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MODERN KNITTED FABRICS FOR UNDERWEAR

Željka PAVLOVIĆ & Zlatko VRLJIČAK

Abstract: In the total world production, the share of cotton fibres is gradually decreasing, so that new fibres are needed to replace or supplement them. A double bed circular knitting machine with a machine gauge of E17 was used to knit five samples of knitted fabrics in plain double jersey weft knitted structure made of 20 tex yarns. The samples were knitted using cotton, Lyocell, modal, micromodal and viscose yarns. The ring spinning method was used to spin cotton and micromodal yarns, Lyocell yarns were spun using the air-jet spinning method, modal yarns were spun using the rotor spinning method, and viscose yarns were spun using the SIRO spinning method. The structure parameters and the tensile properties were determined for the unfinished and finished knitted fabrics, with emphasis on the percentage of elasticity when the knitted fabric was stretched in the course and wale direction. The mass per unit area of the analysed knitted fabrics ranged from 128 to 180 g/m², while the volume mass ranged from 0.21 to 0.40 g/cm³. All the manufactured and analysed knitted fabrics were compared with cotton knitted fabrics.

Keywords: Knitted fabric, double knit structure, underwear, raw material composition, cotton, modal, micromodal, Lyocell, viscose, SIRO

1. Introduction

In the total world production, the share of cotton fibres is gradually decreasing. In 2017, the world's total production of 100 million tons of fibres was exceeded for the first time, with cotton accounting for around 28%, or 28 million t. Cotton fibres are mainly used for making single yarns [1,2]. Yarns with counts of 14, 17, 20, 22 and 25 tex are widely used for the production of various knitted fabrics that are used to make more lightweight clothing, most commonly underwear or summer wear. Classic knitted underwear is most commonly made of cotton single jersey weft knitted fabrics, double jersey weft knitted fabrics and interlock fabrics. One part of the women's lingerie is made of polyamide warp knitted fabrics. For the production of classical women's lingerie, single cotton yarns with counts of 14, 17 and 20 tex are mostly used. For the production of knitted fabrics single bed circular knitting machines with gauges of E18, E20, E24 or E28 are used to make knitted fabrics with mass per unit area of 80 to 140 g/m², Fig. 1. Men's classic underwear is made of knitted fabrics with mass per unit area of 140 to 200 g/m². For its manufacture, cotton yarns of 17, 20, 22 or 25 tex are also used, as well as single or double bed circular knitting machines of the mentioned gauges. Quality winter men's underwear has a mass per unit area from 180 to 250 g/m² and is made of single cotton yarns of 17 or 20 tex, most commonly on interlock knitting machines of the specified gauge. Pyjamas and nightgowns are also made of these knitted fabrics. However, ply yarns of 10 tex x 2, 14 tex x 2 or 17 tex x 2 are sometimes used for their manufacture. Men's winter, bulky pyjamas are made of cotton plush knitted fabric with a mass per unit area from 200 to 350 g/m², [3,4].

![Figure 1: Knitted underwear: a) women's underwear, b) men's underwear](image)

For a number of reasons the share of cotton fibres in total world production decreases, while the population grows from year to year, and in 2019 the consumption of fibres per capita was about 13 kg. For this reason, research in the production of artificial fibres of plant origin is increasingly being conducted in the world. Such fibres have some properties similar to cotton fibres and are suitable for making knitted fabrics in various structures that adhere to the skin of the human body. The products are comfortable to use, easy to take care of, not significantly expensive and environmentally friendly. For these purposes, viscose, Lyocell, modal,
micromodal and other fibres are used in addition to cotton fibres. Such fibres and various spinning processes such as: ring-, rotor-, air-jet, compact and other spinning processes are used for making yarns with some properties better than classic cotton yarns made by employing the ring spinning process [5,6].

2. Structures and tensile properties of weft knitted fabrics

To make simpler knitted fabrics intended for classic underwear, single jersey, double jersey and plain interlock structures are mostly used. All the yarns used for knitted fabrics have the same raw material composition, structure, fineness and colour. In addition to the use of cotton yarns, modern yarns, which are interlooped independently or in combination with other yarns, are commonly used in the production of modern underwear, mostly in partial or single plaiting, Fig.2. In order to enhance the fit of the knitted fabric on the body and to increase the elasticity of the knitted fabric, in addition to the base yarn, the elastic yarn is interlooped in the course direction.

![Figure 2: Single jersey weft knitted and double jersey weft knitted plated structures, which are mostly used to manufacture knitted fabrics for underwear](image)

Plain single jersey weft knitted fabrics stretch about two times more in the course direction than in the wale direction, and double jersey weft knitted fabrics stretch up to five times more. When making knitted fabric for contemporary underwear, length contraction of the stretched knitted fabric is significant so that the knitted fabric fits the body comfortably. In the force / extension diagram, three regions are very often significant, Fig. 3.

![Figure 3: Force/extension diagrams for double jersey weft knitted fabric: a) extension diagrams of the knitted fabric in the wale direction (I) and in the course direction (II): T1 - end of the elastic region, T2 - point of the onset of plastic deformation, P - point of knitted fabric breakage, b) extension diagram of the knitted fabric in the course direction, knitted fabric made of a 20 tex yarn](image)

It is assumed that the first, linear part of the diagram to point T1 represents the elastic region. The second part of the diagram from point T1 to point T2 encompasses the possibly elongated elastic region. This section can also be analysed as an entire region to the onset of permanent deformation. The part of the diagram from point T1 to point T2 represents the elastic limit or the part connecting the elastic region with the region of permanent deformation. The fourth part of the diagram ranges from point T2 to the point of knitted fabric breakage (P) and represents permanent or plastic deformation. During elongation and at the moment of breaking the knitted fabric, the tensile testing device records the elongation length at break and this information is often not debatable. However, it is not always easy and precise to determine, estimate or calculate the elastic region, i.e. point T1 or the onset of permanent deformation, i.e. point T2. For knitted fabrics made of yarns of different raw materials, yarn counts and structures these regions have not been sufficiently studied.
The elastic limit and the onset of permanent deformation are particularly interesting, as they are very important for the production of quality recreational, especially compression recreational clothing [7,8]. Yarns made of new fibres and by using modern spinning methods have a significantly different structure, and thus have properties compared to cotton yarns made by employing the ring spinning method. Due to different tensile properties of the yarn, different tensile properties of the knitted fabric are also expected, where it is desirable to find out the percentages in the indicated regions of the force/extension diagram. First of all, the elasticity of the knitted fabric or the extension of the fabric to point T1 is significant. In the manufacture of compression garments, the region between the edge of elasticity and the onset of permanent deformation is very significant, i.e., between points T1 and T2, while the percentage of permanent deformation is often not so significant in the garment manufacture. Due to the above, five types of yarn were made according to plan which were used to knit samples of knitted fabrics that can be used for making underwear, lightweight outerwear or recreational clothing. The structure parameters and the tensile properties were determined for knitted fabrics, with particular emphasis on the individual percentages of elongation of the knitted fabric.

3. Yarns and knitting machine for making knitted fabric samples

Five fibre types were used to make yarns: cotton, viscose, Lyocell, modal and micromodal fibres. The ring spinning method was used to spin cotton and micromodal fibres into yarns. The SIRO method was used to spin viscose fibres into yarns. The air-jet spinning method was used to spin Lyocell (Tencel) fibres into yarns, while the rotor spinning method was used to spin modal fibres [2,9]. All the five yarn groups were made with a nominal count of 20 tex. Table 1 lists the basic parameters of tensile properties of the manufactured and analysed yarns at \( p = 5 \).

<table>
<thead>
<tr>
<th>Yarn</th>
<th>Breaking force, cN</th>
<th>Breaking elongation, %</th>
<th>Breaking strength, cN/tex</th>
<th>Work of rupture, cN·cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKK</td>
<td>302 ± 5</td>
<td>3.7 ± 0.1</td>
<td>15.1 ± 0.3</td>
<td>301 ± 10</td>
</tr>
<tr>
<td>MMR</td>
<td>506 ± 11</td>
<td>9.5 ± 0.2</td>
<td>25.3 ± 0.6</td>
<td>1421 ± 50</td>
</tr>
<tr>
<td>SP</td>
<td>393 ± 7</td>
<td>13.6 ± 0.3</td>
<td>19.7 ± 0.4</td>
<td>1700 ± 59</td>
</tr>
<tr>
<td>TAJ</td>
<td>444 ± 12</td>
<td>7.9 ± 0.2</td>
<td>22.2 ± 0.6</td>
<td>1086 ± 56</td>
</tr>
<tr>
<td>MOE</td>
<td>325 ± 9</td>
<td>7.2 ± 0.2</td>
<td>16.3 ± 0.5</td>
<td>738 ± 32</td>
</tr>
</tbody>
</table>

where: PKK – cotton yarn spun on the ring spinning machine, MMR – micromodal yarn spun on the ring spinning machine, SP – viscose yarn spun by employing the SIRO spinning method, TAJ – Lyocell (Tencel) yarn spun on the air-jet spinning machine, MOE – modal yarn spun on the rotor spinning machine.

The lowest breaking force of the yarn amounted to 302 ± 5 cN and was measured for the cotton yarn, and the highest one amounted to 506 ± 11 cN and was measured for the micromodal yarn and spun on the ring spinning machine. The lowest elongation at break amounted to 3.7 ± 0.1% and was measured for the cotton yarn and the highest one amounted to 13.6 ± 0.3% and was measured for the viscose SIRO spun yarn. The smallest amount of work was also measured for the cotton yarn and the greatest amount of work was measured for the viscose SIRO spun yarn. Based on the data obtained from measurements, it can be concluded that the analysed yarns differed significantly in their tensile properties and that all the measured values of tensile properties for the cotton yarn were the lowest. A double-bed circular knitting machine E17 was chosen to make knitted fabric samples [9]. During the finishing process, the knitted fabrics were washed at an initial temperature of 40°C. Washing, bleaching and stabilizing agents were added and the temperature rose to 98°C. After rinsing, a cold wash was performed with neutralization and softening of knitted fabrics. After washing the knitted fabrics were dried at a temperature of 150°C, while the material passed through the dryer at a speed of 0.15 m/s.

4. Results and discussion of structure parameters of knitted fabrics

Appropriate standards and methods were used to analyse basic or technological parameters of the structure of knitted fabrics as they are measured and analysed several times in daily production [10]. Some performance parameters relevant to these investigations were also calculated [11]. Measurements were made in a logical sequence, first those for which no material destruction was required, and then the knitted fabric was unknit and cut. When determining the average stitch length to form a stitch, it was necessary to cut the knitted fabric and to unravel the yarn. From among the performance parameters the following were analysed: knitted fabric shrinkage in the course direction after removal of the fabric from the knitting machine, coefficient of loop density and volume mass of the knitted fabric, Table 3. The results were statistically processed where it was possible.
and purposeful with $p = 0.05$. **Knitted fabric width** ($S_w$) was measured in tubular form. All the made unfinished samples had the width ranging from 36 to 48 cm. The minimum width of the unfinished fabric was 18 cm x 2, (36 cm). It was obtained by knitting with viscose yarns spun by employing the SIRO spinning process (SP). It is important for knitting technologists to know that at the lowest width of the knitted fabric the greatest fabric shrinkage was observed after removal of the fabric from the knitting machine and relaxation, amounting to even 44%. The maximum width of the unfinished knitted fabric was 24.0 cm x 2, (48 cm). It was obtained in knitting Lyocell (Tencel) yarns by employing the air-jet spinning process (TAJ) and modal yarns spun on the rotor spinning machine (MOE). The lowest knitted fabric shrinkage was obtained after the removal from the machine and relaxation amounting to 25%. Based on these two substantially different data, it can be concluded that different yarn structures are obtained by employing the ring, air-jet, rotor and SIRO spinning process. The yarn spun on the rotor and air-jet spinning machine was stiffer. During the stitch formation, it forms a larger stitch skeleton than the stitch made on ring or SIRO spinning machines. This is the reason why wale spacing was larger, consequently the knitted fabric was wider. Knitted fabric finishing substantially changes fabric structure. The width of the finished knitted fabrics ranged from 19.0 cm x 2 to 21.5 cm x 2, (38 do 43 cm). After the finishing process, the knitted fabrics made of SIRO yarns were 16.7% wider, cotton fabrics 10.3% and micromodal fabrics 2.5%. In contrast to these samples, the knitted fabrics made of modal yarns and spun by employing the rotor spinning system (MOE) were 20.8% narrower after the finishing process, and the knitted fabrics made of Lyocell yarns and spun by employing the air-jet spinning process (TAJ) were 10.4% narrower. The cause of this different behaviour of the knitted fabrics after the finishing process should be sought in the structure of fibres, yarn and finishing process, i.e. it is necessary to investigate the optimal parameters of the finishing process for individual raw material compositions and yarn structures. **Stitch length** ($l$) is one of the basic parameters, especially for plain knitted structures. For the unfinished and finished knitted fabrics, it ranged from $3.05 \pm 0.00$ mm to $3.15 \pm 0.02$ mm with a difference of 3.2%, which is significantly less than 5%, so for practical considerations it can be concluded that stitch length does not differ significantly for all analysed knitted fabrics. This is also one of the data that indicates that the samples were knitted under the same knitting conditions. **Coefficient of stitch density** ($C$) describes the general stitch density of the knitted fabric [9], ($C = D_n / D_v = B/A$). For the analysed knitted fabrics it ranged from 0.72 to 0.97, which mainly corresponds to the commercial usage of such knitted fabrics for various purposes. **Mass per square meter of the knitted fabric or mass per unit area** ($m$) is the most significant structure parameter, especially for plain knitted structures [3,9,11]. It determines the purpose and price of the product. For the analysed unfinished samples, the mass per square meter of the knitted fabric ranged from $128 \pm 3$ to $180 \pm 5$ g / m$^2$, and for the finished ones from $147 \pm 3$ to $170 \pm 4$ g/m$^2$. After the finishing process, the mass per unit area significantly decreased for some fabrics, and it increased significantly for some fabrics. Therefore, for each knitted fabric sample the optimum finishing parameters for knitted fabrics should be found. These results are very important for batch and commercial production as they suggest the practical conclusion that it is very complex to make knitted fabrics of one mass per unit area using yarns with the same yarn count, which have different raw material compositions and are spun by employing different spinning methods.

**Table 3: Structure parameters of unfinished and finished knitted fabrics**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$S_w$, cm</th>
<th>$s$, %</th>
<th>$l$, mm</th>
<th>$C$</th>
<th>$m$, g/m$^2$</th>
<th>$m_z$, g/cm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKK</td>
<td>19.5 x 2</td>
<td>39</td>
<td>3.15 ± 0.02</td>
<td>0.97</td>
<td>157</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>21.5 x 2</td>
<td>32</td>
<td>3.08 ± 0.01</td>
<td>0.85</td>
<td>162</td>
<td>0.27</td>
</tr>
<tr>
<td>MMR</td>
<td>20.0 x 2</td>
<td>37</td>
<td>3.14 ± 0.02</td>
<td>0.87</td>
<td>154</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>20.5 x 2</td>
<td>36</td>
<td>3.09 ± 0.01</td>
<td>0.74</td>
<td>153</td>
<td>0.34</td>
</tr>
<tr>
<td>SP</td>
<td>18.0 x 2</td>
<td>44</td>
<td>3.13 ± 0.01</td>
<td>0.89</td>
<td>180</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>21.0 x 2</td>
<td>34</td>
<td>3.05 ± 0.00</td>
<td>0.82</td>
<td>147</td>
<td>0.40</td>
</tr>
<tr>
<td>TAJ</td>
<td>24.0 x 2</td>
<td>25</td>
<td>3.15 ± 0.02</td>
<td>0.73</td>
<td>132</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>21.5 x 2</td>
<td>33</td>
<td>3.12 ± 0.02</td>
<td>0.72</td>
<td>156</td>
<td>0.32</td>
</tr>
<tr>
<td>MOE</td>
<td>24.0 x 2</td>
<td>25</td>
<td>3.14 ± 0.02</td>
<td>0.74</td>
<td>128</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>19.0 x 2</td>
<td>40</td>
<td>3.09 ± 0.01</td>
<td>0.94</td>
<td>170</td>
<td>0.34</td>
</tr>
</tbody>
</table>

where: $U$ – unfinished knitted fabric, $F$ – finished fabric, $S_w$ – fabric width, cm, $s$ – fabric shrinkage in course direction after removal from the machine, %, $l$ - stitch density, mm, $C$ – coefficient of stitch density, $m$ – fabric mass per unit area, g/m$^2$, $m_z$ – fabric volume mass, g/cm$^3$

**Knitted fabric volume mass** ($m_z$) was significantly higher for all analysed finished fabric samples than for the unfinished ones. For the unfinished knitted fabrics it ranged from 0.21 to 0.25 g/cm$^3$, and for the finished ones from 0.27 to 0.40 g/cm$^3$, i.e. it was higher by 7.2 to 38.4%. Knitted fabrics with an increased volume mass can be used for garments worn at lower temperatures [9].
5. Results and discussion of tensile properties of knitted fabrics

To measure tensile properties of knitted fabrics, 50 mm wide and 200 mm long samples were cut out. The distance between the grips of the tensile tester was 100 mm. The STATIMAT M tensile tester was used to measure unfinished and finished knitted fabric samples cut out in course and wale direction. While tensile force acts, the sample is elongated with continuous measurement of force-elongation data. In case of a break of the knitted fabric the last measurement is recorded which represents the force/elongation of the knitted fabric. After the measurements were performed, the tensile properties of knitted fabrics in course direction or transversally and in wale direction or longitudinally were studied separately. The analysis of all the results of stretching the knitted fabrics up to breakage in course direction or transversally, which ranged from 300 to 400 %, showed the percentages of the individual mentioned regions. Fig. 4 shows the force/elongation diagram of the micromodal knitted fabric (MMR) whose breaking elongation in the course direction amounted to about 320 %.

![Figure 4](image)

Figure 4: Elongation of the knitted fabric in the course direction – transversally; force/elongation diagram for the knitted fabric knitted of micromodal yarns spun by employing the ring spinning method (MMR), b) percentages per individual elongation regions; S – unfinished fabric, D – finished fabric

Figure 4 shows the percentages of the mentioned regions for all analysed knitted fabrics. The data were sorted according to the raw material composition of the knitted fabric. The diagram shows that the highest elasticity in the course direction was found for the unfinished cotton knitted fabric made of the yarns spun on the ring spinning machine (PKK). The percentage of elasticity amounted to 55% of the total elongation, the percentage of plasticity amounted to 29% and the rest of 16% belonged to the region between points T1 and T2. The modal knitted fabric made of the yarns spun on the rotor spinning machine (MOE) had the lowest elasticity, which accounted for 39%. For this knitted fabric sample the smallest differences were recorded among the individual percentages. The elastic region had a percentage of 39%, the elastic region had a percentage of 37% and the region between elasticity and plasticity had a percentage of 24%. The smallest difference in the tensile properties of the unfinished and finished knitted fabrics was recorded for the micromodal fabric (MMR). By finishing the knitted fabric, the percentage of the elastic region decreased for the cotton and slightly for the micromodal knitted fabrics, and increased for all other knitted fabrics.
Figure 5: Elongation of the knitted fabric in the wale direction – longitudinally; a) force/elongation diagram of the knitted fabric knitted of the Lyocell (Tencel) yarns spun by employing the air-jet spinning method (TAJ), b) percentages per individual regions of elongation; S – unfinished fabric, D – finished fabric

In the production of classic underwear it is significant to observe that the percentage of elasticity ranged from 39 to 55%, and if gentle compression garment is made, the knitted fabric can be elongated from 65 to 70% in the course direction. Elongation at break of the knitted fabric in the wale direction or longitudinally ranged from 30 to 50%, and it was significantly lower than the elongation at break in the course direction, whereby the percentage of the elastic region was also lower, Fig. 5b.

The percentage of elasticity ranged from 21 to 41%. The lowest percentage of elasticity was recorded for the unfinished Lyocell knitted fabric (TAJ-S), amounting to 21% and the highest percentage was recorded for the micromodal knitted fabric (MMR-D), amounting to 41%. For the finished cotton (PKK) and viscose knitted fabrics (SP), the percentage of elasticity was lower than for the unfinished knitted fabrics, and it was higher for all other samples. The highest percentage of elasticity in both the finished and unfinished knitted fabrics was recorded for the micromodal yarns (MMR), and it was significantly higher than in the cotton knitted fabrics. The percentage between the end of the elastic region and the onset of plastic deformation ranged from 21 to 37%, and it was the lowest in the unfinished Lyocell knitted fabrics (TAJ-S) and the highest in the finished cotton knitted fabrics (PKK-D). The percentage elongation of the knitted fabric to the onset of permanent deformation amounted to 50% in four samples, and in the remaining six samples it ranged from 50 to 65%. During elongation of the knitted fabric in the wale direction the percentage of permanent deformation was high, ranging from 40 to 58%.

6. Conclusion

On the basis of the investigations conducted the following basic conclusions can be reached: The yarns for making samples had the same nominal count, but their tensile properties were significantly different. All the knitted fabric samples were made on one machine under the same knitting conditions. All the knitted samples were of the essentially different structure. The finishing process significantly changed the structure. The percentage of elasticity in the course and wale direction was different depending on the raw material composition of the yarn, its manufacturing process and fabric finishing. Raw material composition, yarn structure and tensile properties of the knitted fabric as well as fabric finishing caused all other differences. Particular attention should be paid to the finishing of knitted fabrics, which will be adapted to the yarns of certain structures. The research results suggest that it is relatively difficult to obtain the same knitted fabric structure with the mentioned yarns that will be used for the manufacture of one product.

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References:
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