EVALUATION OF ELASTICITY AND RECOVERY PROPERTIES OF SWISS DOUBLE PIQUÉ KNITS WITH FLAX-CONTAINING YARNS

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This study examined how the characteristics of flax-containing yarn affect the elasticity and recovery properties of Swiss double piqué knitted fabrics. Using three types of yarn – cotton/flax blend (70% cotton, 30% flax), PAN/flax blend (70% PAN, 30% flax), and pure flax – various knitted fabrics were produced with different stitch lengths on a 10-gauge circular knitting machine. The research focused on torsional stiffness, tensile stiffness, and yarn flexibility to understand their impact on the stretch properties of the fabrics. Results indicated that these properties significantly influence the stretch characteristics, particularly concerning average stitch length. Pure flax yarn exhibited reduced flexibility due to its higher torsion stiffness, low elasticity, and flexibility properties. As a result, the knitted fabrics produced from pure flax yarn showed the lowest level of widthwise elastic contribution and the highest level of widthwise residual contribution range, indicating lower stability than those from blended yarns. Blending flax with cotton or PAN in a 70/30 ratio decreased torsional and tensile stiffness compared to pure flax yarn. Fabrics made from blended flax yarns, such as cotton/flax and PAN/flax, demonstrated similar flexibility and loop shapes, which explained the comparable levels of density of the knitted fabrics. The similarity in flax blended yarn's flexibility and the relatively small differences in tensile stiffness contributed to insignificant discrepancies in elastic deformation. Understanding the factors that impact the shape and stability of fabrics is fundamental for developing high-quality knitted textiles and clothing that are comfortable and visually appealing to meet consumers' expectations.

Keywords: flax yarn, blended flax yarn, Swiss double piqué, stretch properties, elasticity

INTRODUCTION

Natural plant-based fibers like cotton and flax have been integral to the textile industry for centuries. Despite polyester's dominance as the most produced fiber globally, cotton maintains a significant position, holding a 27% market share in 2021/2022. Its popularity speaks to its quality and versatility, making it an essential component of fabric production.[1] Flax fiber has a market share of less than 1% and is mainly produced in France, Belgium, and the Netherlands, accounting for 80-85% of global production. As environmental sustainability becomes more important, flax fibers are increasingly used as biodegradable and non-toxic alternatives to synthetic materials. They also offer excellent specific strength and are non-abrasive.[2] Fibers can have different anatomical features even within the same species, affecting their density and mechanical properties. Generally, fibers with higher cellulose content and crystallinity are stronger. Their mechanical properties can also be influenced by microstructure and chemical composition. The variable cross-sectional area plays a key role in fiber strength. Also, plant-based fibers are hydrophilic, allowing them to absorb water, due to the presence of hydroxyl groups of hemicelluloses and cellulose.[3]

Growing environmental concerns have increased the relevance of plant-based natural fibers, particularly flax fiber. Researchers are exploring these sustainable alternatives to synthetic fibers and examining blends to enhance textile properties. Emphasizing plant-based fibers can lead to a more sustainable future, while meeting the needs of the modern textile industry.[4] Flax fiber has an average length of 33 mm, excellent mechanical properties, low density, high toughness, and significant strength. Its tensile and compressive strength and versatility make it popular for applications in clothing, composites, and cigarette papers.[5] Flax fibers are strong, highly absorbent, and hygroscopic. They protect against UV radiation, are skin-friendly, and do not cause allergies. With excellent thermal properties and low electrostatic charge, flax fibers are ideal for various textiles.[6] Combining different textile materials can enhance flax fiber's low elasticity, producing durable and versatile fabrics for various applications.[7] Researchers have investigated blending flax with other fibers to create yarns with different ratios, which could significantly enhance the use of flax in the textile industry. Combining cotton and flax improves moisture-wicking, air permeability, and durability. Unlike traditional cotton garments that can feel clammy when wet, cotton/flax blends dry faster and provide greater comfort, making them ideal for active individuals.[8,9] Research indicates that flax blend ratios of 80/20 or 70/30 with other fibers are optimal for the spinning process and yarn quality. After analyzing their relationship with the spinning process, these ratios are determined to provide the best yarn characteristics.[10-12]

Knitted products face various stresses and deformations during manufacturing and use, which can differ in intensity, direction, and duration. Repeated loading and unloading can compromise their integrity, causing dimensional changes and deformation, ultimately affecting their functionality and appearance. To reduce these issues, developing textiles that can withstand different stresses through careful selection of knitted structures is essential[13-15] or yarn types,[16] as the yarn's composition or the right knitted structure aids in recovery. Knitted fabrics are well-known for their distinct stretch characteristics, which make them popular for different clothing and textile uses. The elasticity of these fabrics is determined by several key factors, such as the type and arrangement of knitting elements like knit loops, misses (floats), and tucks.[17-23] Fabrics with the right stretch are versatile, suitable for casual wear, sports gear, and therapeutic compression garments.[24] The properties of strength, compression, and comfort in single jersey weft-knitted fabrics made from pure flax yarn are influenced by their structural characteristics.[25,26] The stretch properties of single-weft knitted fabrics depend on their structure. Stretch values typically decrease compared to plain knits, except in the wale-wise direction of single miss stitches.[27] The stretch properties are contingent on the types of knitted structures[28] and their structural characteristics.[29] The 1x1 rib's stretch properties depend on the direction of the tensile force.[30] According to the study,[31] the stretch properties of ribbed knit structures made from different types of yarn depend more on the ribbing variation than the type of yarn used. The tensile properties of knitted fabrics, such as 1×1 rib, half-cardigan rib, half-Milano rib, interlock, single-pique, and crossmiss interlock, are greatly affected by their density - higher fabric density results in increased tensile strength. Structures with combined miss and tuck stitches are ideal for winter outerwear fabrics,[32] and the properties of double-knitted fabrics are influenced by the miss-knit repeat[33] and tuck-knit repeats.[34] Research on knitted fabrics with different structures has shown that the knitting pattern significantly affects the strength and stretchiness of the fabrics.[35] Fabrics made with only stitches or stitches and short floats are the most stretchy and strong when pulled sideways, while fabrics with tucks in their structure are the most stretchy and strong when pulled lengthwise. The stretch properties of fabrics are primarily shaped by the choice of stitch length and heat-setting treatments in knitted fabrics[36] and elastane content.[37]

This study examines the influence of flax-containing yarn on the stretch properties of Swiss double piqué knitted fabrics. The findings aim to enhance our understanding of material behavior in textile applications. The analysis shows incomplete single stitches reduce fabric stretch across the width while enhancing dimensional stability. Unlike French piqué, Swiss piqué exhibits a less pronounced diagonal effect. Investigating both blended and pure flax yarns on a circular knitting machine expands the application of flax yarn and increases product variety. Combining single and double-knitted stitches reduces stitch density and saves on raw materials while maintaining thermal properties. To assess stretch properties, various yarns were used, including a cotton/flax blend (70% cotton, 30% flax), a PAN/flax blend (70% PAN, 30% flax), and pure flax with different stitch lengths. This research aims to provide a comprehensive understanding of the physical characteristics of flax yarns and their fabrics, particularly their stretch properties, which are crucial for producing high-quality, comfortable knitwear that meets consumer expectations.

EXPERIMENTAL

Materials

Variants of yarn

Three variants of flax-containing yarn (cotton/flax, PAN/flax, and pure flax) were used to produce Swiss double piqué knitted fabrics. The main characteristics of the yarns are presented in Table 1.

Knit fabrics

All samples were produced on a 10-gauge circular knitting machine, maintaining consistent main knitting parameters like the distance between cylinder (C) and dial (D) stitch cams, yarn tension during input, and fabric take-downs. However, the stitching cam position on the machine was subsequently adjusted.[20] Before knitting, the yarn underwent wax finishing treatment with 0.5% wax.[16] Figure 1 presents the illustrations of the Swiss double piqué knit structure with graphical representation.

Table 1
Main characteristics of the flax-containing yarns

Characteristics of yarns	Variants of yarn		
	I	II	III
Materials of yarn, %	70% cotton, 30% flax	70% PAN, 30% flax	100 % flax
Nominal linear density T_n in tex	25x2	31x2	46
Experimental linear density T_e in tex	49.2±1.0	61.5±1.0	50.9±0.5
Twist T in turns/m	303.1±9.4	100.9±6.7	246.3±28.9
Yarn thickness:			
- nominal diameter d_n in mm	0.288	0.379	0.289
- conditional diameter d_c in mm	0.205	0.250	0.198
- average diameter d_a I n mm	0.247	0.315	0.244
Torsional stiffness C_t	0.66±0.06	0.79±0.04	0.88±0.11
Breaking force P in cN	489±49	619±79	880±221
Tenacity P_u in cN/tex	10.69	10.09	17.12
Breaking elongation E in %	5.43±0.55	11.24±3.24	2.05±0.35
Tensile stiffness C_b	0.952	1.385	3.660
Spinning system	rotor	ring	wet
Standard	GOST 32086-2013[38]	GOST 32086-2013[38]	GOST 10078-85[39]

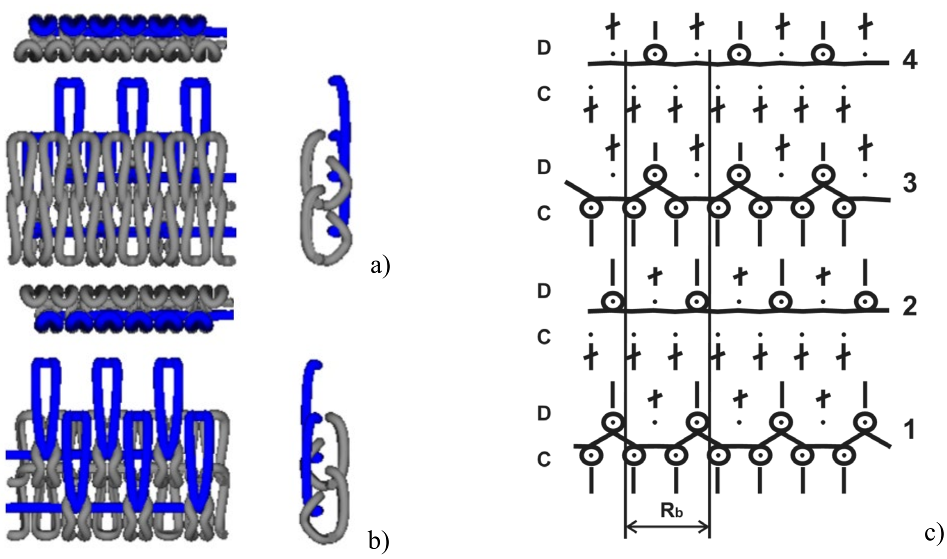


Figure 1: Illustrations of Swiss double piqué knit structures for the technical face (a) and back (b) with the graphical representation (c)

After knitting, all the fabrics underwent conditioning and stress recovery following the guidelines of ISO 139:2005[40] for standard atmospheres in textile conditioning and testing. Then, the knitted fabrics were washed according to ISO 6330:2021[41] for textile testing.

As shown in Figure 1, the Swiss double piqué structure includes four courses: two courses of 2x1 rib produced by the 1st and 3rd cam systems and two courses of single float stitches produced by the 2nd and 4th cam systems. This fabric's technical face and back differ (Fig. 1 (a, b)). The needles on the dial (D) are active when creating knit loops for the 2x1 rib stitch and single float stitch in the 1st and 2nd systems. The other needles are not in action on the dial in the first two systems: creating the knit loops for the 2x1 rib stitch and single float stitch in the 3rd and 4th systems. This process aligns the 2x1 rib loops and loops of the single float stitch created by different cam systems. The needles on the cylinder (C) create loops for the 2x1 rib stitch only in the 1st and 3rd cam systems; in the 2nd and 4th cam systems, they are inactive.

Methods

Determination of linear density, twist, and mechanical properties of the yarn

The samples were stored under standard atmospheric conditions[41,42] before the main characteristics of the yarns were measured. According to ISO 2060:2012,[43] the linear density was measured and presented as an average of twenty measurements per variant of yarn.

The yarn thickness of the yarn[44] was determined using the following equations:

nominal diameter d_n: $d_n = 0.0357 \cdot \sqrt{T\,\delta^{-1}}$, [mm] (1)

conditional diameter d_c: $d_c = 0.0357 \cdot \sqrt{T\,\gamma^{-1}}$, [mm](2)

where: T – the linear density of the yarn in tex, δ – the yarn volume mass in g/cm³ (δI = 0.77, δII = 0.55, δIII = 0.70), γ – density of yarn substance in g/cm³ (γI = 1.514, γII = 1.262, γIII = 1.500).

average diameter d_a: $d_a = \frac{d_n + d_c}{2}$, [mm] (3)

According to ISO 2061:2016,[45] yarn twists were measured, and the results presented are averages of twenty measurements per yarn type. The strength (breaking force and tenacity) and breaking elongation, as per ISO standards 2062:2012[46] and 6939:1988,[47] are based on an average of fifty measurements per yarn type. After that, tenacity P_u was calculated:

$$P_u = \frac{P}{T_n}, \text{[cN/tex]} \quad (4)$$

The resistance to extension was determined by analyzing the force elongation curve for each type of yarn to determine its tensile stiffness (C_b) characteristic (Young's modulus).[48] This value is obtained from the slope of the least squares fit a straight line made through the steepest linear region of the curve:

$$C_b = \operatorname{tg} \alpha \quad (5)$$

where α – angle of inclination of the tangent to the force elongation curve.

Determination of torsional stiffness of the yarn

To determine torsional stiffness (C_t), a torsion pendulum (Fig. 2) was developed by I.S. Pavlov.[49]

Determining torsional stiffness (C_t) involves folding yarn 1 as a loop 15 cm long and securing it in device clamp 2 (Fig. 2). Then, the secured yarn is thrown over hook 4 on the crossbar of stand 5. A light disc is suspended from the loop using hook 3, forming a torsion pendulum (Fig. 2). It begins to unwind in the opposite direction under the influence of reversible deformations of the yarn, and repeatedly winds and unwinds again as the torsion gradually fades away. The duration of the second period of unwinding (t) is measured using a stopwatch. Torsional stiffness (C_t) is expressed in conventional units, taking the yarn stiffness as a unit, with an oscillation period of 100 seconds, and is calculated using the formula:

$$C_t = \frac{10000}{t^2} \text{ [conventional units]} \quad (6)$$

where t is the time of the unwinding period, in seconds.

The presented results represent an average of thirty measurements per type of yarn.

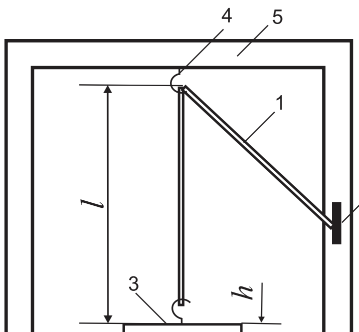


Figure 2: A torsion pendulum (l – suspension length (15 cm), D – disk diameter (6.3 cm), h – disk thickness)

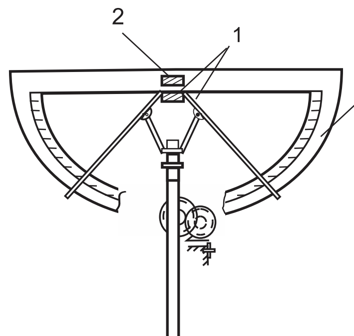


Figure 3: GV-2 flexometer device (1 – shelves, 2 – clamp, 3 – scale)

Determination of yarn flexibility

The method for determining the flexibility or stiffness of yarn is based on measuring the deflection of the test sample, which provides insights into the characteristics being studied. To assess the flexibility of flax-containing yarn and examine the impact of the sample size (a cantilever section of yarn) on yarn flexibility, an established method[50] was used, which consists of measuring the deflection of a cantilevered section of a yarn sample. For measurements utilizing this method, it is recommended to use the GV-2 flexometer device (Fig. 3).

After conditioning under a standard atmosphere according to ISO 139:2005,[40] at least 3 meters of yarn are unwound from the package before testing begins. The free end of the yarn is placed on a flat surface with an attached measuring ruler. An appropriate preload is applied to the yarn.[48] The required length of the sample is measured using a ruler and cut with a blade. To maintain a constant preload, samples are initially cut from the end of the yarn on the flat surface. The samples prepared are slightly straightened and placed between two glass plates, which are kept as such for at least 4 hours to induce relaxation. The distribution load on the samples is 0.1 g/cm. The length of the tested yarn samples was determined based on the device's design capabilities. The prepared samples are placed individually on horizontally positioned flexometer shelves 1, with clamp 2 securing the middle of each sample (Fig. 3). It is essential to ensure that the ends of the sample do not slide off the flexometer shelves. When the flexometer shelves are lowered, both ends of the sample, forming cantilevers, bend under their weight. When the sample detaches from the shelf, the deflection of any cantilevered section is measured using a scale of 3 (Fig. 3). The test result is calculated as the arithmetic mean of the deflection values from the two cantilevered sections of the test yarn. The presented results represent an average of thirty measurements per type of yarn.

Determination of strength properties of the knitted fabrics

The breaking force (P) and breaking elongation ($\mathcal{E}$) of knitted fabrics were determined after washing using ISO 13934-1:2013.[50] The results were obtained by averaging five measurements for both directions (lengthwise and widthwise) and for each variant of yarn tested. The results presented are an average of five measurements taken for each variant of knitted fabrics in each direction.

To calculate the dependence between the strength of knitted fabrics and the yarn used, the breaking force element (P_e) of the knit structure was calculated for each direction (breaking force per course or lengthwise and breaking force per wale or widthwise) using the following equations:

$$P_{e\,l} = k_l \cdot \frac{P_l}{W}, \text{ [N/course]} \quad (7)$$

$$P_{e\,w} = k_w \cdot \frac{P_w}{C}, \text{ [N/wale]} \quad (8)$$

where: k_l, k_w – the ratio of the length of the section (width) used in determining the density to the width of the test strip (in this case, $k_l = 1/5$; $k_w = 1/5$); P_l, P_w – the breaking force of the knit fabric lengthwise and widthwise, respectively, in N; W – the number of wales per centimeter in loops/cm; C – the number of courses per centimeter in loops/cm.

The resistance to extension of the fabric (tensile stiffness (C_b) or Young's modulus) was determined by analyzing the force elongation curve for fabrics from each variant of yarn.[48] Determining the tensile stiffness of fabrics (C_b) uses multiple tangents to the tensile curves at different elongation values. The tensile stiffness of the fabric or Young's modulus was determined according to Equation (5).

Determination of stretch characteristics of knitted fabrics

A thorough investigation of the stretch properties of knitted fabrics was carried out by the established standard GOST 8847-85[51] after undergoing washing. To conduct this research, a "rack" relaxometer was utilized, implementing a well-defined "loading-unloading-rest" cycle as described earlier.[16]

The fabric specimens were subjected to a 60-minute loading period with a constant load of 5% of the breaking force of the samples. Following this, the fabrics were allowed to rest for 120 minutes.[52] This cycle allowed for precise analysis and measurement of the stretch behavior of knitted fabrics under controlled conditions (Fig. 4).

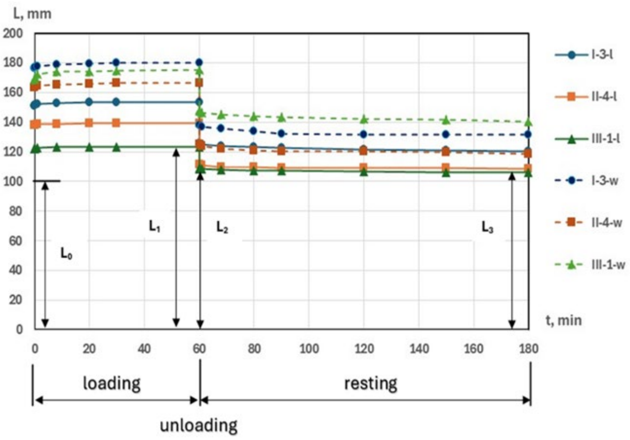


Figure 4: Length changes in specimen's length and width during the 'loading-unloading-resting' cycle for knitted fabrics from cotton/flax (I), PAN/flax (II), and pure flax (III) yarns with a similar average stitch length

For evaluating the elasticity of fabrics, the following types of deformation were calculated:

Fabric's total deformation (E): $E = \frac{L_1 - L_0}{L_0} \cdot 100, [\%]$ (9)

Elastic deformation (E_1): $E_1 = \frac{L_1 - L_2}{L_0} \cdot 100, [\%]$ (10)

Delayed elasticity (E_2): $E_2 = \frac{L_2 - L_3}{L_0} \cdot 100, [\%]$ (11)

Residual deformation (E_3): $E_3 = \frac{L_3 - L_0}{L_0} \cdot 100, [\%]$ (12)

where: L_0 – the specimen length between grips before testing, in mm (L_0 = 100 mm), L_1 – the specimen length between grips under loading for 60 min, in mm, L_2 – the specimen length between grips after unloading in mm, L_3 – the specimen length between grips after 120 min resting in mm.

For evaluating the elasticity of fabrics, the contribution of the components of full deformation was calculated:

Elastic Δ1: $\Delta 1 = E_1/E$ (13)

Delayed elasticity Δ2: $\Delta 2 = E_2/E$ (14)

Residual Δ3: $\Delta 3 = E_3/E$ (15)

Five measurements were taken lengthwise and widthwise to obtain precise measurements of each fabric variant, reflecting mean values. These results can be confidently used for future analysis and decision-making.

RESULTS AND DISCUSSION

Torsional stiffness of the yarn

According to the research findings, pure flax yarn (variant III) shows the highest twist and torsional stiffness irregularities compared to blended flax yarns (variants I and II). The pure flax yarn's torsional stiffness (C_t) is 0.88, while the PAN/flax yarn is 0.79 (refer to Table 1), demonstrating significant resistance to changing its shape during torsional deformation. In contrast, cotton/flax yarn (variant I) has a torsional stiffness value of 0.66, indicating the least resistance to changing its shape during torsion. Combining flax fiber with other fibers, such as cotton and PAN, in a 70/30 ratio reduces torsional stiffness by 25.0% and 10.2%, respectively, compared to pure flax yarn. This finding emphasizes the potential of blending flax with other fibers to effectively address its low torsional stiffness.

Strength properties of the yarn

Table 1 indicates that pure flax yarn (variant III) exhibits significant strength irregularities, increasing yarn breakage, and reduced knitting productivity. In comparison to cotton/flax (variant I) and PAN/flax yarn (variant II), pure flax yarn shows lower breaking elongation (Ɛ) and higher tenacity (P_u). However, the pronounced irregularities in breaking force and elongation of pure flax yarn contribute to knitting challenges. As shown in Table 1, the breaking elongation of PAN/flax yarn is significantly higher than that of cotton/flax (Ɛ-I) and pure flax yarn (Ɛ-III). When 30% flax fibers are added to the yarn composition, the breaking elongation of PAN/flax yarn is reduced, but it still has the highest breaking elongation compared to cotton/flax and pure flax yarns. PAN/flax yarn breaking elongation (Ɛ-II) is 3.7 times higher than cotton/flax yarn (Ɛ-I). PAN/flax yarn outperforms the other yarn types mentioned due to the characteristics of PAN fibers. It's worth noting that pure flax yarn has the lowest breaking elongation compared to blended flax yarns.[18] A comparison of the tensile stiffness or initial modulus (Young's modulus) shows that pure flax yarn demonstrates higher tensile stiffness (C_b) than cotton/flax and PAN/flax blends (Fig. 5).

This indicates that pure flax yarn experiences less extension for a given force, suggesting lower elasticity than blended flax yarn. The cotton/flax yarn has the highest tensile stiffness, indicating higher elasticity than pure flax and PAN/flax yarn. So, when flax fiber is combined with other fibers, such as cotton and PAN, in a 70/30 ratio, the tensile stiffness decreases to 0.952 (a reduction of 74.0%) and 1.385 (a reduction of 62.2%), respectively, compared to pure flax yarn (3.66). This indicates that blending flax with other fibers has the potential to effectively mitigate its low tensile stiffness, making it a promising approach for enhancing the overall performance of flax-based materials.

Yarn flexibility

The relationships obtained between yarn flexibility (f) and the length of the cantilever sample exhibit linearity across all yarn variants (Fig. 6). Notably, there is a significant overlap between the cotton/flax (I) and PAN/flax (II) yarns. Their graphs are nearly coincidental, which can be attributed to their compositions' similar flax fiber content. The pure yarn graph (III) differs slightly from the first two graphs. The deflection value for this yarn is lower by 1.3-3.4 times, compared to the first two, given the same sample cantilever length. This indicates that pure flax yarn exhibits less flexibility, which can be explained by the higher torsion stiffness and the smallest elasticity.

Figure 7 shows the loop formation of the 2+1 rib stitch using different types of yarn: cotton/flax, PAN/flax, and pure flax. The flexibility of the yarn plays a significant role in loop formation during knitting, which affects the shape of the loops and the characteristics of the final knitted fabrics (Fig. 8).

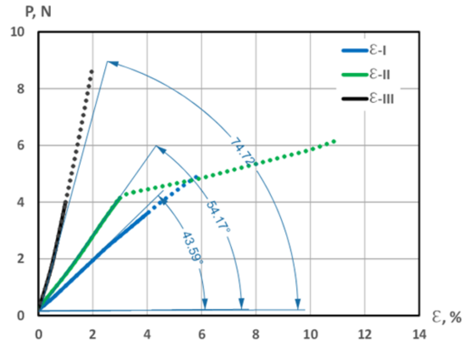


Figure 5: Breaking force (P) and breaking elongation (Ɛ) for cotton/flax (Ɛ-I), PAN/flax (Ɛ-II) and pure flax (Ɛ-III) yarns and their Young's modulus

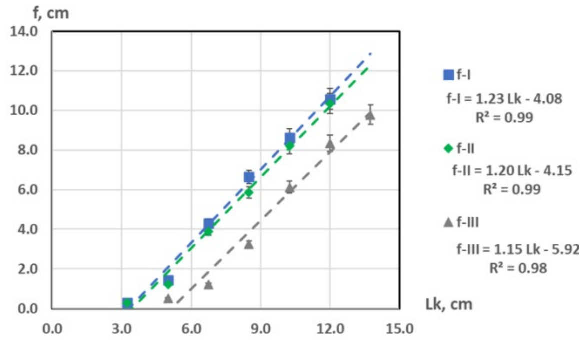


Figure 6: Dependence of yarn flexibility (f) on the length of the sample cantilever L_k for cotton/flax (I), PAN/flax (II) and pure flax (III) yarns

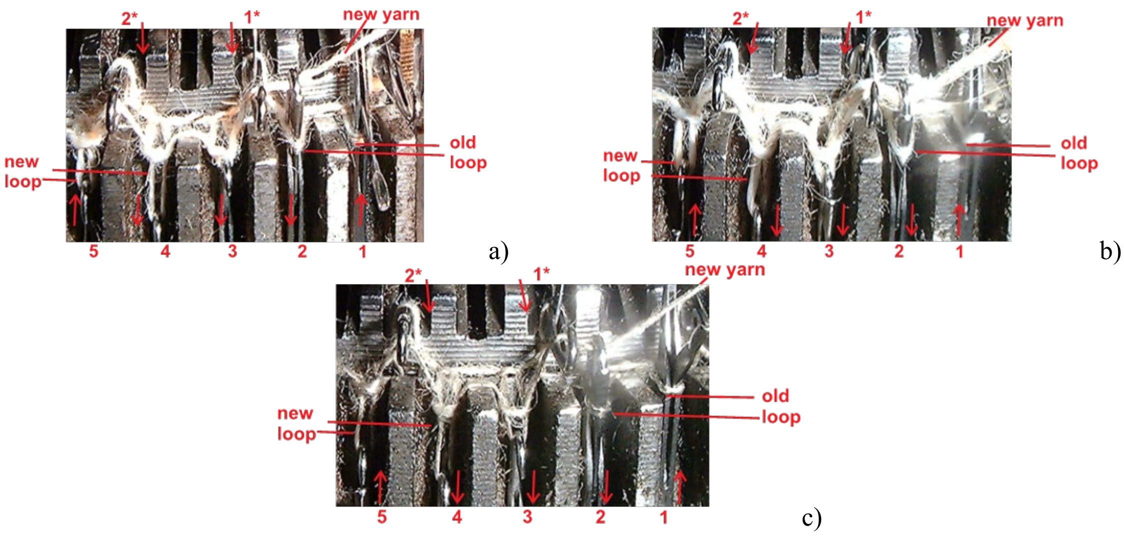
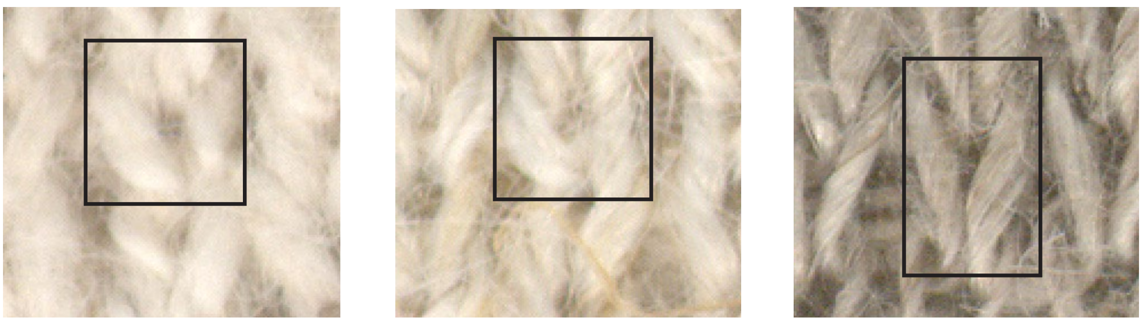


Figure 7: Knitting action during loop formation of the 2+1 rib stitch for cotton/flax (a), PAN/flax (b), and pure flax (c) yarns



a) b) c)

Figure 8: Loop shape on the technical face side of Swiss double piqué fabrics with a similar average loop length at 20× magnification: a) cotton/flax yarn (l_a = 5.85 mm), b) PAN/flax yarn (l_a = 5.85 mm), c) pure flax yarn (l_a = 5.91 mm)

When knitting, the yarn in old loops bends and slides over the hook and latch of the needle (cylinder's needles 1 and 2, disk's needles 1* and 2*), forming new loops (cylinder's needles 4 and

5). Yarn flexibility at this stage is crucial for maintaining the security of the old and new loops. Yarns with higher flexibility and lower stiffness are less likely to break and cause needle issues during processing, leading to a more efficient knitting process and better fabric quality.

Strength properties of the knitted fabrics

The breaking force (P) and elongation (Ɛ) of Swiss double piqué knit fabrics are affected by the variants of yarn, average stitch length (l_a), and weight (W_s) used. The results of measurements of strength properties in both directions (lengthwise and widthwise) of Swiss double piqué knit fabrics after washing are presented in Table 2. The relationships among the breaking force, average stitch length and weight for blended flax yarns (variants I and II) exhibit linear trends (Table 3).

This behavior also extends to breaking elongation, except for the widthwise breaking force element for PAN/flax yarn. When the average stitch length of cotton/flax knitted fabrics (variant I) is increased by 25.3%, the weight decreases by 24.5%, and the lengthwise breaking force element (P_{el}) decreases by 12.9%. The widthwise breaking force element (P_{ew}) decreases by 51.2%. In addition, the breaking elongation of these fabrics in both the lengthwise ($Ɛ_l$) and widthwise ($Ɛ_w$) directions also decrease. Meanwhile, when the average stitch length (l_a) of PAN/flax knitted fabrics (variant II) is increased by 14.1%, the weight decreases by 14.5%, and the lengthwise breaking force element (P_{el}) increases by 16.3%. However, the widthwise breaking force element (P_{ew}) slightly decreases by approximately 1.3% and shows a non-linear trend, as depicted in Table 3.

The lengthwise and widthwise breaking elongation of the PAN/flax knitted fabrics exhibit different trends. Specifically, the lengthwise breaking elongation ($Ɛ_l$) decreases, while the widthwise breaking elongation ($Ɛ_w$) increases. This trend can be explained by considering the influences of yarn composition and its properties. The relationships between the lengthwise breaking force, average stitch length, and weight for pure flax yarn (variant III) show linear trends (Table 2). This behavior also applies to lengthwise breaking elongation.

The relationships between the widthwise breaking force and weight show a non-linear trend (Table 3), and this behavior also extends to widthwise breaking elongation. When the average stitch length (la) of pure flax knitted fabrics (variant III) is increased by 11.3%, the weight decreases by 6.8%, and both lengthwise and widthwise breaking force elements (P_{el} and P_{ew}, respectively) increase by 18.3% and 11.0%, respectively. However, the lengthwise and widthwise breaking elongation of the pure flax knitted fabrics and the PAN/flax knitted fabrics show different trends. The lengthwise breaking elongation ($Ɛ_l$) increases, while the widthwise breaking elongation ($Ɛ_w$) decreases.

Table 2
Experimental values of strength properties of Swiss double piqué knit fabrics

Variant of yarn	Variant of fabric	l_a, mm	W_s, g/m^2	P_l, N	P_w, N	P_{el}, N/course	P_{ew}, N/wale	$Ɛ_l$, %	$Ɛ_w$, %
I	1	5.37±0.04	435.0±8.6	462.0±8.2	295.8±3.8	13.0	5.7	92.9±3.1	98.5±3.4
	2	5.55±0.05	382.5±5.8	412.0±14.4	236.4±11.9	12.1	4.4	88.3±2.5	101.3±3.1
	3	5.85±0.04	351.7±3.9	362.6±8.0	178.6±9.3	11.2	3.5	72.1±3.3	89.4±4.6
	4	6.08±0.11	368.3±3.6	384.6±9.9	180.2±9.9	11.7	3.9	68.0±2.8	93.8±1.5
	5	6.22±0.04	345.8±3.7	388.0±8.6	110.5±7.6	11.9	2.5	74.4±2.8	69.8±2.9
	6	6.53±0.05	338.0±2.3	309.7±10.5	135.3±3.8	10.2	3.2	70.7±2.3	86.1±2.7
	7	6.73±0.03	328.3±4.3	328.9±12.6	104.2±5.7	11.3	2.8	71.3±1.9	76.6±3.1
II	1	5.29±0.02	516.7±7.8	568.9±13.6	468.3±6.2	17.8	10.6	77.8±1.6	96.8±1.1
	2	5.47±0.03	506.7±8.6	562.9±3.9	467.2±2.8	17.1	10.7	79.2±1.9	100.1±1.4
	3	5.55±0.03	490.8±9.9	500.0±2.5	491.5±3.4	14.9	9.1	73.3±2.0	111.0±6.5
	4	5.85±0.04	453.3±7.8	576.8±5.6	369.2±4.5	17.0	7.0	66.6±2.7	109.6±4.6
	5	6.04±0.03	441.7±8.6	596.5±7.0	350.7±3.3	16.8	6.1	70.3±1.4	109.5±8.3
III	1	5.91±0.04	332.5±11.9	328.3±14.5	231.8±15.9	5.1	10.6	49.7±2.7	115.5±8.6
	2	6.18±0.14	328.3±8.5	325.0±13.5	214.3±9.7	5.8	10.0	51.2±3.9	103.3±6.0
	3	6.19±0.06	320.0±8.3	314.2±8.6	184.6±6.4	4.2	9.7	47.4±5.0	101.0±6.2
	4	6.57±0.05	310.0±4.7	363.4±28.7	214.9±9.8	5.9	9.7	57.4±4.4	102.6±3.2

* P_l – breaking force of the knit fabric lengthwise; P_w – breaking force of the knit fabric widthwise; P_{el} – lengthwise breaking force element of the knit structure; P_{ew} – widthwise breaking force element of the knit structure; $Ɛ_l$ – lengthwise breaking elongation; $Ɛ_w$ – widthwise breaking elongation

Table 3
Dependencies of strength properties of fabrics and average stitch length (l_a) and weight (W_s)

Variants of yarn	Lengthwise dependence	R^2	Widthwise dependence	R^2
I	$P_{el} = -1.32\ l_a + 19.59$	0.54	$P_{ew} = -1.86\ l_a + 14.94$	0.72
	$P_{el} = 0.02\ W_s + 4.36$	0.66	$P_{ew} = 0.03\ W_s - 6.80$	0.92
II	$P_{el} = 3.74\ l_a - 4.35$	0.63	$P_{ew} = -7.24\ l_a^2 + 81.62\ l_a - 220.94$	0.91
	$P_{el} = -0.03\ W_s + 32.62$	0.59	$P_{ew} = -0.0008\ W_s^2 + 0.80\ Ws - 183.80$	0.93
III	$P_{el} = 3.20\ l_a - 9.00$	0.62	-	-
	$P_{el} = -0.09\ W_s + 41.03$	0.69	$P_{ew} = -0.01\ W_s^2 - 4.43\ W_s + 718.87$	0.98
I	$\varepsilon_l = -15.65\ l_a + 171.44$	0.64	$\varepsilon_w = -17.41\ l_a + 193.18$	0.57
	$\varepsilon_l = 0.23\ W_s - 5.68$	0.71	$\varepsilon_w = 0.23\ W_s + 4.85$	0.52
II	$\varepsilon_l = -14.35\ l_a + 154.33$	0.68	$\varepsilon_w = 16.50\ l_a + 12.36$	0.58
	$\varepsilon_w = 0.14\ W_s + 5.13$	0.80	$\varepsilon_w = -0.15\ W_s + 179.33$	0.61
III	$\varepsilon_l = 12.31\ l_a - 25.02$	0.62	$\varepsilon_w = -17.44\ l_a + 213.95$	0.52
	$\varepsilon_l = 0.07\ W_s^2 - 44.61\ W_s + 7187.80$	0.88	$\varepsilon_w = 0.04\ W_s^2 - 28.33\ W_s + 4642.30$	0.82

Stretch characteristics of the knitted fabrics

The findings from the measurements of stretch characteristics, both lengthwise and widthwise, of Swiss double piqué knit fabrics post-washing are detailed in Tables 4 and 5, respectively.

The results showed that cotton/flax and PAN/flax knitted fabrics demonstrate a widthwise full deformation approximately 1.5 times greater than their lengthwise counterpart. In contrast, pure flax knitted fabrics exhibit a widthwise full deformation of 2.4 times more significant. The yarn variants influenced this process because the internal connections are influenced by the friction and adhesion forces between the individual fibers comprising the yarn and the intermolecular interaction forces within the fibers. The bent yarn's elasticity impacts the friction forces between the yarns in the knitted fabric. Pure flax yarn has the lowest torsional stiffness, tensile stiffness, and yarn flexibility than blended flax yarns. Figure 9 displays the distribution of deformations in Swiss double piqué knit fabrics, indicating the contributions of elastic (Δ1), delayed elasticity (Δ2), and residual (Δ3) deformations in both directions (lengthwise and widthwise). The analysis can provide insightful information about the individual contributions of distinct deformation components to the full deformation (E) in Swiss double piqué knit fabrics.

The results reveal that the knitted fabrics' lengthwise elastic contribution (Δ1l) remains consistent across various yarn variants.

Table 4
Lengthwise stretch characteristics of Swiss double piqué knit fabrics

Variants of yarn	Variant of fabric	l_a, mm	Type of deformation, %				Contributions		
			E	E_1	E_2	E_3	Δ1	Δ2	Δ3
I	1	5.37±0.04	43.4±3.7	25.2±1.3	3.6±2.0	14.1±1.3	0.59	0.08	0.33
	2	5.55±0.05	57.8±2.9	32.5±1.8	4.4±0.9	20.8±2.4	0.56	0.08	0.36
	3	5.85±0.04	52.5±6.3	27.9±2.3	5.0±0.6	20.4±3.7	0.52	0.10	0.38
	4	6.08±0.11	56.3±1.2	34.2±1.1	4.5±0.4	17.3±1.6	0.61	0.09	0.30
	5	6.22±0.04	53.0±5.3	32.7±2.5	4.4±1.1	15.5±2.2	0.62	0.09	0.29
	6	6.53±0.05	47.3±5.5	30.0±2.0	3.3±0.6	13.6±2.8	0.64	0.07	0.29
	7	6.73±0.03	54.3±1.8	33.9±2.7	5.2±1.0	15.4±1.4	0.62	0.09	0.29
II	1	5.29±0.02	38.4±2.4	27.4±2.1	2.8±0.8	8.0±1.4	0.72	0.07	0.21
	2	5.47±0.03	38.3±2.2	27.4±1.1	3.0±0.6	8.0±1.8	0.72	0.08	0.20
	3	5.55±0.03	41.9±1.5	29.2±0.7	3.4±0.4	9.3±1.0	0.70	0.08	0.22
	4	5.85±0.04	39.4±2.8	27.4±1.7	3.5±0.9	8.4±1.1	0.70	0.09	0.21
	5	6.04±0.03	42.5±5.2	29.5±2.3	2.8±0.6	10.2±1.7	0.69	0.07	0.24
III	1	5.91±0.04	23.4±4.3	14.2±1.5	2.8±1.0	6.0±2.5	0.62	0.12	0.26
	2	6.18±0.14	38.1±4.3	19.2±2.2	3.6±1.1	15.0±3.0	0.51	0.09	0.40
	3	6.19±0.06	28.7±1.4	16.8±0.5	2.9±0.2	9.1±1.4	0.58	0.10	0.32
	4	6.57±0.05	37.3±4.0	20.0±1.7	4.4±0.4	12.2±2.5	0.55	0.12	0.33

Table 5
Widthwise stretch characteristics of Swiss double piqué knit fabrics

Variant of yarn	Variant of fabric	l_a, mm	Type of deformation, %				Contributions		
			E	E_1	E_2	E_3	Δ1	Δ2	Δ3
I	1	5.37±0.04	65.5±6.7	33.7±2.5	5.7±1.7	25.6±2.5	0.52	0.09	0.39
	2	5.55±0.05	81.1±4.6	39.3±3.0	5.6±1.5	35.8±3.3	0.49	0.07	0.44
	3	5.85±0.04	80.1±6.0	42.1±1.7	6.4±1.1	31.5±2.8	0.53	0.08	0.39
	4	6.08±0.11	91.3±9.7	46.3±4.5	5.9±0.9	39.3±5.7	0.51	0.06	0.43
	5	6.22±0.04	65.0±7.7	43.4±3.6	6.7±1.6	15.2±1.5	0.67	0.10	0.23
	6	6.53±0.05	89.3±10.7	48.4±4.9	6.6±1.3	34.0±7.9	0.54	0.08	0.38
	7	6.73±0.03	65.5±6.2	33.7±3.8	5.7±1.2	16.2±1.9	0.67	0.10	0.23
II	1	5.29±0.02	47.4±1.9	31.4±1.8	5.6±1.1	10.2±1.2	0.66	0.12	0.22
	2	5.47±0.03	58.0±6.0	37.0±3.5	5.5±0.4	15.4±2.0	0.64	0.09	0.27
	3	5.55±0.03	56.4±5.4	34.2±2.2	4.8±0.8	16.6±2.5	0.61	0.09	0.30
	4	5.85±0.04	66.2±2.7	40.9±3.0	6.2±1.5	18.8±2.3	0.62	0.10	0.28
	5	6.04±0.03	63.4±5.8	36.3±1.9	7.7±1.2	19.2±2.5	0.58	0.11	0.31
III	1	5.91±0.04	75.1±11.8	27.4±3.3	7.9±1.2	40.2±9.7	0.36	0.10	0.54
	2	6.18±0.14	57.6±7.0	23.8±3.1	5.9±1.0	27.7±5.8	0.41	0.11	0.48
	3	6.19±0.06	66.4±14.2	29.4±4.4	6.0±0.7	30.5±9.8	0.44	0.10	0.46
	4	6.57±0.05	64.3±7.6	27.4±3.9	7.5±1.2	29.4±4.8	0.43	0.11	0.46

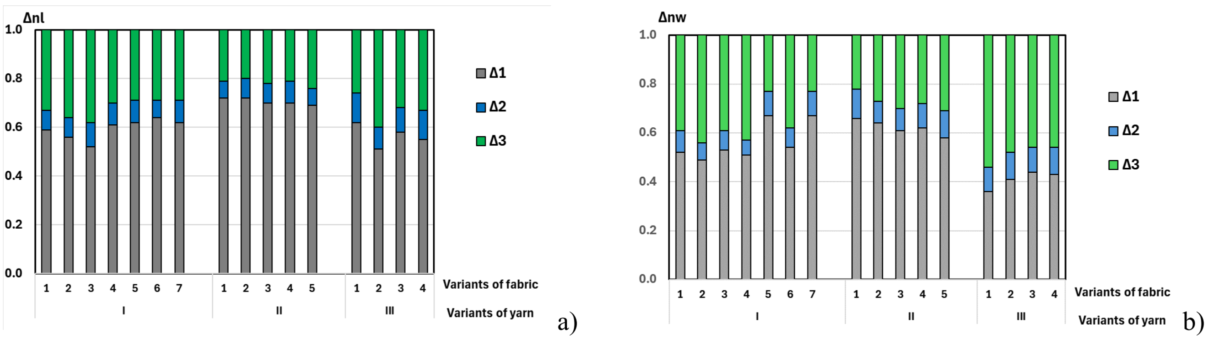


Figure 9: Contribution of elastic (Δ1), delayed elasticity (Δ2), and residual (Δ3) components of lengthwise (a) and widthwise (b) full deformation (E) of Swiss double piqué knit fabrics

These fabrics demonstrate a notable lengthwise elastic contribution (Δ1l), ranging from 0.56 to 0.70, emphasizing their ability to maintain their original lengthwise shape and dimensions. The most comprehensive range of average stitch length in knitted fabrics made from cotton/flax yarn explained the higher ranges of all types of deformations in both directions. As the average stitch length of knitted fabrics increases across all yarn variants, lengthwise and widthwise elastic deformation (E_1) rises. Knitted fabrics incorporating blended flax yarns, such as cotton/flax and PAN/flax, showcase a widthwise elastic contribution (Δ1w) of approximately 0.58 and 0.62, respectively. On the other hand, knitted fabrics produced from pure flax yarn exhibit a widthwise elastic contribution (Δ1w) of around 0.40.

The residual component in total deformation is an essential indicator for assessing the stability of knitwear. Its determination hinges primarily on the yarn variants and the direction of deformation, whether lengthwise or widthwise (refer to Fig. 9). The lengthwise and widthwise residual contribution (Δ3) depends on the variability of the yarn. The knitted fabrics from cotton/flax blended yarn and pure flax yarn have the lengthwise residual contribution (Δ3l), particularly in the same ranges (0.26-0.39).

The knitted fabrics from PAN/flax yarn have a lower range of the lengthwise residual contribution (Δ3l) between 0.21 and 0.24. The variability of yarn (Fig. 9) significantly impacts the widthwise residual contribution (Δ3w). The widthwise residual contribution of cotton/flax knitted fabrics ranges from 0.22 to 0.44, while the widthwise contribution of PAN/flax knitted fabrics ranges from 0.22 to 0.30. Pure flax knitted fabrics have an excellent widthwise residual contribution range, ranging from 0.46-0.54.

CONCLUSION

This study investigates the stretch properties of Swiss double piqué knitted fabrics made from yarns with varying flax content: a cotton/flax blend (70% cotton, 30% flax), a PAN/flax blend (70% PAN, 30% flax), and pure flax yarn. It highlights significant differences in stretch properties based on yarn characteristics, particularly between widthwise and lengthwise directions. Pure flax yarn displays reduced flexibility due to higher torsional stiffness and lower elasticity. Its fabrics have the lowest elastic widthwise contribution and the highest widthwise residual contribution, indicating lower stability. In contrast, the cotton/flax blend shows the highest tensile stiffness, suggesting greater elasticity. Blending flax with cotton or PAN reduces torsional and tensile stiffness, compared to pure flax yarn. The fabrics from these blended yarns exhibit similar flexibility and density levels.

This research focuses on stretch properties to enhance understanding of the physical properties of flax-containing yarns and their resulting fabrics. The insights gained are vital for producing high-quality, comfortable knitwear that meets consumer expectations, while contributing to sustainable fabric development.

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