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Impact of the Bijective Relationship between Single and Bundle Cotton Fiber's in Cotton Breeding Programs

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Additional information is available at the end of the chapter

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Abstract

In this chapter, we focus on the relationship between fibers' mechanical properties and yarns' ones by studying their relative behavior and the relationship between single and bundle cotton fibers (respectively, dispositions 1 and 2). For this purpose, three different types of cotton fibers were studied. These cottons were chosen from a list of 12 cottons covering a large panel of varieties and physical properties (maturity, fineness, micronaire, length, tenacity, etc.). Classifications per length classes and linear densities were done in order to have more precision and knowledge of cotton fiber behavior. Modeling the creep behavior of single and bundle fibers will help exploring data for the bijective relationship between the two dispositions. Properties evaluated will include elongation, single fibers and bundle tenacities, work of rupture, and so on. Quality of bundle fibers will be a good tool in predicting spinning performances and thus yarn quality.

Keywords: fiber, yarn, single, bundle, length classes, linear densities, modeling

1. Introduction

Cotton fibers are trichome from plants of the order *Malvales*, the family *Malvaceae*, the tribe *Gossypieae*, and the genus *Gossypium*. There are four domesticated species of cotton sorted by decreasing commercial importance: *G. hirsutum*, *G. barbadense*, *G. arboreum*, and *G. herbaceum* [1, 2]. Fiber traits of few cotton species have been shown in **Table 1**.

Cotton fiber's characterization is very complex and depends on the growing and harvesting conditions of the plant. It is very important for cotton breeders to understand the relationships

	% word prod	Distribution	Commercial varieties	Length (mm)	Tensile strength at zero-gauge (cN/Tex)	Linear density (mTex)
<i>G. hirsutum</i>	90	Central America	Upland cottons	25–32 →medium	40	Up to 200
<i>G. barbadense</i>	5–7	South America, Egypt, Soudan, and Peru	Egyptian, Sea Island, and Pima cottons	Superior to 33 →long to extra long-staple cotton	55	100–140
<i>G. arboreum</i> and <i>G. herbaceum</i>	3–4	Africa, Asia, and India	Pakistan and India	Inferior to 25 →short fibers	35	300

Table 1. Fiber parameters of *G. hirsutum*, *G. barbadense*, *G. arboreum*, and *G. herbaceum* species.

existing between specific fiber properties, overall fiber, and yarn qualities [3]. All of these factors interact and are critical to the development of cottons that can compete in a global market.

Understanding these interactions will allow breeders for using the data more effectively for selecting the best cotton plants for developing a cotton variety with improved yarn quality [3, 4]. For this purpose, following properties of cotton fiber were described.

2. Cotton fiber properties

2.1. Physicochemical properties

The cotton fiber consists of a primary and secondary cell wall [5]. These latter are the key determinant of the cotton fiber growth and development and are primarily composed of cellulose (about 96% of pure cellulose: which is a naturally occurring crystalline carbohydrate polymer), hemicellulose, pectin, lignin, and structural proteins [2].

Numerous studies comprehensively describe the structure and development of cotton fibers [6, 7]. In brief, cotton fibers develop in three phases: initiation, elongation, and maturation through secondary wall thickening. The initiation of cotton fibers begins from the epidermal cells on the ovule surface to the elongation and the development of the primary cell wall. This latter, covered with a cuticle, continues to elongate until reaching the final fiber lengths. The secondary wall, which makes up 90% of fiber weight, consists of cellulose fibrils arranged in a layered helical structure. This layer contributes to the tensile properties of the cotton fiber and gives the final mechanical properties of the fiber. The final stage in the fiber development consists of the removal of moisture, during which the fiber collapses. Fibers are then converted from a cylindrical shape to a twisted ribbon. **Figure 1** shows the changes in fiber length, diameter, and wall thickness during the development of the cotton fiber.

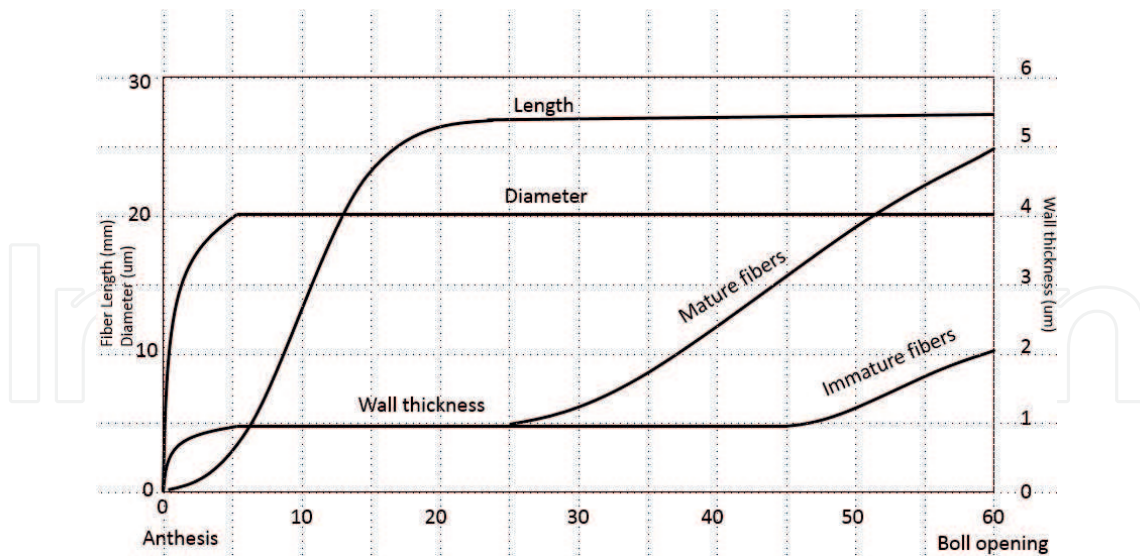


Figure 1. Different developmental stages of fiber.

2.2. Physical properties

2.2.1. Fiber linear density or fineness

Cotton fineness [8–10] is the linear density or weight per unit length of fiber. In fact, for a given fiber (that is assumed of a fixed density), its mass is proportional to its cross-sectional area:

$$\text{Mass of a fiber} = \text{cross - sectional area} \times \text{length} \times \text{density} \quad (1)$$

This relationship is used in the gravimetric definition of fiber fineness. The primary unit of fiber fineness is Tex (g/1000 m).

2.2.2. Fiber maturity

The maturity [11, 12] of cotton fibers is the degree of thickening, which is defined as the ratio of the area of the cell wall to the area of a circle having the same perimeter as the fiber cross section. Thus, measuring the maturity of cotton fibers involves measuring the thickness of their secondary cell wall. The degree of wall thickening increases as the fiber matures.

Based on microscopic observations, wall thickness can be denoted by the degree of thickening (θ) as shown by the equation below [9]:

$$\theta = \frac{\text{cross - sectional area of fiber wall}}{\text{area of circle of same perimeter}} \quad (2)$$

When the degree of thickening is equal to one, the fiber is then completely solid. When the value of θ is above 0.6, the fiber is considered mature. In the contrary, when θ is below 0.6, the fiber is considered immature.

2.2.3. Fiber micronaire

Micronaire is an indicator of both fineness and maturity. Its value is determined by the measurement of the air permeability of a mass of cotton fibers under specified conditions. Micronaire [13, 14] measurement fails to properly distinguish fine and mature cotton fibers from coarser with lesser maturity. The empirical relationship combines the maturity, fineness, and micronaire:

$$(MR)^2 Tt = 3.86 (IM)^2 + 18.16(IM) + 13 \quad (3)$$

where IM is the micronaire, Tt is the fiber fineness, and MR is the maturity ratio.

2.2.4. Fiber length

Enhancing fiber length is a complex issue because fiber samples from cotton bales contain a range distribution of fiber lengths [15].

The prevailing environmental conditions during a growing season affect the length distribution of cotton fibers [16]. The length of cotton fibers fluctuates significantly not only among cultivars but also within a cultivar. It is because of the prevailing environmental conditions within the same plant due to position of the boll, within the same boll due to the flow of nutrients toward the developing individual seed, and within the same seed due to the positions of fibers on the seed. Besides, harvesting, ginning, and processing methods change the length distributions of cotton [17]. Determining the length of individual fibers is time consuming and difficult, so various methods for estimating fiber length have been devised. Most test methods and instruments for fiber length analysis measure the length and the weight of each group of fibers in order to determine the fiber length characteristics.

2.3. Mechanical properties

Mechanical properties are the most important indicators for breeders to produce fibers that perform better in textile manufacturing and end-user [18]. Fiber mechanics is the study of the tensile, creep, relaxation, and fatigue properties, the key of the mechanical properties, for fibers and fibrous assemblies [19, 20]:

- Tensile test

Tensile test is carried out to achieve fiber parameters such as strength, percent elongation, and initial modulus, and these important parameters are usually obtained after applying axial stress at a constant elongation rate till failure. The applied tensile load and elongation are recorded during the test for the calculation of the stress and the strain.

- Creep test

Creep is a time-dependent deformation under a certain applied load. The rate of deformation is named the creep rate. It is the slope of the line in a creep strain vs. time curve.

- Relaxation test

In the relaxation test, a constant strain is applied, and the stress is measured for a period.

- Fatigue test

In a fatigue test [21], a fiber may be cycled over a wide range of frequencies under a variety of imposed extension rate conditions. The fiber is held between two clamps one of which connected to a vibration generator. An oscillatory force is applied to the fiber and is chosen as a percentage of the breaking force.

3. Measurements of cotton fiber properties

Cotton fibers are not homogeneous in their physical properties. Their maturity, fineness, and lengths vary from fiber to fiber. Sometimes, even alongside the length of a fiber, there is a variation in physical properties. Thus, the mechanical properties are affected by these variabilities.

Table 2 regroups almost all the apparatus allowing to determine the physical and mechanical properties of cotton fibers.

Physical properties	<i>Fineness</i>	<ul style="list-style-type: none"> - Projection microscope - Airflow - Advanced Fiber Information System (AFIS ®) [22] - Vibroscope
	<i>Maturity</i>	<ul style="list-style-type: none"> - Goldthwait differential dyeing [23] - Double compression airflow measurement - Polarized light analysis - Causticaire - Centrifugal methods - Image analysis - Near-infra-red (NIR) spectrometry - X-ray fluorescence spectroscopy
	<i>Micronaire</i>	<ul style="list-style-type: none"> - Fineness and Maturity Tester (FMT) - Fibronaire - Cottonscope [24] - Advanced Fiber Information System (AFIS ®)
	<i>Length</i>	<ul style="list-style-type: none"> - Zweigle Sorter - WIRA fiber length machine - Fibrograph - Almeter - High Volume Instruments (HVI ®) [23] - Advanced Fiber Information System (AFIS ®)

Mechanical properties		Single fibers	Bundles
		<div><div></div><div>- Mantis Single Fiber Tester [25]</div><div>- Favimat [26]</div><div>- Universal Fiber Testing Machine (UFT®) [20]</div><div>- Dynamometer MTS</div><div>- Dynamometer MTS</div><div>- UFT®</div></div>	<div><div></div><div>- Stelometer</div><div>- HVI®</div><div>- Dynamometer MTS</div><div>- Dynamometer MTS</div></div>
	<i>Tensile</i>		
	<i>Creep relaxation and fatigue</i>		

Table 2. Apparatus allowing measuring fiber physical and mechanical properties.

4. Case study

4.1. Materials and methods

To determine the bijective relationships between single and bundle cotton fibers, 12 bales of cotton were selected based on their distinct physical properties. These cover a large panel of cotton micronaire, tenacity, and lengths. Prior to testing, all cotton samples were conditioned for at least 48 h at 65 ± 2% RH and 21 ± 1°C.

4.1.1. Physical property measurements

The mean values of fineness, maturity, micronaire, and length were determined by the Fineness Maturity Tester and Micromat. The results are shown in **Figure 2a** and **b**.

The principle of the AFIS consists of single fiber measurements with an opto-electronic sensor. Fiber creates signal/impulse converted to an electrical signal, which is analyzed and evaluated

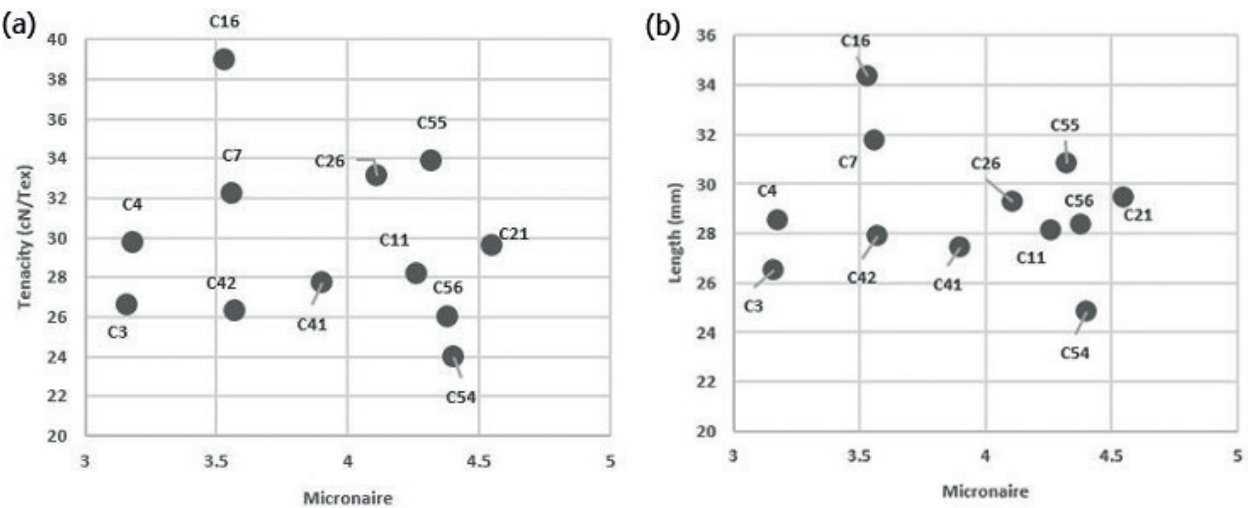


Figure 2. (a) Tenacity vs. micronaire. (b) length vs. micronaire.

by computer. For instance, for length values, the main measurements include: mean length, length upper percentiles, length CV%, short fiber content (defined as the percentage of fibers less than 12.7 mm in length), upper half mean length (UHML), and upper quartile length (UQL).

However, for determining the length, Zweigle sorter method was used. It allows sorting fiber length into groups. It is based on using a Johannsen-Zweigle apparatus (**Figure 3**). The device consists of two steel comb fields to align and straighten the fibers. For cotton sample testing, the combs are spaced from each other for a distance of 4 mm, and the weight of the test specimen is 100 mg. Once prepared, the fibers go through repeated drawing and doubling processes to form straight and parallel bundle of fibers. Length intervals are obtained allowing classification of the fibers into groups. In order to obtain a mass distribution of sample, the fibers of each group are then weighed. The length's interval of each group is determined by the spacing of the combs. We must have at least 10 sample groups extended on the longest fiber. Thus, the longest fibers are drawn and weighed first, followed by the shorter.

4.1.2. Mechanical property measurements

4.1.2.1. Single fiber testing

For measuring single fiber properties, Favimat (Textechno Herbert Stein GmbH and Co. KG, Möchengladbach, Germany; **Figure 4**) was used. The typical testing methods of the Favimat

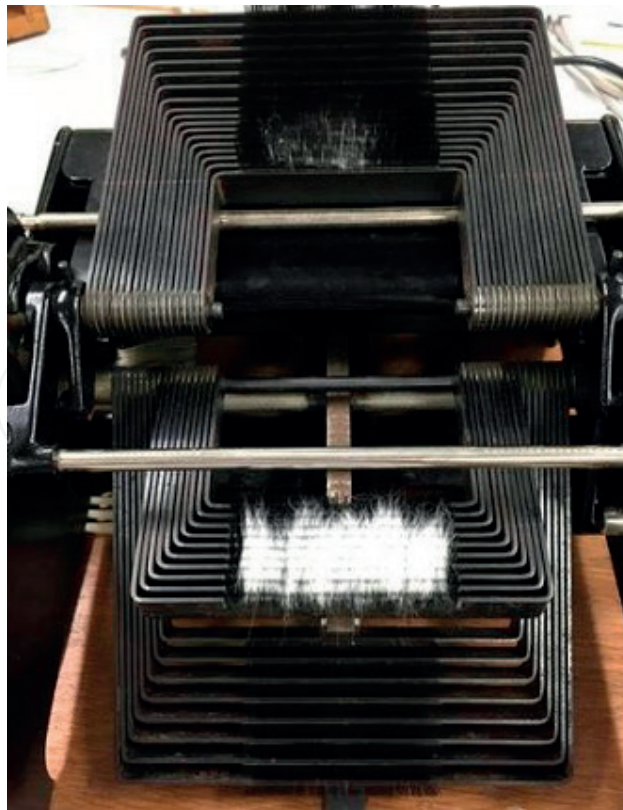


Figure 3. Zweigle sorter apparatus of the Laboratoire de Physique et Mécanique Textile (LPMT).

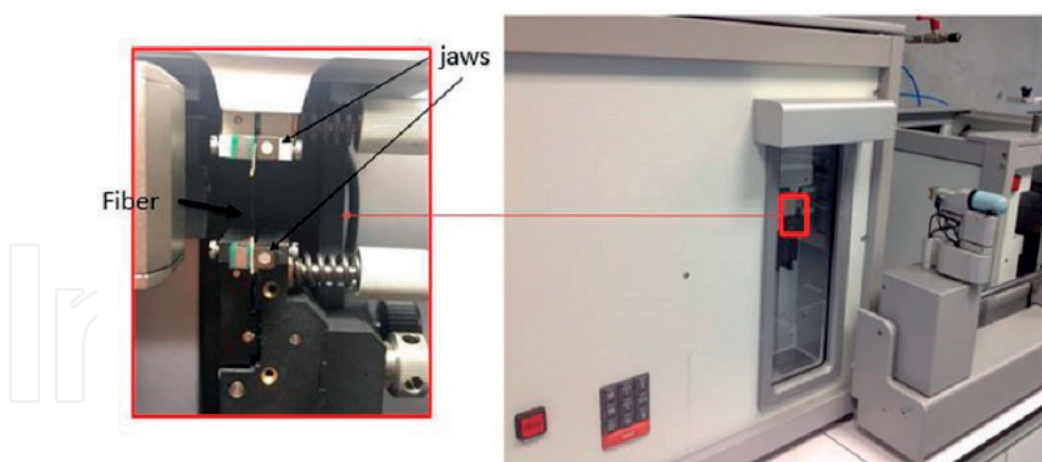


Figure 4. The Favimat device for tensile and linear density measurements.

are the static tensile test, linear-density (fineness) measurement, and measurements of crimp extension, crimp stability, and number of crimps.

The main principle is that both single fiber ends are clamped between two sets of jaws. The displacement is insured by a constant speed motor with interchangeable equipment to vary the rate of elongation. For the tensile tests, the data of the load and elongation are transferred to a computer to be plotted and analyzed.

Universal fiber testing machine (UFT) was also used. This apparatus allows to carry out the testing of single fibers in tensile, creep, relaxation, and fatigue. It was developed by Bunsell and Hearle in the 1970s. **Figure 5** shows the UFT device of the LPMT laboratory.

In addition, the dynamometer MTS with a 2 N sensor was used for the single fiber creep and relaxation tests. The fibers are glued with a cyanoacrylate glue in the extremities of a 15-mm diameter paper. Once placed in the two jaws of the dynamometer MTS (**Figure 6**), paper is cut on its extremities to allow the extension of the fiber.

4.1.2.2. Bundle fiber testing

For bundle testing, Pressley clamps were used and placed on a dynamometer device. An attachment system was compatible with the dynamometer MTS, and the jaws were designed in our laboratory as shown in **Figure 7**. The sensor used for the bundle fiber test had a 2-kN sensibility.

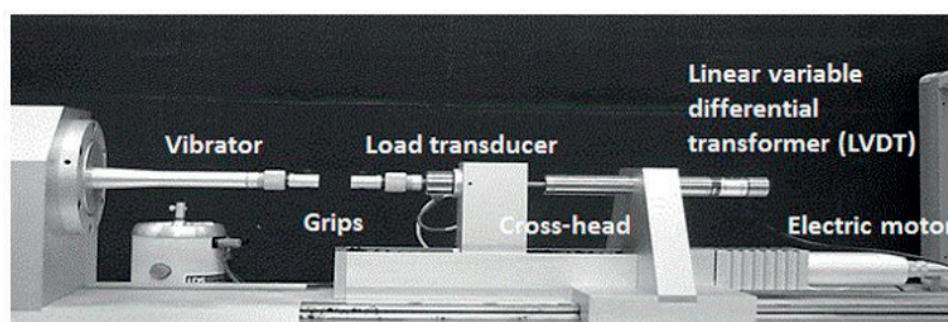


Figure 5. UFT device of the LPMT laboratory.



Figure 6. Single fiber disposition in the dynamometer MTS.

Preparation of the samples in the Pressley jaws is similar to the one used for the Stelometer measurements. In fact, the specimen is pulled manually through the teeth of a comb several times to straighten fibers and remove all the neps. A flat bundle of fiber is placed in the device (**Figure 8**) and is fixed with in a special vise, which provides a pre-stressing load at a 100-g tension. A torsion spring ensures uniform tightening of the clamps. The ends of the sample are then cut off with a special knife, and finally, the clamps are placed in the instrument.

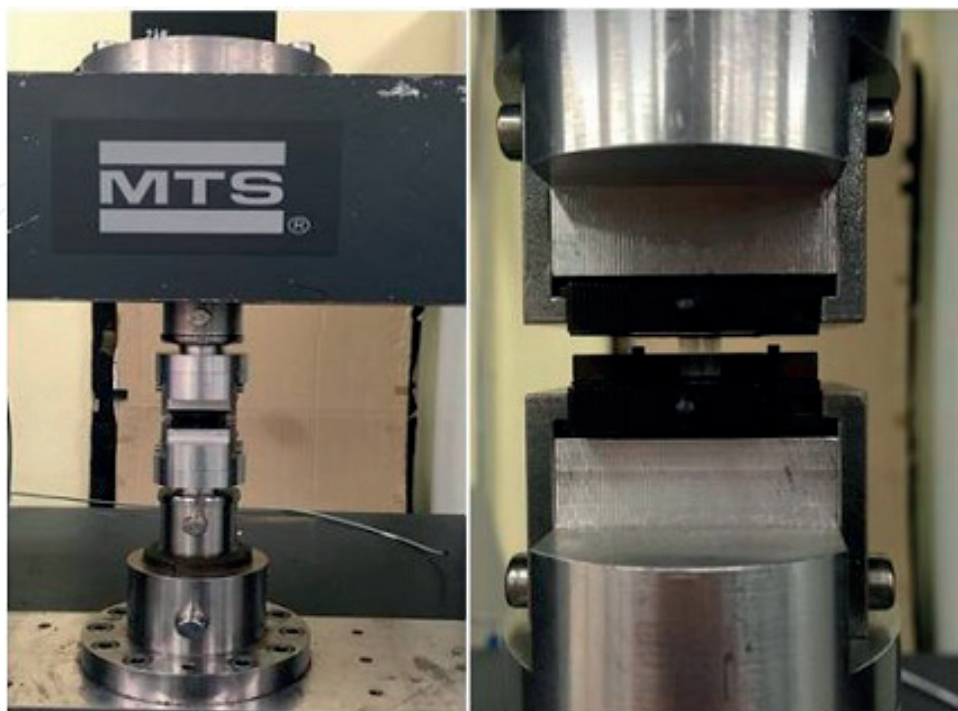


Figure 7. Pressley clamps in the dynamometer device.

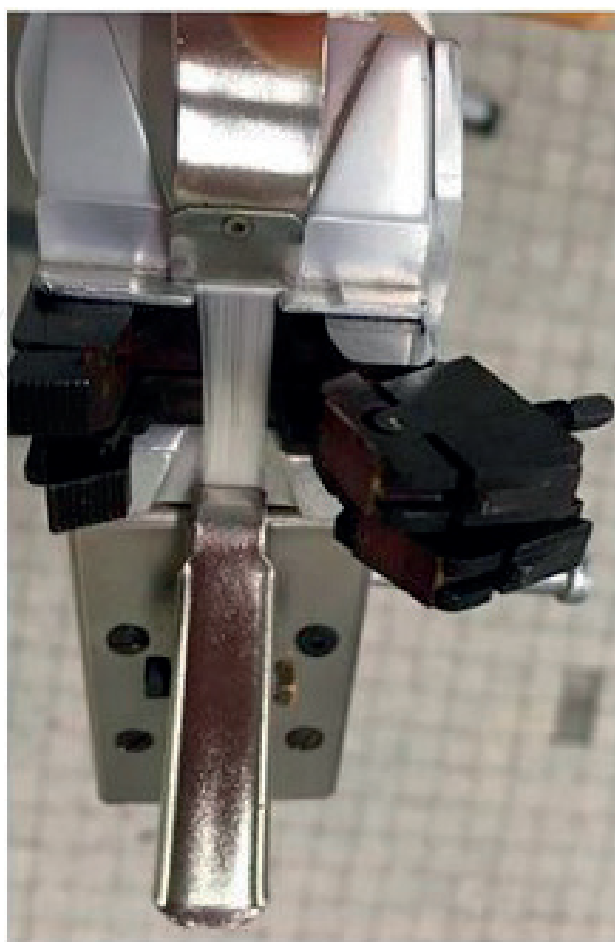


Figure 8. Stelometer device of the LPMT.

4.1.3. Analogical modeling

Tests allowed to determine the physical properties of cotton fibers are good indicators of the global behavior of fiber. In fact, many parameters can be determined from these tests (such as E -initial modulus, σ -stress, ε -strain, η -viscosity, etc.). Analogical modeling can be a way to simulate cotton fiber behaviors, whatever the disposition tested.

Analogical models are represented based on the assembly of simple mechanical elements (springs, dashpots, skidding blocks, or stopping blocks) having the same responses to those expected by the real material. These models are very useful to clarify how the fiber (single or bundle) behaves. The most common elements are shown in **Table 3** [27]. The mechanical elements can be assembled both in series or in parallel or in mixed groups (networks). Thus, more complex mechanical responses can be simulated to illustrate the behavior of the material submitted to the tensile, creep, relaxation, and fatigue tests [21, 28].

Cotton fibers are viscoelastic. Creep and stress relaxation tests demonstrate this characteristic. In creep test, a constant stress is maintained on a specimen while its deformation is monitored as a function of time, and deformation increases with the time. In stress relaxation test, a constant deformation is maintained while the stress on the specimen is monitored as a function of time, and stress decreases with time.

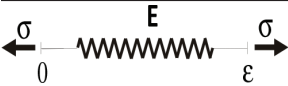
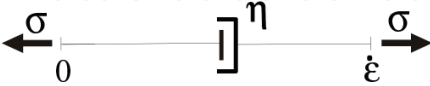
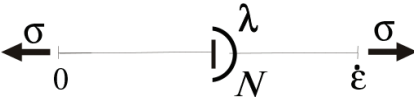
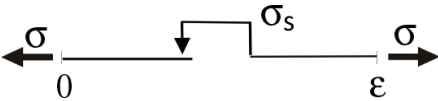
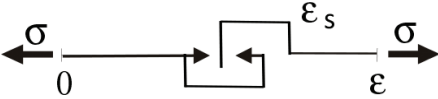
Analogical model	Equation	Mechanical element	General signification
	$\sigma = E \varepsilon$ where σ is the stress, ε is the strain, and E is Young's modulus	Spring	Linear elasticity presented by a linear relationship between the stress and the strain, and the model obeys to Hooke's law
	$\sigma = \eta \dot{\varepsilon}$ where σ is the stress, $\dot{\varepsilon}$ is the strain rate, and η is the viscous coefficient	Dashpot	Linear viscosity presented by a linear relationship between the stress and the strain rate, and the model obeys to Newton's law
	$\sigma = \lambda \dot{\varepsilon}^{1/N}$ where λ is a constant related to the material used and N is a constant characterizing the flow		Non-linear viscosity that depends on the material tested and the flow
	$-\sigma_s < \sigma < \sigma_s$ where σ_s is the stress threshold	Skidding block	Plasticity that depends on the stress threshold
	$-\varepsilon_s < \varepsilon < \varepsilon_s$ where ε_s is the strain threshold	Stopping block	Plasticity that depends on the strain threshold

Table 3. Standard linear solid models.

The classical viscoelastic constitutive models are represented by Maxwell and Kelvin-Voigt models using springs and dashpots to simulate elasticity and viscosity, respectively. The respective equations are:

$$\dot{\varepsilon} = \dot{\varepsilon}_{\text{elastic}} + \dot{\varepsilon}_{\text{viscous}} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta} \quad (4)$$

$$\sigma = \sigma_{\text{elastic}} + \sigma_{\text{viscous}} = \eta \dot{\varepsilon} + E \varepsilon \quad (5)$$

In the case of the Maxwell model, the behavior is modeled by a spring and a dashpot connected in series:

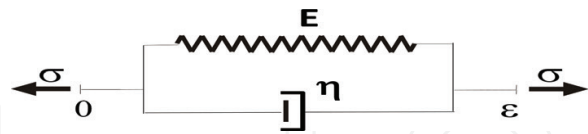


Eq. 6 gives response of the Maxwell model. For example, for the creep and relaxation tests, where a constant strain ($\varepsilon = \varepsilon_0$) and a constant stress ($\sigma = \sigma_0$) at $t = 0$ are applied, respectively, the respective following responses are obtained:

$$\varepsilon = \frac{\sigma_0}{E} + \frac{\sigma_0}{\eta} t$$

(6)

In the Kelvin-Voigt model, the spring and the dashpot are connected in parallel:



The Kelvin-Voigt response of the creep test at a constant stress σ_0 at $t = 0$ is:

$$\varepsilon(t) = \frac{\sigma_0}{E}(1 - e^{(-E/\eta)t})$$

4.2. Results

Among these 12 varieties of cotton fibers, C7, C42, and C55 were selected. In fact, C7 and C42 have the same micronaire but showed different tenacities and lengths. However, C7 and C55 showed the same length and tenacity but different micronaires. Classification per length using the Zweigle Sorter was carried out in order to get more information about the variability of tensile properties across various length classes. The classes found for each cotton are shown in **Table 4**.

Single and bundle tests are carried out for each length class of each cotton fiber.

Tensile tests of single fibers can be undertaken with the Favimat, which determines the linear densities. This latter is measured according to the vibroscopic testing principle. Two stickers are attached in extremities of the cotton fibers and placed between the two jaws of the Favimat. Test parameters are as follow, and the test results are shown in **Table 5**:

- Test speed: 5 mm/min.
- Gauge length: 15 mm.
- Sensor: 210 cN.
- Pretension: 0.06 cN/Tex.
- Nominal linear density: 10 dTex.

Creep and relaxation tests of single fibers were done with a dynamometer MTS.

	[38–36]	[36–34]	[34–32]	[32–30]	[30–28]	[28–26]	[26–24]	[24–22]	[22–20]	[20–18]
C7										
C42										
C55										

Table 4. Length classes for cottons C7, C42, and C55 (the shading illustrates the length classes).

	Elong max (%)	Elong rupt (%)	Force max (cN)	Work of rupt (cN cm)	Tenacity (cN/tex)	Linear density (dtex)	Time (s)	Specific modulus E
C7 [38–36]	7.12	7.62	5.34	0.26	94.85	0.58	13.83	13.54
C7 [36–34]	8.16	8.30	5.35	0.30	72.48	0.76	15.04	9.11
C7 [34–32]	7.66	7.83	4.84	0.27	58.18	0.84	14.19	7.81
C7 [32–30]	8.50	8.64	4.78	0.28	62.33	0.78	15.70	7.95
C42 [34–32]	7.23	7.37	4.09	0.21	42.86	1.04	13.40	6.00
C42 [32–30]	9.02	9.17	4.42	0.26	42.28	1.08	16.71	4.96
C55 [36–34]	9.24	9.38	6.90	0.41	99.96	0.71	16.99	11.48
C55 [34–32]	8.04	8.18	5.00	0.29	65.79	1.04	14.88	7.89
C55 [32–30]	7.66	7.80	5.65	0.29	85.05	0.68	14.15	11.36

Table 5. Tensile tests results for some length classes of the cottons C7, C42, and C55.

Test parameters are as follow:

- Test speed: 5 mm/min.
- Gauge length: 15 mm.
- Sensor: 200 cN.

Results (**Figure 9**) showed that fibers behaved similarly during the creep test for the length class [34–32] for the cottons 7, 42, and 55. This result is in coherence with the values of the initial modulus E determined from the tensile tests for the same length class.

We can also note that the strain increased and asymptotically approached the value of $\ln(\sigma_0/E)$ when t tended to infinity. The response of this model to an applied stress is characterized by a fast-increase part explained by the fact that the stress is at first carried entirely by the viscous element. The second part characterized by a very slight increase explains the elastic element in the continuous elongation of the viscous element. The transition time between the two parts represents the creep time constant, t, which is equals to η/E , where η is the viscosity and E is the initial modulus given by the tensile test at a given constant rate of extension [28].

We concluded that the creep response was viscoelastic and therefore that we could apply a Kelvin-Voigt model.

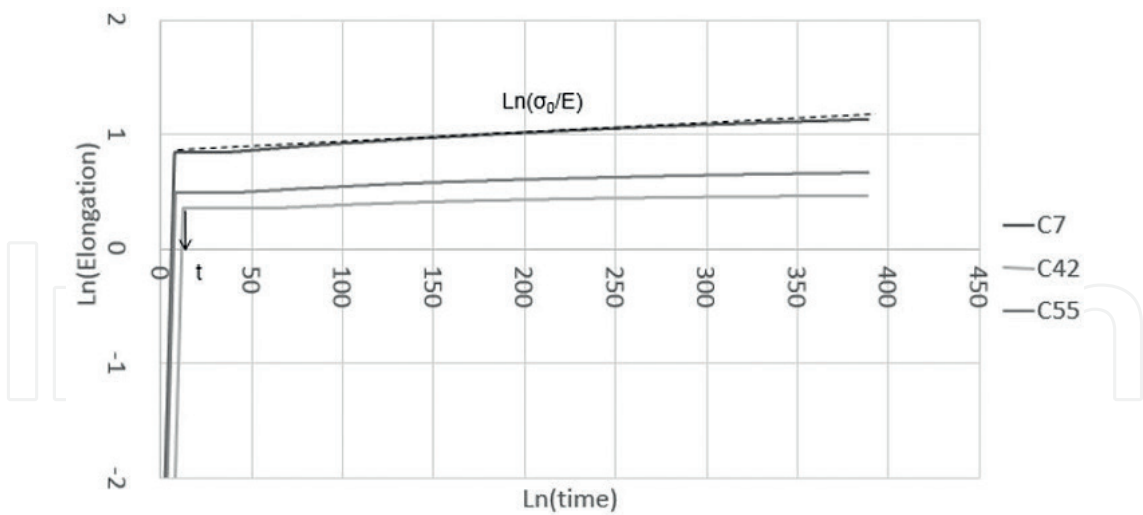


Figure 9. Creep test responses for cottons C7, C42, and C55 for length class [34–32].

As for breeders and geneticists, new cotton varieties developed either by the conventional techniques or by genetic engineering, and detailed characterization of physical and mechanical properties of cotton fibers is essentially required. These properties must be tested fiber-to-fiber, which is very lengthy, tedious, and expensive procedure. Finding a relationship between single and bundle fiber models would therefore be desirable. The aim is then to be able to test these varieties in bundles and to directly determine the single properties.

For bundle testing, the tests were carried out with a speed of 50 mm/min.

Data acquired from the tensile tests are:

- Load and elongation at peak.
- Initial modulus.
- Work of rupture.

The examination of the behavior from the load-elongation curve (**Figure 10**) revealed that we could approximate their shapes to a right-angled triangle, with the base being the elongation and the height being the peak load.

Evaluation of cotton fiber tensile properties serves multiple purposes [29]. The results obtained enable to estimate the performance of raw materials during the transformation procedures of fibers. It is also used to predict the tensile properties of spun yarns or woven textiles. Fiber bundle tensile tests can appear to satisfy the objective because of their relationships with tensile properties of yarn. However, this relationship can be rapidly expected in assemblies of parallel fiber factors such as the degree of fiber-to-fiber interactions and twist contribute to fiber bundle strength.

Regarding creep test results for bundles, we are working on to find out the corresponding models of each cotton variety and comparing them with the single ones. We estimate the bijective relationships existing between the two cotton fiber testing dispositions.

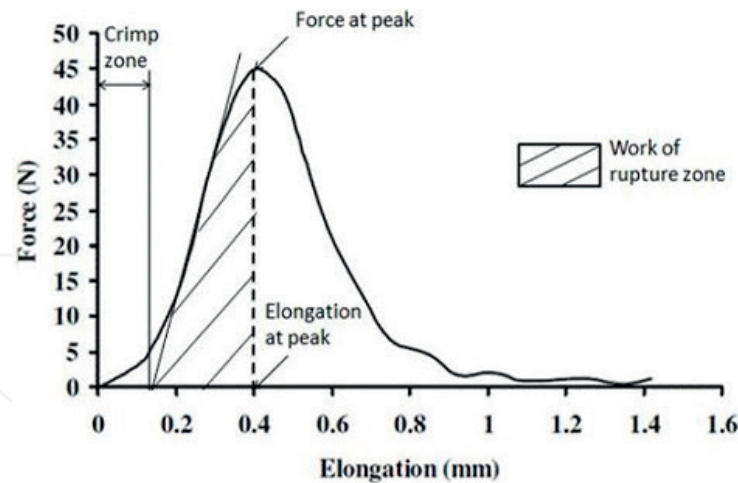


Figure 10. Response of the bundle fibers to tensile tests.

5. Conclusion

Being among the finest natural fibers, cotton is subjected to a variety of characterization tests. These latter can be classified into moisture absorption, electrical, thermal, physical, and mechanical. Cotton breeding programs must deliver fibers that better perform in textile manufacturing in order to compete effectively with international growths of cotton and with the various man-made fibers. In fact, the performance of fibers in textile processing and the quality of the final fabric are highly dependent on the mechanical properties of raw fibers.

Tensile properties of yarns and fabrics depend on both complex fiber arrangements (including length, diameter, friction, etc.) inside the yarn and fabric structure and on the tensile properties of fibers. Thus, it is necessary for the breeders to know about the complex relationships between the fiber arrangements parameters.

In this chapter, we showed that the mechanical behavior of fibers can be analogically modeled and that we assimilate the cotton single fibers creep response to a Kelvin-Voigt one. Nevertheless, the relationship between fiber-to-fiber testing and bundles remains to be clarified through further research.

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