases in the course direction, which is an expected observation. Statistical results (Table 5) reveal that the effect of weft yarn laying on the tensile strain of the fabric in the course direction is significant and only WR fabric is different from others.

Figure 6 shows that as in course direction, the weft-inserted fabrics display higher tensile strain than rib fabric in the wale direction. As the weft yarns become more straight in the fabric structure, the tensile strain in the wale direction decreases. It can be attributed to the fact that the use of tuck stitches in the fabric structure causes the wales to become far from each other due to bias orientation of the tuck stitch's shanks. This leads to decrement in the wale density (w.p.c) of the fabric (Table 3). Consequently, when the weft-inserted fabrics are subjected to load in the wale direction, the fabrics exhibit higher tensile strain as compared to rib fabric, due to the closing of wales to each other.

Table 5 — Statistical results for the effect of weft yarn laying on tensile strain in course direction

Fabric	N	Duncan	
		Subset for alpha = 0.05	
		1	2
WR	5	186.00003	
R	5		245.99998
WR3	5		254.99981
WR1	5		261.99999
$WR2_2$	5		268.99999
Sig.		1.000	0.265
p-value	0.002		

According to the statistical results, the effect of weft yarn laying on the tensile strain of the fabrics in wale directions is found significant (p-value = 0).

3.3.3 Effect on Elastic Modulus

Table 4 shows that weft-inserted fabrics possess higher elastic modulus compared to rib fabric in the course direction. When the rib fabric is stretched in the course direction, at the first stage, slippage and movement of loops in the fabric structure occurs, which leads to fabric deformation. In the second stage, elongation of the yarns in the fabric structure happens, which eventually leads to fabric rupture. Consequently, the rib fabric displays high elasticity until the breaking point. Meanwhile, when the weft-inserted fabric is stretched in the course direction, at the first stage, weft yarns which are inserted almost straight in the fabric structure, withstand the applied force. Since these yarns are quasi-straight with little crimp, the elongation of the fabric due to the elongation of the inserted yarns is low and breakage of the straight yarns occurs fast. Hence, the weft-inserted fabrics exhibit lower elasticity and higher stiffness compared to rib fabric.

According to the statistical result (p-value = 0.00), WRI, WR2, WR3, and WR fabrics are in the same group but rib fabric is different from others.

On the contrary, Table 4 shows that weft-inserted fabrics display lower elastic modulus than the rib fabric in the wale direction, and when the inserted yarns are more straight in the fabric structure, the modulus of the fabric increases. The reason is the lower wale density of weft-inserted fabrics (as explained formerly), which decreases the resistance of the fabric to elongation in the wale direction. According to the statistical results, the effect of weft yarn laying on the elastic modulus of the fabrics in wale directions is significant (p-value = 0.00).

With regard to the results of tensile properties of weft-inserted fabrics (strength, strain, and modulus), it can be said that if weft inserting system does not exist on a weft knitting machine, a combination of tuck and miss stitch can be used as an alternative method to lay straight weft yarns in the fabric structure and achieved similar tensile properties.

4 Conclusion

In this research, the effect of weft insertion on the tensile properties of weft-knitted fabrics has been investigated. For this purpose, straight yarns with various densities and arrangements are laid in the course direction of rib weft knitted fabrics using tuck and miss stitches. Thereafter, the tensile characteristics of these fabrics are compared with rib fabric. The following influences are drawn :

4.1 The uase of straight yarns (weft yarns) in the fabric structure increases the tensile strength of the fabric in both course and wale directions.

4.2 The use of straight yarns in the fabric structure leads to an increase in the tensile strain of the fabric in the wale direction.

4.3 The use of straight yarns in the fabric structure increases the tensile strain of the fabric in the course direction, except sample with complete straight weft yarn.

4.4 By using straight yarns in the fabric structure, the elastic modulus of the fabric in the course direction increases.

4.5 The tensile strength and elastic modulus of the weft-inserted fabrics increase in both directions due to an increase in the weft yarn density.

4.6 The tensile strain of the weft-inserted fabrics decreases in both directions by increasing the weft yarn density.

4.7 Arrangement of the weft yarns in the fabric structure has no remarkable effect on the fabric tensile strength and tensile modulus, but as the weft yarns lay straighter in the fabric structure, the tensile strain of the fabrics decreases.

4.8 Combination of tuck and miss stitches can be used as an alternative method to produce weft-inserted fabrics, in cases where the knitting machine is not equipped with a weft insertion system.

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