Influence of properties at micro- and meso-scopic levels on macroscopic level for weft knitted fabrics

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Knitted fabrics and particularly weft knitted fabrics are used as composite material reinforcements due to their ability to be draped and to give three-dimensional shape by molding or by knitting. This paper presents the strong connection of all the scales of the knitted fabric (fiber, yarn and fabric) on the final knitted fabrics and its mechanical and physical properties. For this purpose, only one polymer material is used, made of two different fibers in terms of length and fineness. These fibers are used to make different yarns with two structures then three plain-weft-knitted-fabrics are considered in terms of the loop length. The fibers have not the same bending rigidity because fiber cross-section areas are different. This has an influence on the three-dimensional loop shape and on the roughness, thickness and real area of contact of fabrics. This phenomenon is the same with the two yarn structures. The results presented here bring into light that the loop length does not influence the fabric thickness.

1. Introduction

Compared with others fabrics structure, such as woven, nonwoven, and even warp knitted fabrics, weft knitted fabrics show the following specific properties. In a weft knitted fabric, a yarn forms three-dimensional loops, named stitches (Fig. 1) that can be flattened out and/or that can move over each others, thus such a kind of fabric can be easily deformed and is easily formable. Moreover, new knitting processes allow to make directly, without any other intermediate operation, complex three-dimensional shape as elbowed tube or half-sphere, . . . [1–3]. These properties make composite materials reinforced with weft knitted fabrics convenient for many applications. However only limited research on weft knitted fabric composites has been reported [4–8, 9–13]. The composite properties are determined firstly by, the properties and relative proportions of fiber and polymer-matrix materials and secondly, by the fiber architecture in the composite. The purpose of this paper is indirectly the second point, that is to show the influence of fiber architecture, whatever the fiber material, on the properties of the fabric which can be used as composite reinforcement. This work shows the strong influence of morphological and structural parameters at three scale levels on the loop shape and then on the surface state. Actually, a knitted fabric is constituted of three scales: the first one being the microscopic scale, i.e. the fiber (from 0.1 to 10 microns), the second one being the mesoscopic scale, i.e. the yarn (from 10 microns to 1 millimeter) and the third one being the macroscopic scale, i.e. the fabric (from 1 to 100 millimeters). In this work, two different fibers in terms of length and fineness are used. Different yarns are made with them in order to obtains two structures, then three plain-weft-knitted-fabrics are considered in terms of loop length. These features are connected to the loop shape and therefore to the fiber architecture in the three-dimension space. Presently, it is very hard and long to measure the loop shape directly. Some methods, such as tomography, can be used, but they are not correct in a statistical point of view. In fact, a small geometrical or mechanical irregularity in the yarn leads to the loop shape totally modified, because the loop mechanical equilibrium is changed. Therefore an important number of measurements is drastically necessary. This paper present non-direct methods in order to qualitatively deduce the loop shape. The compression behavior of the fabrics is studied with the help of tribological and transient state thermal behaviors. These measurements are compared with basic two-dimensional geometrical measurements.

2. Description of the methods used

2.1. Fibrous materials tested

2.1.1. Microscopical scale

For this study, cotton is the used material. Cotton is a polymer: a poly-D-glucose. The only existing form of cotton is fiber (from several millimeters to several

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TABLE I Fiber characteristics

	Cotton 1	Cotton 2
Length (mm)		
Mean	29.8	25.9
Standard deviation	0.5	0.4
Mass per unit length (μg/m)		
Mean	140	166
Standard deviation	3.0	2.0

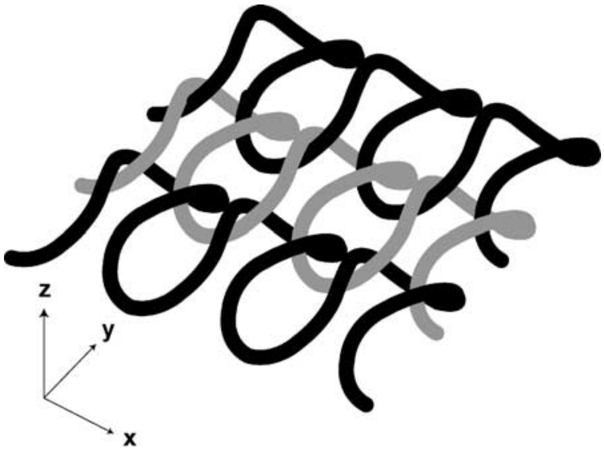


Figure 1 Three-dimensional loop shape in a weft knitted fabric.

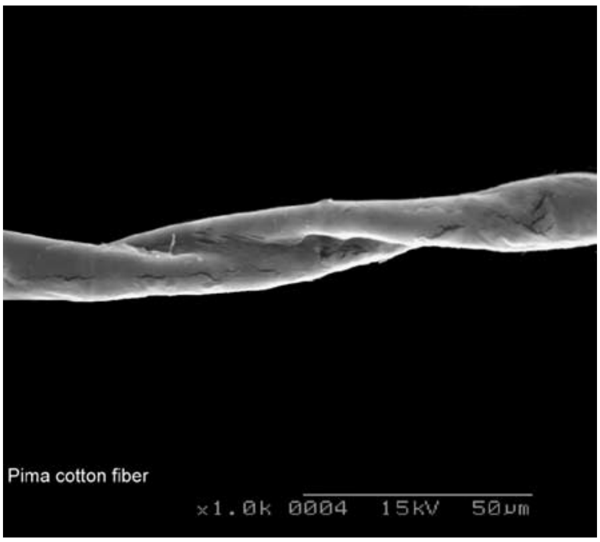
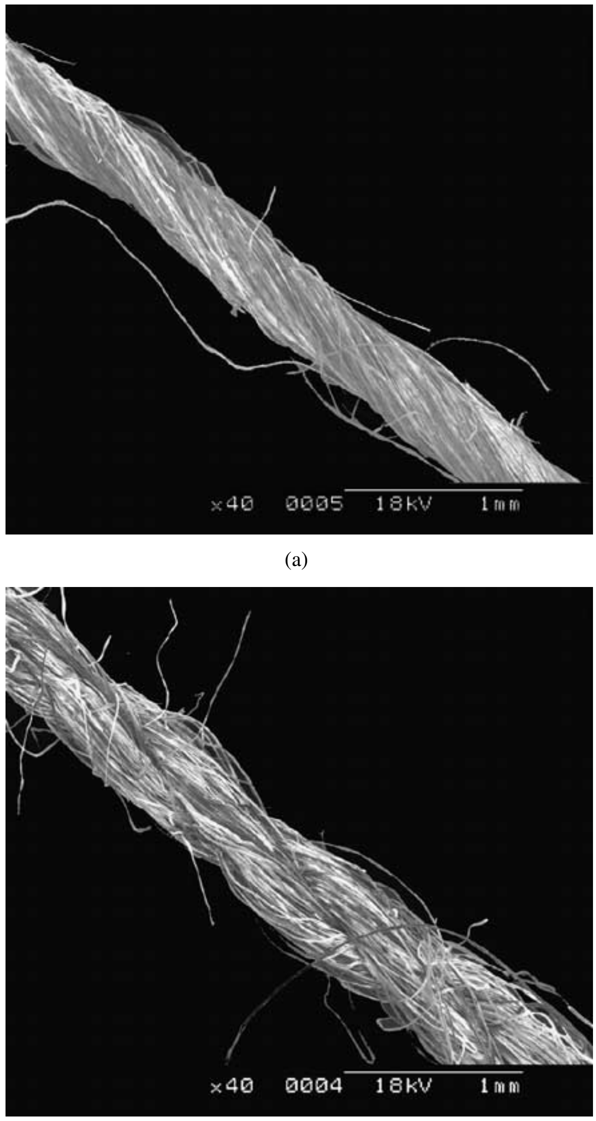


Figure 2 Cotton fiber.

centimeters long) and not in a filament form, i.e. with a length of several meters to several kilometers, as it is the case for silk for instance. The cross-section of the cotton fiber has a bean shape (Fig. 2). For this work two varieties of cotton fiber have been used, differences being in the fiber length the cross-section area, i.e. the mass per unit length (Table I). Cotton 1 is longer and finer than cotton 2.

2.1.2. Mesoscopical scale

Fibers are organized in a yarn (Fig. 3). In most cases, yarn is a single yarn fiber bundle obtained by ring spinning process. Then, yarn shows parallel fibers. These fibers are oriented with an angle relative to yarn axis. This angle comes from a twist that gives cohesion to the yarn. In fact, the fiber twist induces normal forces between fibers and then increasing interfiber friction



(b)

Figure 3 Yarn structure (a) single yarn, (b) balanced two-plied yarn.

gives yarn cohesion. This specific arrangement gives to a yarn of a given mass per unit length a low bending rigidity compare to a unique fiber of the same mass per unit length. This kind of fiber doesn't exist within the range of natural fiber like cotton. This can be available for man-made fibers.

It is possible to twist two single yarns together, thus a two-plied yarn is obtained. If the two-plied yarn is twisted in the opposite direction of the initial twist of each single yarn, both single yarns loose twist to give it to the assembly. If the twist value of the two-plied yarn is 2/3 of the twist for the single yarns, fibers are parallel to the two-plied yarn axis. This kind of yarn is a balanced two-plied yarn.

All the used yarns have the same mass per unit length (35 mg/m $\pm$ 1 mg/m), thus the material quantity in a yarn cross-section is always the same. Therefore the number of fibers in a yarn cross section N_f is:

$$N_f = \frac{M_y}{M_f} \quad (1)$$

where M_y: yarn mass per unit length, M_f: fiber mass per unit length.

TABLE II Yarn characteristics

	Cotton 1		Cotton 2	
	Single yarn	Two-plied yarn	Single yarn	Two-plied yarn
Mass per unit length (mg/m)	34	36	34	36
Irregularity (%)	12.4	11.5	14.5	10.3

Yarn irregularity is characterized by the quadratic variation coefficient:

$$\text{Irregularity} = 100 \cdot \frac{\sigma}{M_y} \quad (2)$$

where σ: standard deviation of the yarn mass per unit length.

The higher the mass/unit length of fiber is, the more irregular is the mass/unit length of the yarn (Table II). This is due to the fact that the smallest irregularity is the fiber.

The Martindale formula brings into light this phenomenon:

$$\text{Irregularity} = 100 \cdot k\sqrt{\frac{M_f}{M_y}} = \frac{100 \cdot k}{\sqrt{N_f}} \quad (3)$$

where k: constant which depends of the material ($k = 1.06$ for cotton), N_f: number of fibers in a yarn cross-section.

2.1.3. Macroscopic scale

All the fabrics used are plain-knitted fabrics (Fig. 4) and further their stitch length is changed. The stitch length is the length of yarn in one stitch (loop). Three different stitch lengths are used: a small one that gives tight fabrics (0.4 centimeter per stitch), a middle one that gives standard fabrics (0.5 cm/stitch) and a large one for loose fabrics (0.6 cm/stitch). These differences are really significant because with 0.4 cm/stitch the fabric is very tight and with 0.6 cm/stitch it is loose like a net.

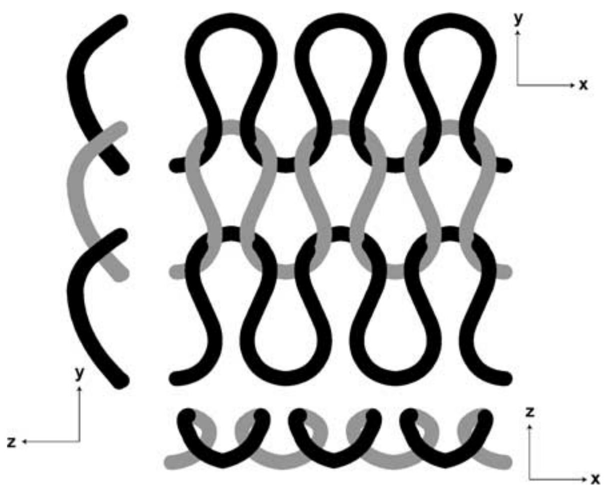


Figure 4 Plain jersey fabric in three planes of the space.

These fabrics have been characterized by three complementary ways: a transverse compression behavior measurement, a tribological measurement and a thermal measurement.

2.2. Measurement methods used

2.2.1. Assessing transverse compression behaviour

The purpose of this measurement is to obtain the yarn or fabric thickness under a fixed load. Because a yarn or a fabric is very easily deformed thickness strongly depends on the load or on the tension.

The transverse compression behavior of the yarns before knitting process as well as of the knitted fabrics has been measured by using transverse compression machine for textiles. The probe used is different for yarns and fabrics: for yarns, the probe is a 0.4 cm × 0.4 cm steel plate, therefore a 4 mm piece of yarn is tested, for fabrics, a circular steel plate with an area of 2 cm^2. The traverse speed is 0.002 cm/s for fabrics and 0.0007 cm/s for yarns. As for viscous materials, a yarn or a fabric thickness at a fixed pressure depend on the transverse speed. The speed values used in this study are recommended for fibrous materials. For yarns, this device measures the thickness in millimeters for a low "pressure" (0.05 cN/mm) and a higher "pressure" (5 cN/mm). For fabrics, the thickness under a pressure of 50 cN/cm^2 is obtained.

2.2.2. Assessing indirectly the real contact area

The co-authors developed an apparatus for assessing warm/cool feeling. This latter reveals to be very useful for characterizing indirectly the real contact area of fabric when this measurement is done under vacuum. In fact, real contact area is at present almost impossible to measure without deform the fabric in the transverse direction. In this measurement, the surface measured is only deformed by its own weight, as the fabric is simply put on the test plate, thus fabric surface is not considered to be strained during measurement. This apparatus measures a transient heat conduction in a vacuum environment, which is the transfer of thermal energy as a result of molecular interactions under a non-homogeneous temperature distribution. Heat conduction needs a contact and then, for a same material, the more important is the contact, the more important the conduction phenomenon is and further the more the material absorbes energy.

For homogeneous materials, Equation 4 (Fourier's equation) shows that at a given temperature gradient, heat flow increases with the thermal conductivity of the material. The more a material absorbs thermal energy during a contact, therefore by conduction, the more it is thermal conductor:

$$\vec{\varphi} = -\lambda \vec{\nabla} T \quad (4)$$

where, in considering the heat flow in the normal direction of the surface: $\vec{\varphi}$: heat flow density in the normal

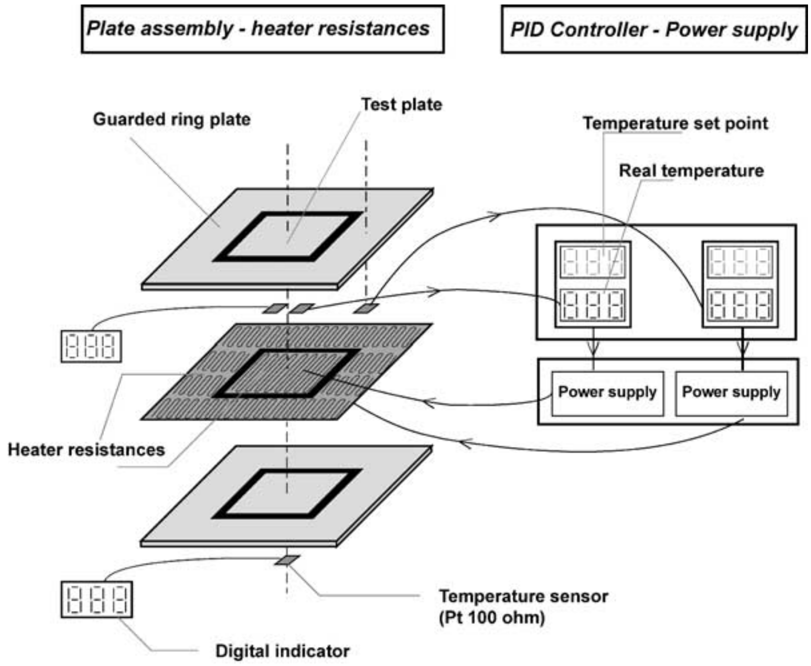


Figure 5 Guarded hot plate arrangement.

direction of the surface (W/m^2), λ: thermal conductivity of the material in the heat flow direction (W/m/K), T: temperature field depending on the time (K).

For a fibrous material, the thermal conductivity is a combination of thermal conductivity of the air and of the fiber (weighted respectively by the fraction of the volume taken up by each component). But, in this case, the fabric is in a vacuum, then the air quantity in the fabric is small and the most significant phenomenon is the conductivity between fibers.

In order to measure the thermal energy absorbed by a fabric, an apparatus based on a hot guarded plate has been developed (Fig. 5). It is made up of a square and thin central aluminum test plate (100 mm^2-area) surrounded by a coplanar ring aluminum plate (292 mm^2-area). The central plate and the guard ring, separated by a thin polystyrene band (2 mm-width), are heated by two independent assemblies of heater wire cemented resistances. The ring plate is at a temperature of 0.5°C higher than the test plate, i.e. 33.5°C, to avoid lateral heat loss from the central test plate but this temperature is not higher because the ring plate must not heat the test plate.

The system has two independent proportional integral derivative (PID) process controllers, one for each heater resistance assembly. The device includes several thin and flat packaging platinum film probes (Pt 100 Ω) in order to control and measure the temperature in different points.

An axial symmetry of the plate arrangement is used. The latter is equivalent to build the resistances in the middle of the thickness of a plate 4-mm thick. Thus, the heat flows in an homogenous way along the plate thickness. So, it is possible to know the rate of the heat flowing only through the upper plate with the value of the rate of electrical power supplied by the heater resistances.

After bringing the test plate and the guard ring plate to the expected operating temperature, 33°C and 33.5°C respectively, it is necessary to wait for equilibrium between the system and the ambient environment to occur. When the equilibrium state is reached, the electrical power supplied by the resistances remains constant. At that stage, the fabric sample is placed on the surface of the test plate. Immediately, heat is lost by the plate and a temperature gradient exists through the fabric. The signal of the electrical power required by the system (plate plus sample) to reach 33°C again is recorded relative to time. The guard ring avoids lateral heat loss, so, the measurement is done through the vertically heat flow between the test plate and the sample. The thermal energy lost by the test plate is equal to the energy absorbed by the fabric plus a constant C_1, and the heat flow which heats the test plate is equal to the electrical power supplied by the heater wire resistances plus a constant C_2. The constants C_1 and C_2 are independent from the fabric. They only depend on the imposed temperature gradient, ΔT. In our study, this gradient is constant and equal to 13°C, i.e. the temperature difference between the atmosphere temperature (20°C) and the operating temperature (33°C).

Under these conditions, the thermal power transferred to the fabric is the difference between the power measured at the equilibrium state without sample and the power measured with a sample on the test plate,

$$P_f(t) = P_{pf}(t) - P_p \quad (5)$$

where P_f: power absorbed by the fabric, in Watt (W), P_{pf}: power lost from the test plate when a sample covers it, in Watt (W), P_p: constant power lost from the test plate without fabric at equilibrium state, in Watt (W).

The thermal energy, absorbed by the sample is calculated by multiplying the instantaneous power absorbed by the fabric by the time interval.

$$E = P_f(t) * \Delta t \quad (6)$$

where E: energy absorbed by the fabric, in Joule (J), Δt: time interval of the acquisition, in second (s).

For this experiment action, it is very important to have a short time interval (less than one second), while for a longer interval, i.e. in a steady state, the energy absorbed is mostly due to the raw material rather than to the structure and to the real area of contact. We have measured the energy absorbed in 0.8 s. The value obtained quantitatively characterized the real contact area, therefore different fabrics made from the same material can be compared. The more the fabric absorbs energy, the larger is the real contact area.

2.2.3. Assessing fabric surface roughness

The purpose of the roughness measurement is to confirm and complete the real contact area measurement.

The surface roughness is the characterized friction behavior of the fabric, which is studied with a multi-directional tribometer [14]. The multi-directional tribometer includes three parts elements: the drive for the sample, the sensor and the signal-processing unit. The sample-carrier is a 140-mm-diameter rotary disk. The sensor is positioned at one end of a balance arm with counterweight at the other and this arm is fixed on the frame which supports the sample-carrier (Fig. 6). The sensor is a piezo-electric accelerometer. The probe fixed on this sensor is a steel wire (0.5 mm in diameter and 5 mm in length) with its axis radial to the sample-carrier. The scanned surface on the rotary disk is a 110-mm-diameter ring. Measurements are performed at a rotation speed of 0.258 rps; while the linear speed is 89 $\text{mm} \cdot \text{s}^{-1}$.

The Fourier analysis of the electrical signal from the sensor consists in computing the autospectrum relative to frequency by a spectrum analyzer. The autospectrum is the average of several instantaneous spectra at least during a sample carrier rotation. Each spectrum is expressed in power spectral density (PSD) relative to frequency.

The power spectral density is obtained as follows:

$$PSD(f) = \frac{|X(f)|^2}{K * \Delta f} \tag{7}$$

where f: frequency in Hertz (s^{-1}), $X(f)$: Fourier transform of the temporal signal $x(t)$, which corresponds here to the signal from the sensor, *PSD*: power spectrum density, Δf: step in frequency domain, $\Delta f = 1$ Hz, K: Coefficient relative to the windowing. In our case, we used a Hanning window, then $K = 1.5$.

All the fabrics have a periodical structure due to their basic pattern (kind of weave or knit). Thus, the power spectral density shows one or several peaks corresponding to the periodicities of the fabric structure. The number of peaks is equal to the number of periodicity scanned by the probe at least during a sample carried rotation. For jersey fabrics, the power spectral density has one peak which corresponds to the wales.

The frequency value of each peak is equal to:

$$f = \frac{\pi D \omega}{l} \tag{8}$$

where D: diameter of the scanned surface (mm), ω: rotation speed (rps), f: frequency (Hz), l: length of a spatial period (mm).

A spatial period shows the distance between two asperities (in our case two wales). The height of the frequency peak corresponding to this spatial period evolves in the same direction as the friction force due to these asperities. This friction force depends on the height of the asperities and on the material. Therefore, for a same material, the maximum magnitude of the peak is relative to the asperity height, and then it characterizes the fabric surface roughness. The asperity height depends on yarn undulation in the fabric. Thus, the rougher the structure is, the higher is the maximum frequency peak.

3. Results

3.1. Transverse compression

The results of yarn transverse compression (Fig. 7) show that under a low pressure (0.005 cN/mm) all the yarns have similar thickness except cotton 1 single yarn, and further with a high pressure (5 cN/mm) all the yarn have similar thickness.

For knitted fabric thickness, Fig. 8 shows three phenomena. Firstly, cotton 1 gives thinner fabrics than

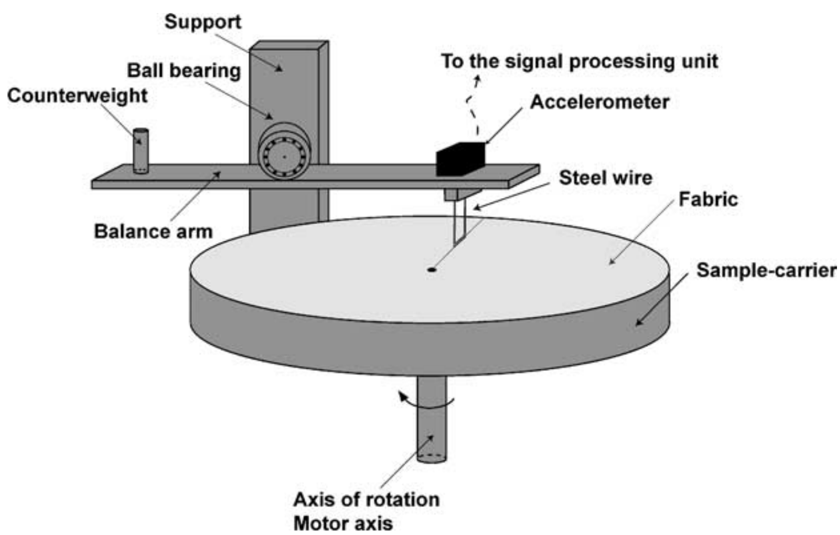


Figure 6 Multi-directional tribometer.

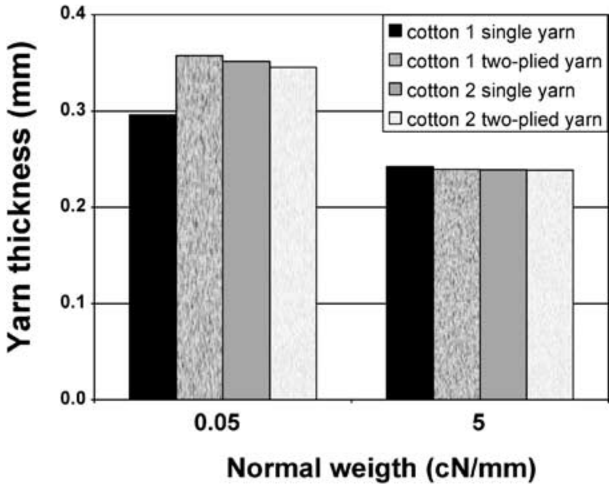


Figure 7 Yarn thickness results.

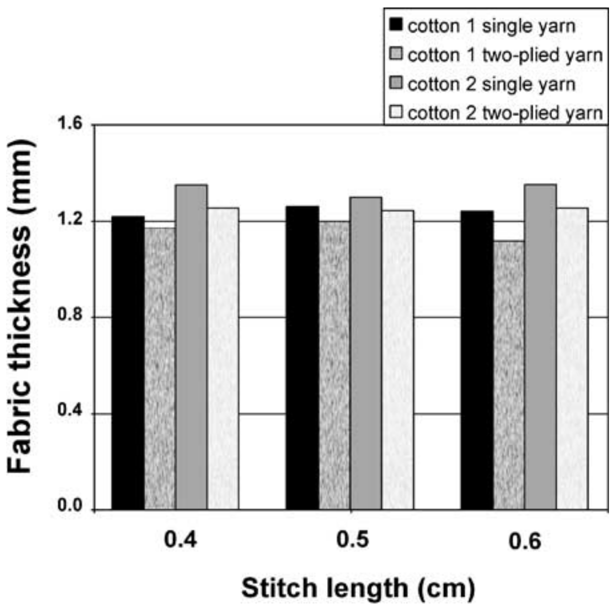


Figure 8 Fabrics thickness results.

cotton 2, for the same yarn and fabric structure. Secondly, single yarns give thicker fabrics than two-plied yarns, for the same cotton and fabric structure. Lastly, stitch length doesn't really influence fabric thickness, even if the stitch length differences are very significant. These results will be explained in the discussion.

In summary, these results for fabrics do not come from yarn thickness as they do not follow the same trends. The fabric thickness evolution has to be explained. Further, more investigation has to be carried out in order to understand this phenomenon. In fact, this kind of phenomenon has not been reported yet in previous papers.

Previous research on plain-knitted fabric properties [15, 16] showed that with a same raw material, in this case cotton, the stitch density only depends on stitch length because:

$$N = \frac{K_N}{l^2} \qquad (9)$$

where N: stitch density in number of stitches (loops) per cm^2, K_N: constant that depends only on the raw material, l: stitch length in centimeter.

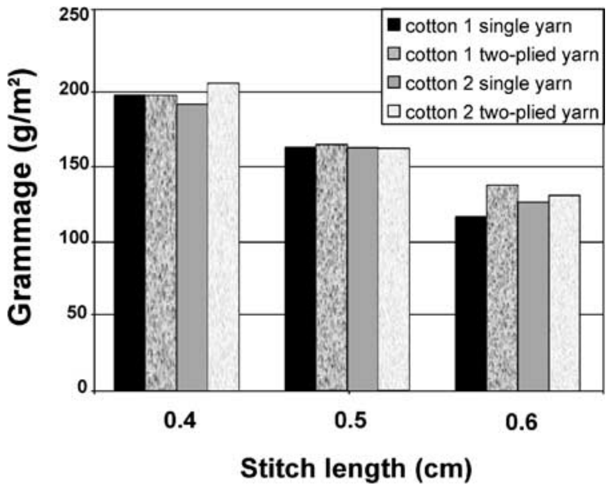


Figure 9 Fabric grammages.

Therefore, grammage (fabric weight per area) can be expressed as follows:

$$G = \frac{N \times l \times t}{10} = \frac{K_N \times t}{10 \cdot l} \qquad (10)$$

where G: grammage in g/m^2, t: yarn mass per unit length in mg/m.

In formula (9) and (10), K_N only depends on the raw material, even if all the experiments done to give this constant for different raw take into account a yarn structure only, the most used and common: the single yarn. Therefore, it is interesting to measure grammage of the knitted fabrics used in this study to confirm or not Munden theory. Fig. 9 shows that all the fabrics with the same stitch length have very closed grammages. Moreover, grammage decreases when stitch length increases according to Munden theory. Therefore, there is no correlation between fabric thickness and grammage.

Because of fabric thickness variation, the number of wales and courses should change, even if the stitch density remains constant for a given stitch length. Then, wales and courses per centimeter have been measured. Figs 10 and 11 do not show correlation between fabric

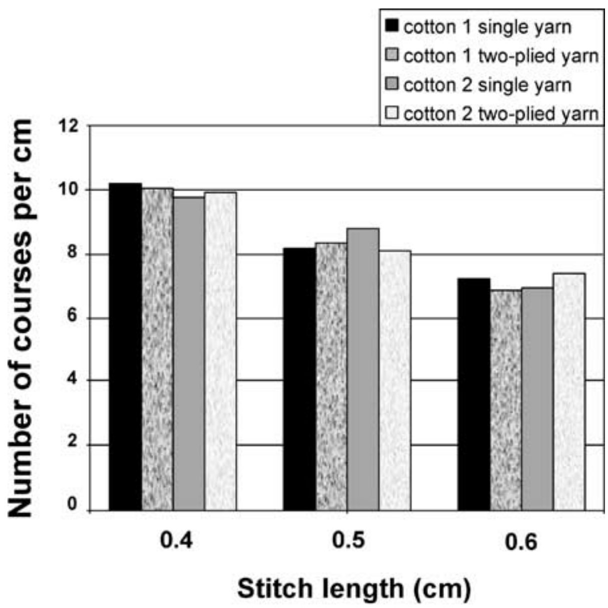


Figure 10 Number of courses per centimeter in the fabrics studied.

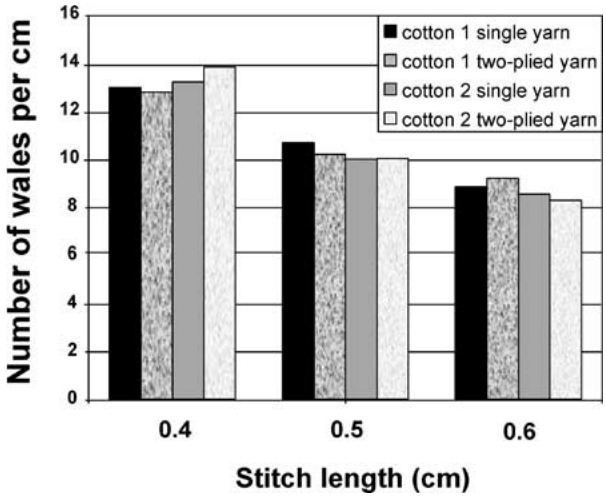


Figure 11 Number of wales per centimeter in the fabrics studied.

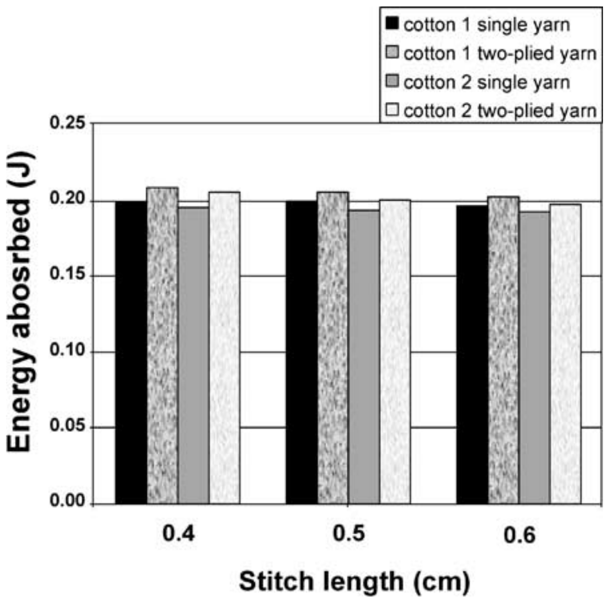


Figure 12 Thermal energy absorbed by the fabrics in vacuum.

thickness and the number of stitches in walewise or coursewise. Morevover, for a given stitch length the number of courses or wales per centimeter can be consider to be constant because it is very difficult to be accurate during this kind of measurement. In summary, fabric thickness changes but not yarn thickness, fabric grammage or number of courses or wales per centimeter.

3.2. Real contact area

The quantity of heat energy absorbed by the different kinds of fabrics during the first 0.8 second of contact of plate to fabric are shown in Fig. 12. The latter value has been chosen because at this time the power supplied by the heater resistances is at its maximum value, which is necessary for the test plate to reach the temperature set point; this maximum value depends on the fabric. Each value of thermal energy absorbed is the average of twenty samples.

The data, first, points out that the cotton 1 fabrics absorb more energy than the cotton 2 fabrics made of similarly constructed. Secondly, the fabrics knitted with two-plied yarns absorb more heat than those constructed with single yarns. Lastly, the longer the stitch length is, the less the fabric absorbs energy. This effect is so small that it is not the case for cotton 1 single yarn.

Therefore, fabrics made of cotton 1 present a greater real contact area than the fabrics made of similarly constructed cotton 2. The longer and/or thinner the fiber is, the larger is real contact area. Fabrics made of two-plied yarns have a greater real contact area than the ones made of single yarns of the same fiber and fabric construction (stitch length). Yarn structure and cotton features have very significant influence on real contact area in comparison with stitch length. The very low influence of stitch length is probably due to the fact that when the stitch length increases the yarn is bulkier because it is not stressed in compression (Fig. 13). Thus, the important porosity due to large stitch is partially compensated by this relaxation of the yarn.

3.3. Surface roughness

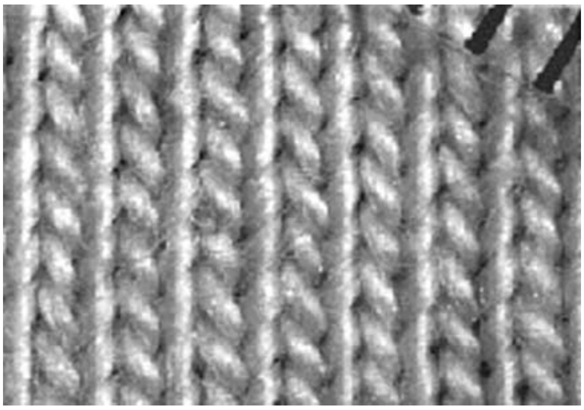
Fig. 14 shows the maximum wale peak measurements of the tested fabrics. From these data, it can be noticed that fabrics made of cotton 1 are less rough than the ones made of cotton 2. Cotton 1 fibers are finer than cotton 2 fibers, therefore, the yarn made of cotton 1 is less rigid. That changes the loop shape as it will be explained in the discussion. Then, fabrics are smoother when using finer fibers. Moreover, while cotton 1 fibers are longer than cotton 2 fibers, the yarn made of cotton 1 is more regular in diameter (Table II). Therefore, yarns as well as fabrics are smoother when using longer fibers.

Fabrics made of two plied yarns display a lower fabric roughness than fabrics made of single yarns. In a two-plied yarn fibers are parallel to the axis of the yarn, while in a single yarn fibers have an angle with this axis due to the twist. While during bending movement interyarn pressure and therefore interyarn friction increase, this twist makes the single yarn more rigid than the two-plied yarns. Then, the loop shape is different with these two kinds of yarn and therefore the fabric is smoother with two-plied yarns. Moreover, as a two-plied yarn is of two single yarns, it is more regular in diameter than a single yarn (Table II), irregularities of both yarns being partially compensated. Thus fabrics are smoother when they are made of two-plied yarns than with single yarns.

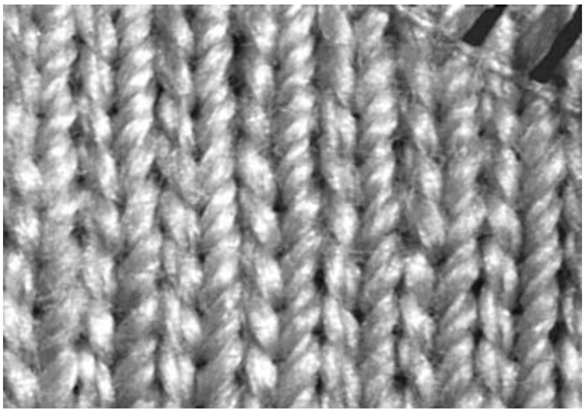
Finally, fabric roughness increases with the fabric stitch length as the knitted structure is looser and the asperities are bigger. The influence of stitch length on roughness is significant while during the measurement it does exist a contact between the probe and the surface. Then the yarn is probably stressed and not relaxed as it is the case for real contact area measurement.

4. Discussion

From the previous results, it appears that it exists a link between fabric thickness, roughness and transient thermal energy absorbed under vacuum, that has the same trend than when considering real contact area. In one hand, fabrics made of cotton 1 present a greater real contact area, and they are smoother and thinner than ones made of similarly constructed cotton 2. The longer and/or finer is the fiber, the larger is the real



(a)



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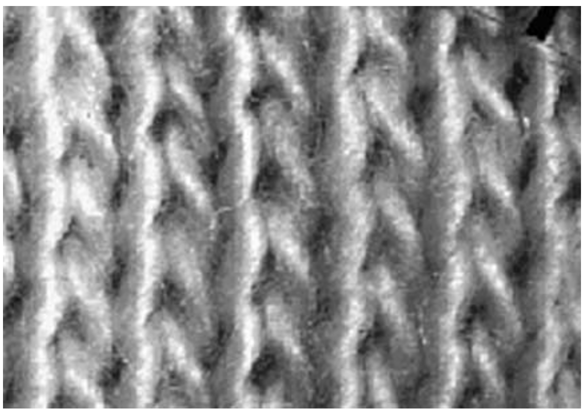

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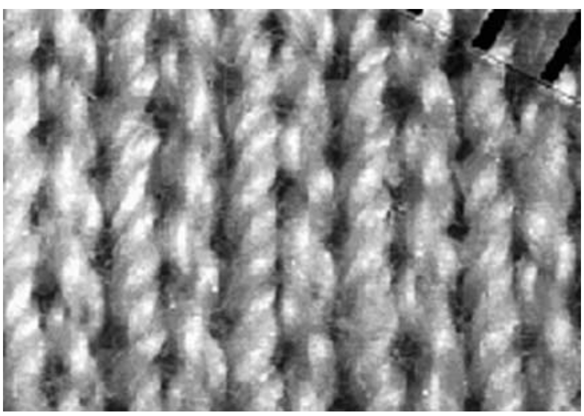

(d)

Figure 13 Photographs of knitted fabric tested with the same magnifying factor (a) single yarn, 0.4 cm-stitch length, (b) two-plied yarn, 0.4 cm-stitch length, (c) single yarn, 0.6 cm-stitch length, (d) two-plied yarn, 0.6 cm-stitch length.

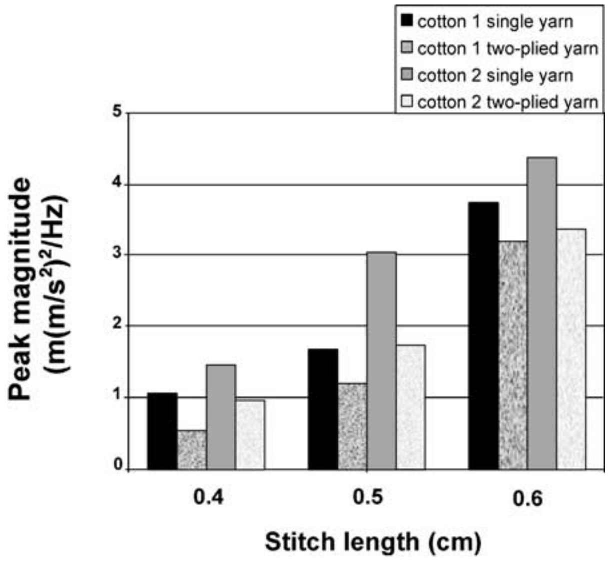

Figure 14 Roughness of fabrics studied.

contact area, then smoother the surface is and the fabric are thinner. In the other hand, fabrics made of two-plied yarns have a greater real contact area, they are smoother and thinner than the ones made with single yarns of the same fiber and fabric construction. Finally, while stitch length increases, while fabric thickness remains constant, real contact area slightly decreases and fabric roughness strongly increases.

The bending moment in a beam of a given material, for a given deformation, is proportional to its moment quadratic of bending. Moreover, a free beam bends in the direction of its minimum quadratic moment. A cotton fiber has a bean shape and can be approached by a half of cross (Fig. 15). In that case, the minimum moment quadratic of a single fiber can be simplified (Fig. 16):

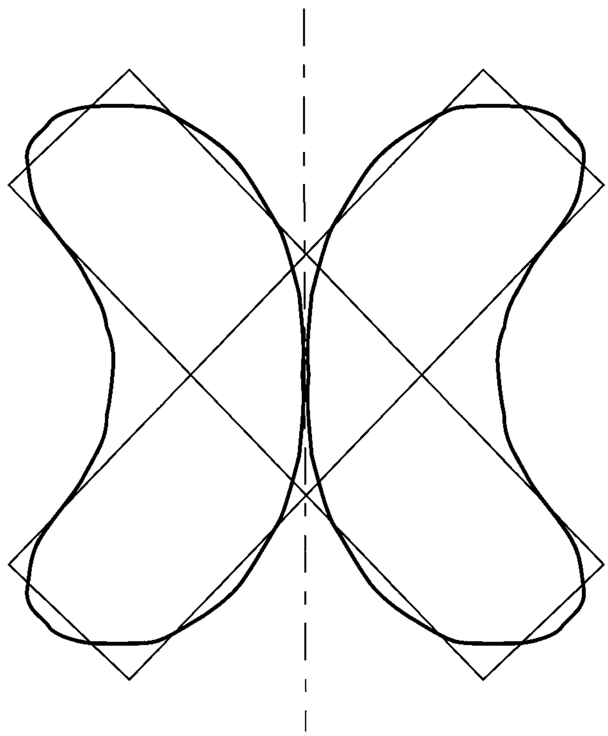

Figure 15 Two cotton fibers as a cross.

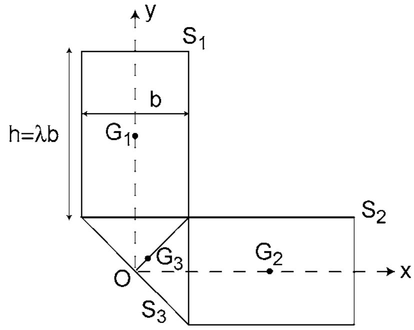

Figure 16 Half cross considered for the approach of the cotton quadratic moment. It is constituted by two rectangles S1 and S2 and a triangle S3.

$$I_{\min} = \frac{1}{2}[I(O,\vec{x}) + I(O,\vec{y}) - \sqrt{[I(O,\vec{x}) + I(O,\vec{y})]^2 + 4I(O,\vec{x},\vec{y})^2}] \quad (11)$$

where

$$I(O,\vec{x}) = I(O,\vec{y}) = \frac{b^4}{384}[32\lambda(13\lambda^2 + 12\lambda + 4) + 13] \quad (12)$$

$$I(O,\vec{x},\vec{y}) = \frac{b^4}{32} \quad (13)$$

where

$$\lambda = \frac{h}{b} \quad (14)$$

Therefore:

$$I_{\min} = \frac{b^4}{12}\left[13\lambda^2 + 12\lambda^2 + 4\lambda + \frac{1}{32}\right] \quad (15)$$

b can be expressed relative to the fiber fineness (mass per unit length) as following:

$$b^2 = \frac{2t}{\rho(4\lambda + 1)} \quad (16)$$

where t: fiber fineness in kg/m, ρ: fiber density in kg/m^3.

Equations 14 and 15 show that the minimum quadratic moment is proportional to the square fiber fineness. Therefore, for cotton 1 and 2, according to Table I:

$$I_{\min 2} = \frac{166^2}{140^2} \cdot I_{\min 1} = 1.4 \cdot I_{\min 1} \quad (17)$$

Thus, cotton 1 is less rigid than cotton 2 in a bending point of view and cotton 1 gives yarns more flexible for the same yarn construction.

During knitting process, fabric is subject to walewise traction in order to permit the loop sequence. This stress elongates and flattens out stitches. After knitting process, fabric is relaxed according to different methods more or less efficient (in a dry or a wet environment and with or without mechanical external vibration). Nevertheless, the aim of all these methods consists of a walewise retraction of the fabric, due to the mechanical behavior of the yarn in two points of view: bending rigidity and interyarn friction. The retraction is finished when the interyarn friction and bending forces are balanced. For two yarns with similar interyarn friction, the fabric made with the more flexible yarn will keep an elongation in the walewise direction and will also be flattened out. The opposite is the fabric made with the rigid yarn, which will retract in wale and thickness directions. This explains why, when fabric is made with longer and/or finer fibers, the real contact area between the fabric and a plate is larger and the fabric is smoother and thinner.

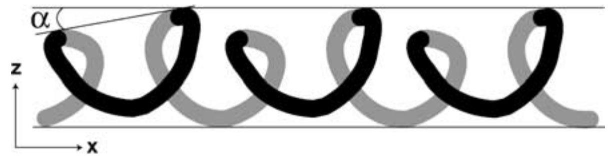

Figure 17 Loop distortion in thickness direction due to the torsion moment of single yarn.

The phenomenon is the same for two-plied yarn compared to single yarn. In fact, the cohesion of a single yarn is only due to the twist of fibers from the yarn axis. Therefore, it is only the consequence of interfiber friction and the more important the yarn twist is, the higher interfiber friction forces are. Thus, a single yarn is rigid while during a bending movement, bending force have to be higher than interfiber friction forces. For a two-plied yarn, the cohesion is very small without tensile stress, but it increases with extensions as the normal forces between the two single yarns twisted together increases. Therefore, a single yarn has higher bending rigidity than a two-plied yarn, and it gives fabrics with a smaller real contact area and rougher and thicker fabrics than the ones made with single yarns of the same fiber and fabric constructions. Another phenomenon for two-plied yarn compared to single yarn has an influence on real area of contact, roughness and thickness: twist induces a torsion moment in the direction of the yarn axis. For a single yarn, the higher the yarn twist is, the higher is the torsion moment. This moment induces a torsion movement inside the loop and then the plane of a single loop surface is not parallel to the plane of the fabric surface, as the loop has a distortion in the thickness direction (Fig. 13, 0.6 cm-stitch length and Fig. 17). This distortion gives a larger thickness, increasing the roughness and decreasing the real contact area.

When stitch length increases, it is obvious that fabric becomes strongly rougher. But it is quite surprising that the real area of contact becomes only slightly lower. When stitch length increases, Fig. 13 shows that yarn is more relaxed. Thus, yarn diameter increases and this phenomenon has a partially compensation effect. Therefore, fabric seems to be much rougher using a mechanical measurement (thus with contact) and the real area of contact is slightly larger.

5. Conclusion

This paper brings into light that knitted fabric morphology and physical properties depend on three scales: the chosen fibers, the yarn spinning and the fabric construction processes. The morphological and structural parameters studied are the cotton fineness and length, the yarn structure and the stitch length of the knitted fabrics.

Fabric morphology and physical properties are characterized with the help of devices developed in the laboratory: a multi-directional tribometer and a measurement of the real area of contact with a thermal method.

Fabrics are rougher, have smaller real area of contact and are thicker as they are made up with coarser fibers. Fabrics made of two-plied yarns are smoother, have larger smaller real area of contact and are thinner than the ones with single yarns. Further, the lower the stitch length of the knitted fabric, the smoother the fabric is, the larger the real area of contact is and the thinner the fabric is.

These results particularly show the predominant influence of the mechanical behavior of yarns on the loop three dimensional shape and then on the fabric properties.

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