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Comparison of Double Jersey Knitted Fabrics Made of Regenerated Cellulose Conventional and Unconventional Yarns

Primerjava desno-desnih pletiv iz regeneriranih celuloznih vlaken, izdelanih iz konvencionalnih in nekonvencionalnih prej

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Abstract

The development of new spinning technologies has produced cheaper yarns and with it, research into the production and application of woven and knitted fabrics from unconventional yarns. The tensile properties of knitted fabrics made of regenerated cellulose fibres (viscose, Tencel™ and modal) of the same count (20 tex) using ring, rotor and air-jet spun yarn were studied. The force/elongation diagram was analysed in order to detect elastic and plastic areas as well as the area of elastoplastic deformations responsible for the behaviour of knitted fabrics. The yarn raw material affects the elastic area of knitted fabrics made from different yarn structures in the course direction whereby the highest elastic area was obtained in the case of ring spun yarns followed by air-jet and finally rotor spun yarns. Regardless of the raw material, the elastoplastic area of the knitted fabric in the wale direction is the lowest for ring spun yarns. There is no visible trend of knitted fabric elastoplastic areas in the wale direction regarding the yarn type and raw material.

Keywords: regenerated cellulose fibres, conventional and unconventional spun yarn, double jersey fabric, tensile properties, elastic and plastic deformation

Izvleček

Razvoj novih tehnologij predenja je pripomogel k izdelavi cenejših prej, s tem pa tudi k raziskavam pri izdelavi in uporabi tkanin in pletiv iz nekonvencionalnih vrst predivnih prej. V prispevku je opisana raziskava nateznih lastnosti pletiv, izdelanih iz regeneriranih celuloznih vlaken (viskoza, Tencel™ in modal). Preje z enako linearno gostoto (20 tex) so bile izdelane po prstanskem, rotorskem in curkovnem postopku predenja. Diagrami sila-raztezek so bili analizirani, da bi ugotovili lastnosti elastičnih in plastičnih območij ter območja viskoelastičnih deformacij, ki so odgovorne za specifično obnašanje pletiv. Vrsta materiala, iz katerega so izdelane preje, vpliva na elastično območje pletiv, izdelanih iz različnih vrst prej v smeri zančnih vrst. Največje elastično območje je imela prstanska preja, sledila je curkovna in nazadnje rotorska preja. Ne glede na vrsto materiala je bilo viskoelastično območje v smeri zančnih stolpcev najmanjše pri prstanski preji. Pri viskoelastičnih območjih pletiv v smeri zančnih stolpcev ni razpoznavnega trenda glede na vrsto preje in vlaken.

Ključne besede: regenerirana celulozna vlakna, konvencionalne in nekonvencionalne predivne preje, desno-desno pletivo, natezne lastnosti, elastična in plastična deformacija

1 Introduction

In the late 1960s, the disadvantages of ring spinning machines (power consumption as well as maximum production speeds) led to the development of various spinning techniques that provide higher production speeds [1]. In the late 1960s and early 1970s, one of the new, completely different spinning systems was introduced which competed with the ring spinning system, i.e. the rotor spinning system. The rotor spinning system has lower production costs and is suitable for further automation; however, with limitations in the production of finer yarn counts (only medium and coarser yarns). Further development of higher production technologies, regarding the ring spinning technology, and finer yarns, regarding the rotor system, brought about the air-jet spinning system. In addition to the air-jet system, friction and wrap spinning systems were introduced as well, although all three mentioned systems were accepted with varying degrees of acceptance [1]. The superiority of the air-jet system over the ring and especially the rotor system was the possibility to produce finer yarn counts (in the range from 7.5 tex to 12 tex). The development of new spinning technologies has resulted in many different types of research that deepen the understanding of yarn structure as well as the structure of textile products made of new, the so-called unconventional yarns. New regenerated cellulose fibres find a wide range of applications in the clothing industry, especially for clothing worn close to the skin, as they offer very good comfort. Previous studies showed that the raw material composition of the yarn as well as yarn type have a significant influence on the properties of knitted fabrics. Regenerated cellulose fibres (viscose, modal, Viloft®, MicroModal®, lyocell and bamboo) were spun in conventional yarn counts for ring spun yarns from 19.7 tex to 21.1 tex, commercially used in the clothing industry (underwear, sportswear, T-shirts) [2]. Basic physical-mechanical yarn properties showed, due to the fibre type, significant differences. Tenacity ranged from 11.7 cN/dtex to 28.3 cN/dtex, elongation from 9.2% to 14.2%, *CVm* from 10.5% to 16.1%, number of thin places from 0 to 75, thick places from 1.3 to 142.5, neps from 25 to 326.3 and hairiness from 6.12% to 10.6%. The investigation of the influence of the fibre raw material on yarn tensile properties showed a significant influence of the raw materials tested in dry and wet state [3]. Yarns were conventional ring spun yarns from cotton, viscose and polyester of similar count (from 14 tex to 17 tex), paper yarns being produced by twisting Manila hemp paper fibres. The paper yarn count ranged from 19 tex to 33 tex. PES yarns have the highest percentage of elongation in the dry state, whereas paper yarns have the lowest. Unlike elongation, paper yarns have the highest breaking force and cotton yarns the lowest. A further investigation of the influence of the yarn raw material (100% cotton and 95%/5% cotton/Lycra) and the knitted structure (single jersey and 1 × 1 rib knitted fabric) on the tensile properties showed a significant influence of both the yarn raw material and the knitted structure [4].

The influence of conventional and compact ring spun yarns spun from American Upland cotton fibres spun in three yarn counts (19.7 tex, 14.8 tex and 11.8 tex) and the same twist factor ($\alpha m = 134$) on the tensile strength, pilling and abrasion properties of fabrics was investigated [5]. The results of tested yarn properties (tensile strength, unevenness and hairiness) showed that compact yarns of all counts had higher tenacity and elongation at break, less yarn unevenness, fewer thick places and neps, but a higher number of thick places and less yarn hairiness. Better properties of compact yarns could be found in a better fibre orientation compared to ring yarns. The fabrics made of compact yarns showed higher tensile strength, the reason being better strength of compact yarns, as the differences in the strength values of fabrics were similar to the differences in the strength between yarns.

The authors Suzuki and Sukigara investigated tensile properties and plain knitted fabric compression, bending and torsion properties, where knitted fabrics were made by conventional ring spun yarns, vortex and open-end spun yarns from rayon fibres [6]. The authors investigated the influence of different spinning systems on the bending and torsion properties of plain knitted fabrics. The authors found out that vortex spinning systems produce yarn structures that differ from ring and open-end spinning; however, they could not find a clear relationship between the mechanical properties of the fabric and yarn.

The dimensional stability of knitted fabrics is one of the most discussed areas in the research field of knitted fabric production. Many authors concentrate on research into the dimensional stability of knitted fabrics; however, only few on the influence of yarn type and yarn raw materials on fabric construction and tensile properties [7]. The influence of the yarn spinning technology on the spirality of jersey fabrics showed that yarns produced with different spinning technologies (ring, rotor, friction and air-jet spinning) affect the spirality of knitted fabrics differently [8].

In addition to different yarn types, the influence of cellulose yarns on the dimensional properties of knitted fabrics showed a significant effect of changes in stitch length on course and wale spacing [9]. The investigation of the physical-mechanical parameters of different yarn types (ring, rotor and air-jet) made of modal fibres showed significant differences in unevenness and yarn faults, hairiness and tensile properties [10].

However, the literature review showed that the influence of different yarn structures and fibre types on the tensile properties of knitted fabrics produced with the same machine parameters has not been systematically researched. In this paper, the tensile properties of knitted fabrics were investigated for spun yarns produced from regenerated cellulose fibres (viscose, Tencel™, modal) using the ring, rotor and air-jet systems. The force-elongation diagram was analysed to determine the elastoplastic deformation range (i.e. area between elastic and plastic deformation) that is responsible for the behaviour of the knitted fabric in use. The part of the diagram where elastoplastic deformations occur is particularly interesting for knitted fabrics used in the manufacturing of recreational clothing and/or clothing with a compression ratio from 0.5 kPa to 1.5 kPa. Testing the tensile properties, the moment of knitted fabric breakage, the maximum force and elongation at break is not disputable. However, it is not always easy to determine the elastoplastic area or the beginning of the permanent deformation of the knitted fabric. In the case of knitted fabrics made of yarns of different raw materials, fineness and structure, this area, i.e. the limit area of elasticity and area of permanent deformation, has not been sufficiently investigated. The mentioned limit area and area of permanent deformation are very important in the production of quality recreational clothing, especially compressional recreational clothes or clothing for professional athletes.

2 Materials and methods

2.1 Yarn and knitted fabric

The ring, rotor and air-jet spun yarns with a nominal count of 20 tex made of viscose, Tencel™ and modal fibres with a count of 1.3 dtex and length of 38 mm were spun. The number of twists for viscose ring spun yarns was 745 m^{-1}, 780 m^{-1} for Tencel™ and 746 m^{-1} for modal ring spun yarns. The rotor yarn twists were 750 m^{-1} according to the end use of spun yarns, i.e. for knitting. The viscose, Tencel™ and modal ring spun yarn were produced with the following procedure: preparation process (opening, blending and mixing), carding process, spinning preparation (drawing, pre-spinning and ring spinning), winding and cleaning. The yarns were spun using a Zinser 351 ring-spinning machine (ring diameter: 42 mm, ring type: f2, spindle speed: 16,500 min^{-1}), wound up and cleaned on an Autoconer X5. The rotor spun yarns made of viscose, Tencel™ and modal fibres were produced using the fibre preparation processes (opening, blending), carding, spinning preparation (drawing) and rotor spinning using a Schlafhorst A8 rotor spinning machine. The air-jet spun yarns were made of viscose, Tencel™ and modal fibres using the preparation (opening, blending) and carding process, spinning preparation (three drawing passages) and air-jet spinning using a Rieter J 20 machine. A double bed circular knitting machine was used to knit fabrics. The machine is generally used for knitting plain double-knit jersey fabrics intended for the production of underwear. It is recommended to knit with single cotton yarns with counts from 12 tex to 36 tex, as the machine gauge is E17. It has 8 knitting systems; therefore, it was necessary to prepare 8 yarn packages for each yarn group. To control the tension of the yarn fed to the knitting system, Coni Memminger IRO positive feeders were used. The force amounted to 3 cN ± 1 cN. The fabric take-down was performed with two pairs of rollers located 70 cm away from the knitting zone. The fabric was not wound onto a fabric roll, but it was plaited down on the tray below the take down rollers. Viscose, Tencel™ and modal ring, rotor and air-jet spun yarns with a nominal count of 20 tex were used to knit the fabrics.

2.2 Test methods for yarns and knitted fabrics

The count of yarns was determined according to the ISO 2060:2008 standard, while ring spun yarns were twisted according to 2061:2015. The twist of rotor spun yarn was determined according to machine parameters (rotor speed), while the air-jet yarn twists were determined according to air pressure (vortex). The twist of rotor spun yarn was determined according to machine parameters (rotor speed), while the twist of air-jet spun yarn was determined according to air pressure (vortex). The yarn tensile properties were determined in accordance to the standard ISO 2062:2009 Textiles – Yarns from packages – Determination of single-end breaking force and elongation at break using constant rate of elongation (CRE) tester. The measurement of tensile properties was made on an Uster Tensorapid 4 instrument, with 100 measurements per package of each yarn type. The images of the ring, rotor and air-jet spun yarn structure were taken with a Dino-Lite digital microscope (constant magnification of 60×).

The tensile properties of knitted fabrics were measured in the course and wale directions with 50 mm wide and 200 mm long samples. The distance between the grippers of the tensile strength tester was 100 mm. Tensile properties were tested on a STATIMAT M tensile tester according to the standard ISO 13934-1. The results of breaking force and breaking elongation, work of rupture, strength and the force-elongation (*F*/*Ɛ*) diagram were determined. The force-elongation diagrams obtained were analysed as follows.

The knitted fabric is subjected to the effect of the tensile force due to the tension elongation that occurs. The *F*/*Ɛ* diagram of knitted fabrics can be divided into three main areas, i.e. elastic area, elastoplastic area and plastic area. In the first, elastic area (from point 0 to T1), the action of the tensile force causes a certain amount of elongation due to the movement of yarn within the knitted structure (cf. Figure 1). In the region from 0 to T1, the stress and strain are not proportional. However, if we remove the load, the body returns to its original dimension. The elastic part of the knitted fabric on the *F*/*Ɛ* curve is linear. In the non-linear elastoplastic or viscoelastic area (from point T1 to point T2), besides the yarn movement within the structure, a loosening of yarns occurs. In the non-linear elastoplastic area (from point T1 to point T2), besides the thread movement within the structure, the threads loosen. Point T2 is the point of inflexion after which the third area begins up to point T3, the area of plastic permanent deformation of the knitted fabric. In point T3 (knitted fabric breakage), individual yarns within the knitted fabric structure break until the complete fabric breakage occurs. The tangents at points T1 and T2 intersect in point T4, which is the point of critical elongation. Critical elongation is associated with force and elongation where the knitted fabric is tightened and the transition of the knitted fabric from the relaxed to the solid state occurs [9].

In the research, the main area of interest is the elastoplastic area or the limit area of elasticity and the area of permanent deformation of knitted fabrics. From the results obtained, parts of the elastic, elastoplastic and plastic surface of knitted fabrics with different yarn structure and fibre type were calculated.

3 Results and discussion

The fineness of yarns is uniform and ranges from 19.9 tex to 20.5 tex with a low coefficient of variation

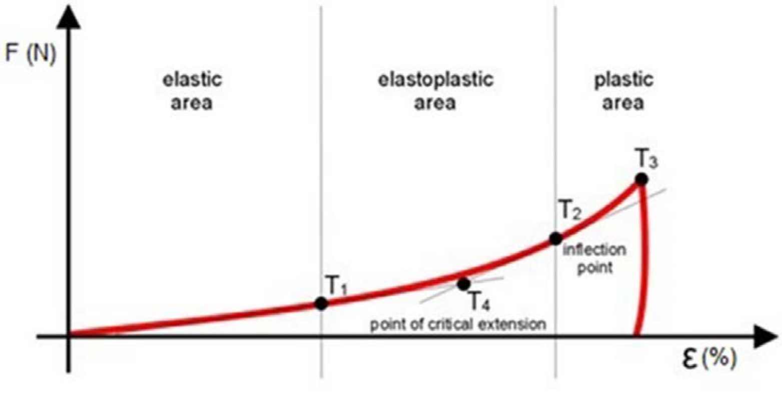

Figure 1: Knitted fabric F/Ɛ diagram

(in the range 0.3% to 1.3%), indicating high quality yarns.

Generally, yarn twist number is defined related to the yarn end use. The yarns used in the experiment are intended for the knitting process and have uniform twists with a low coefficient of variation (1.9% to 4.0%). The twist number of ring spun yarns slightly differs with regard to different raw material, i.e. viscose ring spun yarns have 744.7 m^{-1}, modal 746.1 m^{-1} and Tencel™ spun yarns have 779.7 m^{-1}. The nominal twist number of rotor yarns calculated from the rotor speed amounted to 750 twists per meter. The high pressure of the air in the rotating vortex was 0.6 MPa. The number of twists of all tested yarns was uniform, with a twist coefficient ranging from 3,280 to 3,350 m^{-1} $tex^{0.5}$.

Ring, rotor and air-jet spinning processes produce yarns with completely different structures and thus yarns with different properties. Figure 2 shows the yarn structure with characteristic twists of ring, rotor and air-jet spun yarns. The Tencel™ ring spun yarn consists of straight and parallel fibres twisted in the Z direction (cf. Figure 2a). Figure 2b shows the Tencel™ rotor yarn with disoriented fibres wrapped around the folded core. Tencel™ air-jet yarn fibres are tightly wrapped around the core of parallel, straight fibres (cf. Figure 2c).

The values of the yarn tensile properties, i.e. maximum force, elongation at break, tenacity and work of rupture, are given in Table 1. Viscose, Tencel™ and modal ring spun yarns have a higher maximum force, followed by air-jet and then rotor spun yarns. The difference in the maximum force of tested yarns is the result of yarn spinning techniques that produce different yarn structures. In general, friction forces within the yarns (between the fibres) ensure the resistance of yarn to the applied tensile force. The friction forces between the fibres depend on the number of fibres in the cross-section and the twists of yarns. As the ring, rotor and air-jet yarns

ring spun yarn rotor spun yarn air-jet spun yarn

Figure 2: Tencel™ ring, rotor and air-jet spun yarn images taken with Dino-Lite digital microscope (60× magnification)

Table 1: Yarn tensile properties

Fibre	Spinning process	Tensile properties											
		Breaking force			Breaking elongation			Tenacity			Work of rupture		
		$\bar{X}$ [a] (cN)	SD [b] (cN)	CV [c] (%)	$\bar{X}$ [a] (%)	SD [b] (%)	CV [c] (%)	$\bar{X}$ [a] (cN/tex)	SD [b] (cN/tex)	CV [c] (%)	$\bar{X}$ [a] (cNcm)	SD [b] (cNcm)	CV [c] (%)
Viscose	Ring	347.6	4	1.1	15.2	0.4	2.6	17.4	0.2	1.1	16.8	0.5	2.9
	Rotor	272.7	3	1.1	10.9	0.3	2.7	13.6	0.2	1.1	9.7	0.2	1.9
	Air-jet	313	4.8	1.5	12.4	0.3	2.2	15.6	0.2	1.5	12.1	0.4	3
Tencel™	Ring	551.8	12.7	2.3	10.1	0.1	1.4	27.5	0.6	2.2	16.5	0.5	3
	Rotor	387	4.5	1.2	8.4	0.1	1.5	19.4	0.2	1.2	9.5	0.1	1.6
	Air-jet	403.7	8.5	2.1	8.8	0.2	2.8	20.2	0.4	2.1	10.5	0.4	3.8
Modal	Ring	476.2	8.1	1.7	10.8	0.2	1.5	23.8	0.4	1.7	14.8	0.3	2.1
	Rotor	307.9	5.1	1.7	8.2	0.1	1.6	15.4	0.3	1.7	7.7	0.2	2.7
	Air-jet	415.4	9.4	2.3	9.2	0.2	2.5	20.8	0.5	2.3	11.2	0.4	3.9

[a] average, [b] standard deviation, [b] coefficient of variation

are produced with the same count and have approximately the same number of fibres in the cross section, different maximum forces result from different fibre rearrangement and yarn twist. When comparing the same yarn type made of different fibre types, a significant difference in maximum force is apparent. The maximum force difference for ring spun yarns ranges from 13.7% to 58.8%, for rotor spun yarns from 9.1% to 41.9% and for air-jet spun yarns from 2.9% to 29.0%. Therefore, it can be concluded that the greatest difference in maximum yarn strength within the same group of yarn types consisting of different fibres (viscose, Tencel™ and modal) is found in ring spun yarns, followed by rotor spun and finally air-jet spun yarns, where the difference is the smallest. The type of fibres affects the maximum yarn force regardless of the yarn structure; however, depending on the yarn structure, the difference in the maximum force will be greater or smaller (cf. Figure 3).

The yarn elongation within the same yarn type is the highest for viscose, followed by modal and Tencel™ yarns. Regardless of the fibre type, ring spun yarns have the highest elongation, followed by air-jet and rotor spun yarns (cf. Figure 3). The same trend is visible for yarn work of rupture. Ring spun yarns have the highest work of rupture, followed by air-jet and rotor spun yarns. The difference in work of rupture between the same types of viscose, Tencel™ and modal yarns is not significant (cf. Table 1).

The basic knitted fabric parameters are presented in Table 2. The table shows that the parameters

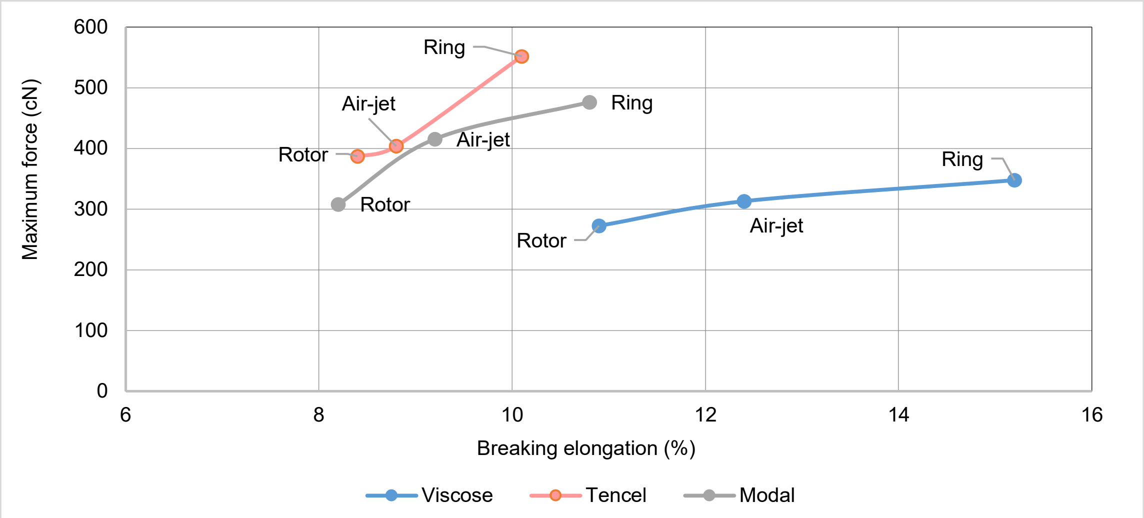

Figure 3: Ring, rotor and air-jet spun yarns F/Ɛ diagram

Table 2: Basic parameters of double jersey knitted fabric

Fibre	Spinning process	D_c a)			D_w b)			T c)			M d) (g/m²)	$L_{u,a}$ e) (1/cm²)	Vm f) (g/cm³)	S g) (%)
		$\bar{X}$ h) (1/cm)	SD i) (1/cm)	CV j) (%)	$\bar{X}$ h) (1/cm)	SD i) (1/cm)	CV j) (%)	$\bar{X}$ h) (mm)	SD i) (mm)	CV j) (%)				
Viscose	Ring	10.9	0.2	1.9	11.8	0.1	1.2	0.63	0.01	1.9	165	257	0.262	39
	Rotor	8.6	0.2	1.8	12	0.1	0.6	0.59	0.01	1.52	131	206	0.222	22
	Air-jet	9	0	0	12	0	0	0.58	0	0.44	127	216	0.219	25
Tencel™	Ring	10.8	0.2	1.6	11.8	0.2	1.5	0.63	0.01	1.64	152	255	0.241	36
	Rotor	9.2	0.2	1.8	12.1	0.1	0.9	0.61	0.01	1.46	128	223	0.21	25
	Air-jet	9	0	0	12.3	0.2	1.7	0.62	0.01	1.17	132	221	0.213	25
modal	Ring	10.3	0.3	2.6	11.8	0.2	1.4	0.58	0.01	1	155	243	0.267	36
	Rotor	9	0	0	12.2	0.2	1.4	0.61	0.01	0.84	128	220	0.21	25
	Air-jet	9.1	0.1	1.3	11.6	0.1	1.1	0.6	0.02	2.76	131	211	0.218	25

a) Loop density in course of fabric, b) loop density in wale of fabric, c) fabric thickness, d) mass per unit area, e) number of loops per unit area, f) knitted fabric volume mass, g) shrinkage in course direction, h) average, i) standard deviation, j) coefficient of variation of knitted fabric structures are influenced by both the yarn types and the raw materials from which the yarns are spun. Mass per unit area (M, g/m^2) is the most significant structure parameter, especially for plain knitted structures. For the analysed unfinished samples of plain double jersey fabrics, the mass per square meter of the knitted fabric ranged from 127 g/m^2 ± 3 g/m^2 to 165 g/m^2 ± 3 g/m^2. The samples knitted with the yarns spun on rotor and air-jet spinning machines have the mass per unit area from 127 g/m^2 ± 3 g/m^2 to 132 g/m^2 ± 4 g/m^2, and statistically speaking, they are not significantly different. The samples knitted with the yarns spun on ring spinning machines have significantly higher mass, ranging from 152 g/m^2 ± 3 g/m^2 to 165 g/m^2 ± 3 g/m^2. The difference of mass per unit area was up to 38 g/m^2 or 23%. This is an important conclusion for the commercial mass production, which leads to the conclusion that it is very complex to produce knitted fabrics with the same yarn counts using different spinning processes. Therefore, it is not recommended to produce the same product in one batch with yarns spun using different spinning processes.

For knitting technologists, it is important to note that fabric mass per unit area is related to the fabric shrinkage in the wale and course direction after the fabric is taken down from the machine and relaxed. The knitted fabric samples with higher mass per unit area had the highest shrinkage (after the removal from the machine and relaxation; from 36% to 39%), while the knitted fabric samples with lower mass per unit area shrank less (from 22% to 25%). On the basis of the above analysis, it can be concluded that the processes of ring, rotor and air-jet spinning lead to substantially different yarn structures, which is manifested in yarn stiffness or flexibility. The rotor and air-jet spinning processes produce stiffer yarn that during knitting forms a larger radius in the stitch curvature, consequently producing wider loops. The wider loop leads to less shrinkage and greater width of the knitted fabric.

Table 3 presents the tensile properties of knitted fabrics produced using viscose, Tencel™ and modal ring, rotor and air-jet spun yarns.

The breaking force of the knitted fabric in the wale direction (ranges from 230.9 N to 491.8 N) is on average 3.12 times greater than the breaking force of the fabrics in the course direction (ranges from 70.9 N to 103.8 N). The breaking force of the fabric depends on the breaking force of the yarn used for knitting. The lowest yarn breaking force was achieved with the viscose yarn spun using the rotor spinning process (272.7 cN); therefore, the samples knitted with this yarn had the lowest breaking force (70.9 N). The highest yarns breaking force was achieved with the Tencel™ yarn spun using the conventional ring spinning process (551.8 cN) and the samples knitted with this yarn had the maximum breaking force (103.8 N). Accordingly, the raw material composition of the yarn and the spinning process affect the breaking force of the yarn and thus of the knitted fabric.

The elongation at break is significant for knitted fabrics used to make different underwear and light clothing. In theoretical considerations, knitted fabrics intended for underwear and light clothing have 4 times larger elongation at break in the course direction than in the wale direction, and in this study, it is 5.7 to 7.3 times larger. The reason for higher elongation at break can be found in the yarn structure and the elongation at break of the yarn (ranges from 8.2 to 15.2%). The knitted fabric elongation at break depends on the elongation at break of the yarn, where the elongation at break of the yarn depends on yarn structure and raw material. As with the two previous parameters, the maximum force and elongation at break of the knitted fabric, the work of rupture lies within a wide range and does not exhibit any particular regularity. In some knitted fabrics, they are larger when stretched in the course direction and in some other fabrics, in the wale direction.

By analysing all results of the knitted fabric elongation in the transverse direction, i.e. in the course direction, and in the longitudinal direction, i.e. in the wale direction, the percentages of elastic, elastoplastic and plastic areas were determined. Figure 4 shows the percentages of elastic, elastoplastic and plastic areas in the course direction, and Figure 5 shows the percentages in the wale direction. Values are sorted by the raw material composition and yarn spinning process. The percentages of elastic, elastoplastic and plastic areas in the course direction are the highest for the elastic area ranging from 32% to 55%, followed by the plastic area from 27% to 41%, and the smallest percentages that connect the elastic and plastic area (elastoplastic area) range from 16% to 32%. For the tested knitted samples, these three areas differ significantly in quantity.

Table 3: Double jersey knitted fabric tensile properties

Fibre	Spinning process	Maximum force in knitted fabric course direction (F_c)			Maximum force in knitted fabric wale direction (F_w)			Elongation at break in knitted fabric course direction ($\mathcal{E}_c$)			Elongation at break in knitted fabric wale direction ($\mathcal{E}_w$)		
		$\bar{X}$[a] (N)	SD[b] (N)	CV[c] (%)	$\bar{X}$[a] (N)	SD[b] (N)	CV[c] (%)	$\bar{X}$[a] (%)	SD[b] (%)	CV[c] (%)	$\bar{X}$[a] (%)	SD[b] (%)	CV[c] (%)
Viscose	Ring	72.8	2.7	3.7	381	9.8	2.3	338.8	33.5	9.9	47.3	1.1	2.3
	Rotor	70.9	2.9	4.2	230.9	13.7	5.9	220.6	9	4.1	33.2	1.4	4.1
	Air-jet	74.4	3.3	4.4	290.2	14.5	5	276.8	5.5	1.9	47.7	1.2	2.5
Tencel™	Ring	103.8	4.8	4.6	491.8	19	3.9	328.2	11.1	3.4	49.3	3.1	6.3
	Rotor	102.2	2.3	2.2	374.7	27.2	7.3	289.7	9.1	3.1	50.3	2.4	4.8
	Air-jet	84.3	5.3	6.3	300.7	16	5.3	266.3	7.8	2.9	46.9	0.9	1.8
Modal	Ring	84.1	3	3.6	392	23.9	6.1	309.5	1.7	0.6	46.5	0.5	1.2
	Rotor	90.8	4.9	5.5	268.4	20.1	7.5	255.4	10.1	3.9	45.2	1.7	3.8
	Air-jet	76.9	2.9	3.8	282.8	20.4	7.2	249.5	8.6	3.5	34.4	0.7	2

[a] average, [b] standard deviation, [b] coefficient of variation

Fibre	Spinning process	Tenacity in knitted fabric course direction (T_c)			Tenacity in knitted fabric wale direction (T_w)			Work of rupture in knitted fabric course direction (W_c)			Work of rupture in knitted fabric course direction (W_w)		
		$\bar{X}$[a] (cN/mm)	SD[b] (cN/mm)	CV[c] (%)	$\bar{X}$[a] (cN/mm)	SD[b] (cN/mm)	CV[c] (%)	$\bar{X}$[a] (cNcm)	SD[b] (cNcm)	CV[c] (%)	$\bar{X}$[a] (cN cm)	SD[b] (cNcm)	CV[c] (%)
Viscose	Ring	145.6	2.7	3.7	762	9.8	2.6	521.6	101.8	19.5	678	23.8	3.5
	Rotor	141.8	3	4.2	461.8	13.7	5.9	429.5	48.6	11.3	317.9	31.1	9.8
	Air-jet	148.8	3.3	4.4	580.4	14.5	5	461.6	26.3	5.7	472.3	35.8	7.6
Tencel™	Ring	207.6	4.8	4.6	983.6	19	3.9	634.1	49.9	7.9	772.2	79.6	10.3
	Rotor	204.4	2.3	2.2	749.4	27.2	7.3	664.8	42	6.3	570	63.1	11.1
	Air-jet	168.6	5.3	6.3	601.4	16	5.3	464.8	32.8	7.1	438.4	19.5	4.5
Modal	Ring	168.2	3	3.6	784	23.9	6.1	494.1	15.5	3.1	555.1	46.1	8.3
	Rotor	181.6	5	5.5	536.8	20.1	7.5	588	85.5	14.6	382.6	35.9	9.4
	Air-jet	153.8	2.9	3.8	565.6	20.4	7.2	464.6	42.3	9.1	367.7	36.3	9.9

[a] average, [b] standard deviation, [b] coefficient of variation

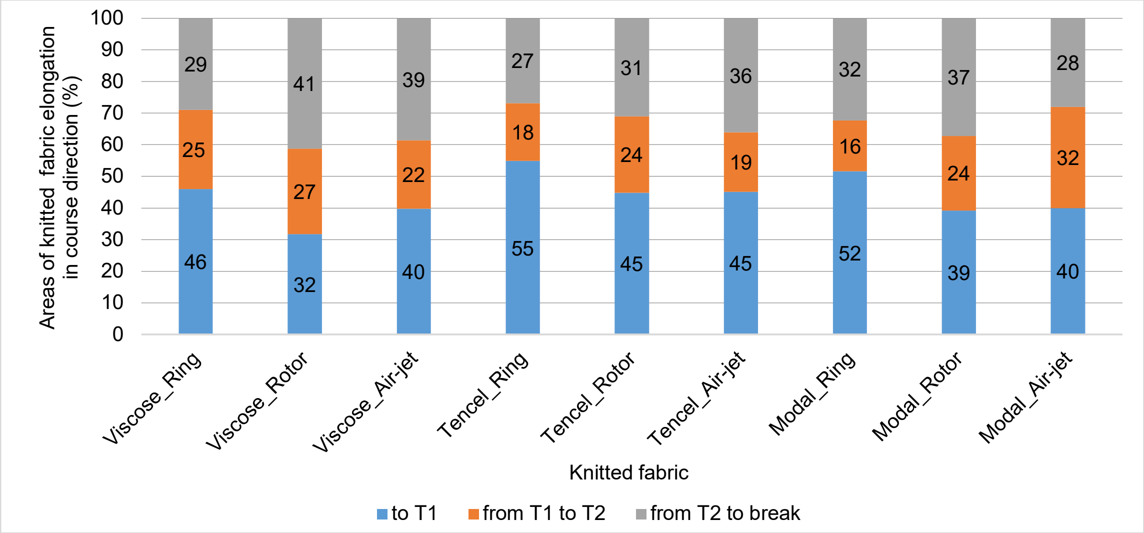

Figure 4: Elastic, elastoplastic and plastic areas of knitted fabric elongation in course direction

The lowest elastic area in the course direction was found for the knitted fabric from viscose rotor yarns (cf. Figure 4). The elastic area was 32% of the total elongation, the elastoplastic area was 41% and the rest of 27% belongs to the area between points T1 and T2 or to the plastic area. The highest elasticity area was found in the sample knitted from the Tencel™ ring spun yarn. The elastic area amounts to 55% in relation to the total elongation, the percentage range between points T1 and T2 (elastoplastic area) is 18% and the percentage of permanent deformation is 27%. It can be seen that the elastic area of knitted fabrics in the course direction is the largest for ring yarns, followed by air-jet and finally rotor spun yarns, regardless of the raw material. The yarn raw material affects the elastic area of knitted fabrics consisting of different yarn structures. The greatest reduction in the knitted fabric elastic area is visible between the viscose ring and rotor spun yarns (reduction of 30%). The reduction in the elastic area of the knitted fabric in the case of viscose air-jet yarns is only by 13% lower when viscose ring yarns are taken into account. Taking Tencel™ ring spun yarns into account, the elastic area reduction for knitted fabrics with Tencel™ rotor and air-jet spun yarns is the same or 18% lower. Elastic area for knitted fabrics made from modal yarns of different yarn structures are 23% less elastic for air-jet and 25% less for rotor yarns compared to ring spun yarns. On the other hand, the elastoplastic area of the knitted fabric is the smallest for ring spun yarns, regardless of the raw material of spun yarns.

When testing the tensile properties of the knitted fabric in the wale direction, individual areas are quite different from those in the course direction due to different stitch directions. The share of the elastic area is represented by a percentage range from 15% to 26%, the plastic deformation from 49% to 70%, and the share from the end of elasticity to the beginning of plastic deformation (elastoplastic area) from 15% to 27% (cf. Figure 5). The diagram (cf. Figure 5) shows that the smallest elastic area in the wale direction was measured for the knitted fabric knitted from viscose rotor spun yarns and was the same as in the course direction. The elastic area was 15% of the total elongation, the elastoplastic areas was 15% and the share of permanent deformation was 70%. The largest elastic area was found for the sample of the knitted fabric knitted from the modal ring spun yarn. The elastic area was 26% relative to the total elongation, the elastoplastic area was 27% and the plastic area was 51%. Nevertheless, there is no trend in elastoplastic areas with regard to the yarn type and raw material as there is in the course direction.

4 Conclusion

The fineness and the twist of yarns are uniform with a low coefficient of variation, which indicates high quality yarns. The difference in the tensile properties of tested yarns is the result of yarn spinning techniques that produce different yarn structures.

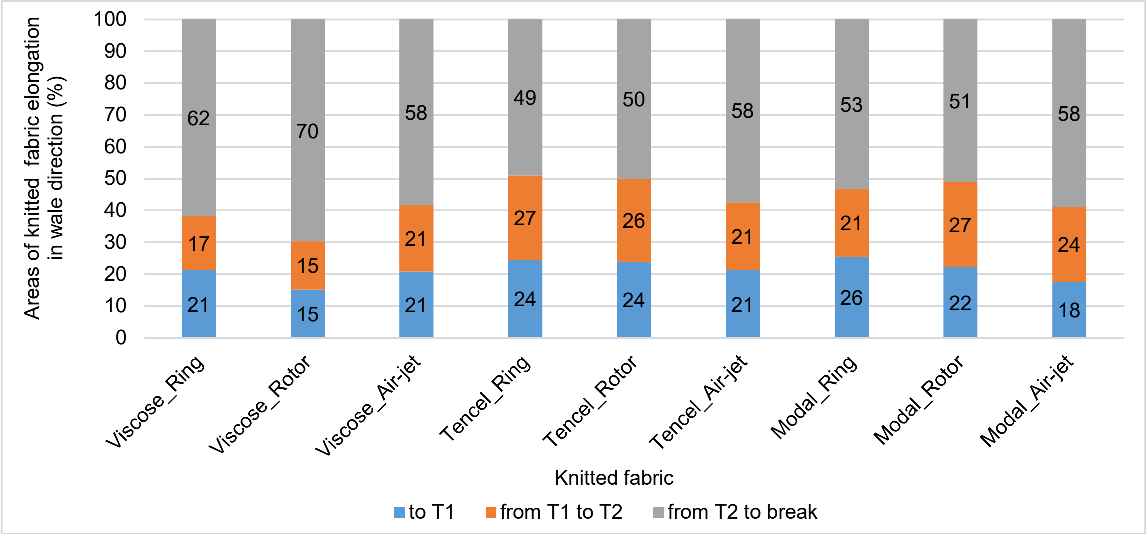

Figure 5: Elastic, elastoplastic and plastic areas of knitted fabric elongation in wale direction

The type of fibres (viscose, Tencel™ and modal) influences the maximum yarn strength regardless of the yarn structure; however, depending on the yarn structure, the difference in maximum force will be greater or smaller. Ring spun yarns have the greatest elongation followed by air-jet and rotor spun yarns, regardless of the fibre type. The fabrics were knitted using the same machine parameters, and the results show that the knitted structures are influenced by both the yarn types and the raw materials from which the yarns were spun. The difference in mass per unit area, one of the most important parameters of the knitted structure, was up to 38 g/m^2 or 23%. This is an important factor for the commercial mass production, which leads to the conclusion that it is very complex to produce knitted fabrics in one batch with the same yarn counts spun using different spinning processes. Knitted fabrics made of ring spun yarns have much higher mass (up to 38 g/m^2) compared to knitted fabrics made of rotor and air-jet spun yarns. The knitted samples with higher mass per unit area had the highest shrinkage after the removal from the machine and relaxation, which leads to the conclusion that the processes of ring, rotor and air-jet spinning produce substantially different yarn structures manifested in stiffness where stiffer yarn during knitting forms a larger radius in the stitch curvature, consequently forming wider loops. Wider loops result in less shrinkage and greater width of the knitted fabric.

The percentages of elastic, elastoplastic and plastic areas in the course direction are the highest for the elastic area ranging from 32% to 55%, followed by the plastic area from 27% to 41%, and the lowest percentages connecting the elastic and plastic area (elastoplastic area) range from 16% to 32%. When testing the tensile properties of the knitted fabric in the wale direction, individual areas are quite different due to different loop directions. The share of the elastic area is represented by a percentage range from 15% to 26%, plastic deformation from 49% to 70% and the percentage of the elastoplastic area from 15% to 27%. For the tested knitted samples, these three areas differ significantly in amount, both in the course and wale direction.

The elastic area of knitted fabrics in the course direction is the highest in ring spun yarns, followed by air-jet and finally rotor spun yarns, regardless of the raw material. The yarn raw material affects the elastic area of knitted fabrics consisting of different yarn structures. The greatest reduction in the knitted fabric elastic area is visible between viscose ring and rotor spun yarns (reduction of 30%). On the other hand, the elastoplastic area of the knitted fabric is the smallest for ring spun yarns, regardless of the raw material of the spun yarn. In the elastoplastic areas of the knitted fabric, there is no visible trend in the yarn type and raw material in the wale direction as in the course direction.

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