Fibers in the CES EduPack – A White Paper

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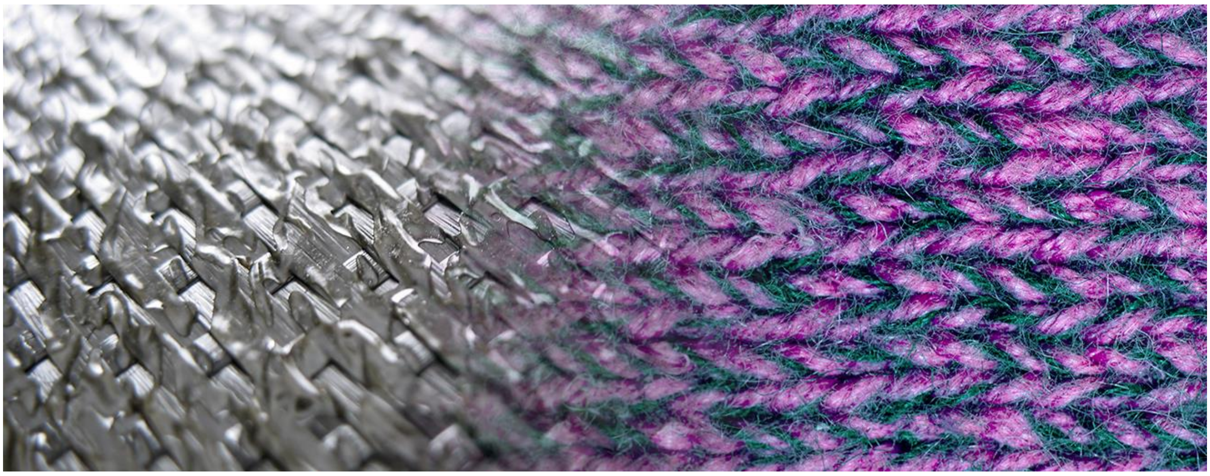

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Mike Ashby, January 2018

1. Introduction

Past editions of the CES EduPack have contained records for a limited number of fibers. In this new edition the number of fiber-types has been expanded from 19 to 31, with particular emphasis on the new "super-fibers" and their properties. The nomenclature and units that are standard in the textile community (denier, tex, gf/denier, cN/tex etc) are introduced in the records to make them intelligible to both engineers and textile scientists. All are defined and explained in associated Science notes.

2. Fiber types and global fiber production

From the earliest recorded times, humans have used natural fibers to meet basic needs of clothing, shelter and for subsistence aids like ropes and nets. Vegetable fibers come from stalk (jute, hemp, ramie), stem (banana, palm, bamboo), leaf (palm, sisal, agave), husk (coir) and seeds (cotton); animal fibers from hair, fur and wool; insect fibers from cocoons and webs. From them humans created a remarkable range of textiles: linen (flax), calico (cotton), gabardine (wool), brocade (silk) and many more[1] (Figures 1 and 2).

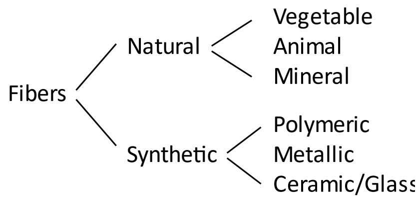


Figure 1. Classification of fibers

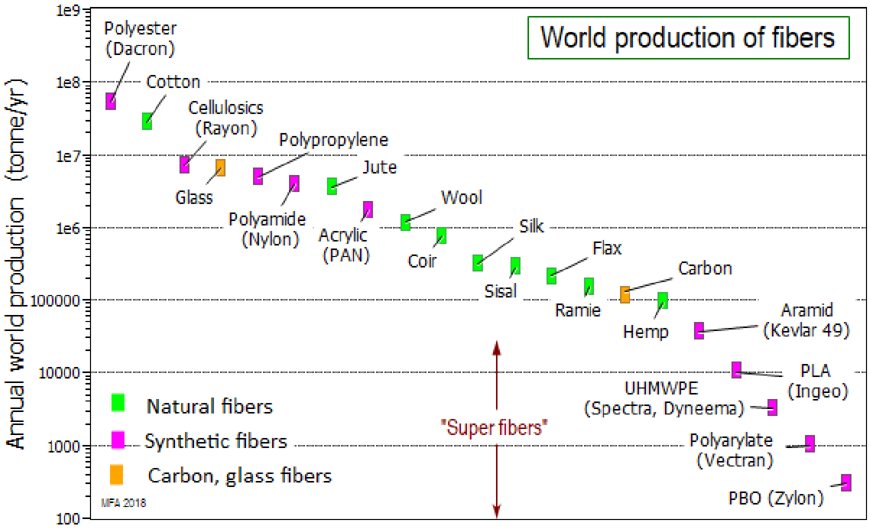


Figure 2. World production of natural and synthetic fibers

[1] http://www.textileschool.com/articles/356/history-of-fibres-natural-and-manmade-fibres

Over the last 100 years many natural fibers have been replaced by those that are synthesized, mainly from oil (Figure 3). The production of synthetic fibers first exceed that of those of nature about 30 years ago; today synthetics account for almost 70% of all fiber production. Why?

- Cost: polypropylene and polyester fibers are cheaper than cotton and flax and they are more reproducible.
- Performance: the recently developed "super-fibers" Kevlar, Spectra, Dyneema, Vectran and Zylon, have properties that, per unit weight, out-perform any other fiber-type.

Synthetic fibers[2] are made by drawing or by extrusion: forcing the molten polymer or polymer-solution through spinnerets from which it cools and solidifies. There are a number of synthetic fiber-types (Figure 3) but four dominate the market: acrylic, nylon, polyester and polyolefin; between them they account for 98% of synthetic polymer production.

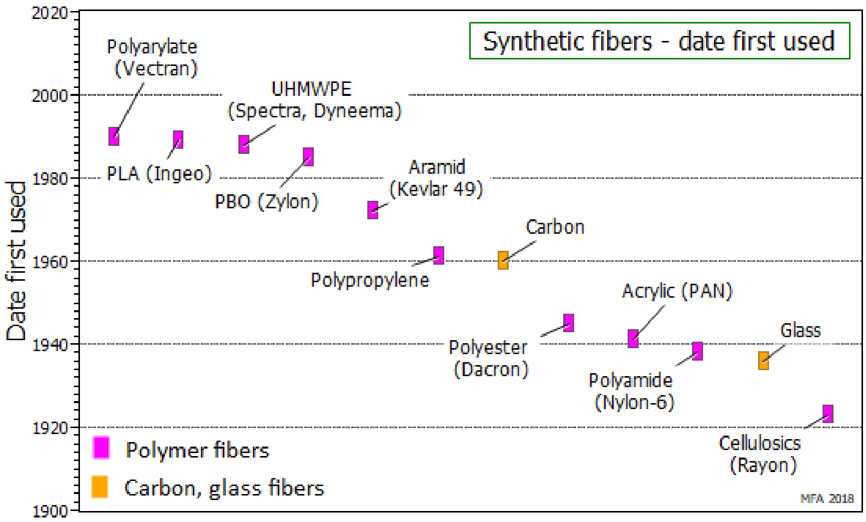


Figure 3. Date of appearance of synthetic fibers

Today, fibers are used in almost every industrial sector (Table 1), and – as Figure 2 demonstrated – they are used in enormous quantities.

Table 1. Uses of fibers

Sector	Examples of use
Aerospace	Parachute fabric, seat belts, textile-reinforced composites, glider fabric
Automotive	Seat belts, tyre cord, drive belts, fiber-reinforced composites, sound insulation
Marine	Rope, sails, awnings, tarpaulins, fiber-reinforced composites
Defense	Ballistic vests, helmets, advanced composites, tents, ropes, tethers
Mining	Sacks, conveyer belts, soil stabilization,
Agriculture	Wind shields, shade cloth, twine, capillary matting
Water	Hoses, filter fabrics, drainage, desalination membranes
Construction	Slings, harnesses, tarpaulins, ropes
Architecture	Floor and wall coverings, drapes, tents, upholstery
Sports	Clothing, shoes, swim suits, archery, kite-surfing tethers, fishing lines, sail cloth
Apparel	Fashion fabrics, sewing thread, waterproof fabrics, protective clothing, hats, shoes

[2] https://www.syntheticgrasswarehouse.com/history-synthetic-fibers/

3. Properties of fibers and unit-conversion tables

Properties[3] are measured using a system of units: cgs, metric, Imperial are examples. Failure to share a common system of units can make communication between disciplines difficult. And, so it is with fibers.

Take Density. Engineers measure density in kg/m^3. The density of textile fibers is reported in grams per 9 kilometers – *denier* – or sometimes grams per km – *tex* – or sometimes grams per 10 km – *dtex* – and thus as a mass per unit length, not per unit volume.

Fiber strength, too, has its mysteries. Tensile strength – *tenacity* – is sometimes reported in meters (how can length be strength?), sometimes in grams-force (gf) per denier, sometimes in centi-Newton (cN) per tex. And these aren't really strength at all, they are strength per unit weight. In engineering units that would be $MPa/(kg/m^3)$ or, simplified, MN.m/kg, or reduced to basic unit, m^2s^{-2}.

There are explanations for this multiplicity of metrics. Some are relics of history: fibers have mattered to humans for much longer than metals or man-made materials. Ways of describing their properties have evolved independently in differing industrial cultures. More significantly – you can't accurately describe density or modulus or strength if you don't know the fiber shape or cross-section. We'll return to this, but first some terminology.

- A *monofilament* is a single, continuous fiber (silk, most synthetic fibers).
- A *staple fiber* is a fiber formed as, or cut to, discrete lengths that must be spun to form a yarn; different staples can be mixed (wool and polyester, for example)
- A *yarn* is a continuous length of interlocking and twisted (spun) fiber staples suitable for making ropes or textiles.
- A tow is an untwisted bundle of continuous parallel monofilaments (carbon fibers, for example)
- The number of filaments in a yarn or tow is $\frac{1000 \times tex}{A \times \rho}$ where A is the cross sectional area of single fiber in mm^2; $A = \frac{\pi d^2}{4}$ where d is the fiber diameter in mm (assumed circular) and ρ is the density of the material of the fiber in kg/m^3.

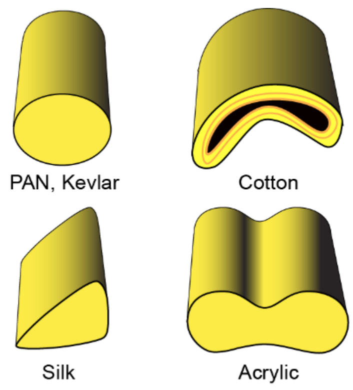


Figure 4. The section-shape of fibers

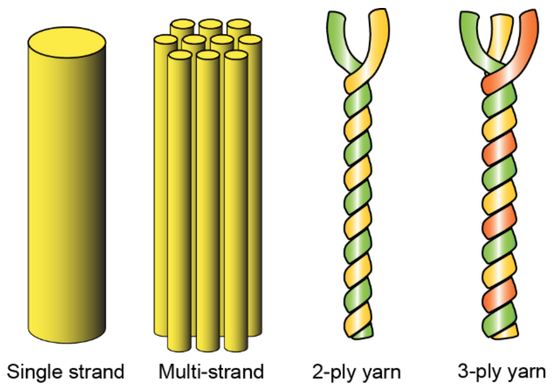


Figure 5. Fibers, tows and yarns

[3] http://nptel.ac.in/courses/116102029/39
http://textilelearner.blogspot.co.uk/2011/07/tensile-properties-of-textile-material.html

Thus single-strand fibers with circular cross-section with a constant diameter – an E-glass fiber or HS carbon fiber, for example – are not a problem. The cross-section, weight, and failure load can be measured and the density ρ (kg/m^3) and tensile strength σ_t (MPa) calculated in the usual way. But many fibers have irregular cross-sections (Figure 4) and the cross-section area of a yarn or fabric is difficult to measure because it is irregular and the packing is imprecisely known (Figure 5). The conventional definitions of density (mass per unit volume) and stress and tensile strength (force per unit area) don't work, so alternatives, linear density and tenacity, have evolved to take their place. You will find definitions of the metrics of stiffness and strength of fibers in Appendix 2, with Unit Conversion Tables for these and other textile units.

With that background we can move on to explore the mechanical properties of fibers.

Mechanical properties

Most fibers have a tenacity of between 2 and 10 cN/dtex or (closely related) gf/denier (Figure 6). A few, all developed since 1960, have tenacities that are much larger than this. These so-called "super-fibers" have a specific strength that far exceeds that of the strongest steels. Their use is at present restricted by their price.

Fiber elongation is, too, as important. The energy required to strain a fiber to its breaking point is $U \approx \frac{1}{2}\frac{\sigma_t \varepsilon}{\rho}$ or, equivalently, to the product (Tenacity x Elongation /2), sometimes called the "work capacity". It is a quantity of importance in spinning and weaving when fibers are exposed to tension. It is shown in Figure 7. The striking feature of the figure is the enormous work capacity of both viscid and drag-line spider silk, despite that fact that neither are particularly strong (Figure 6).

Two further charts give insight into the relative properties of fibers (Figures 8 and 9). The first shows the modulus E and tensile strength σ_t, the second, the specific modulus E/ρ and specific strength σ_t/ρ. The super-fibers lie at the upper right, out-performing all natural fibers both in stiffness and in strength. The much-cheaper fibers (green envelope) and the less strong synthetic fibers (purple envelope) are comparable in their mechanical response.

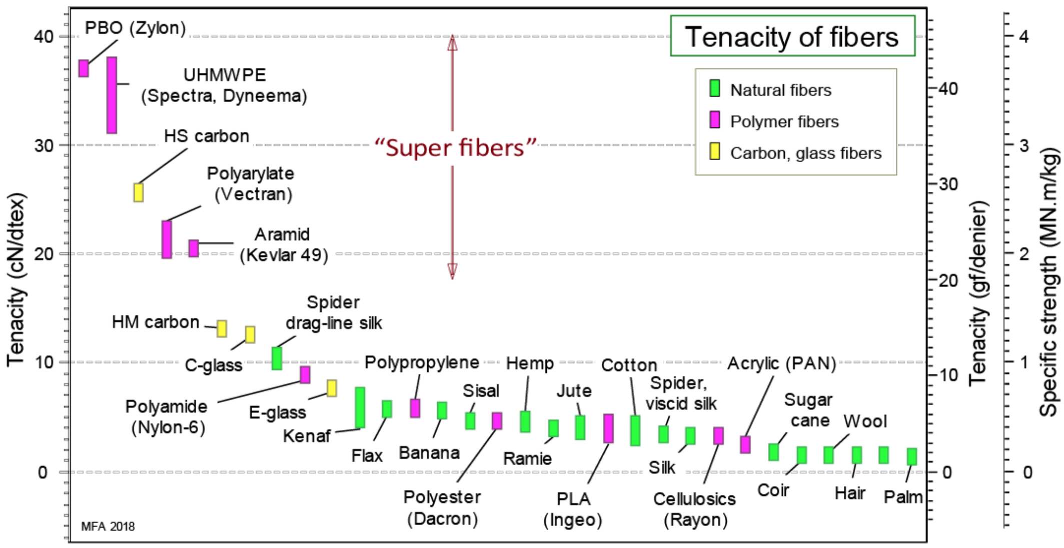


Figure 6. The tenacity or specific strength of fibers

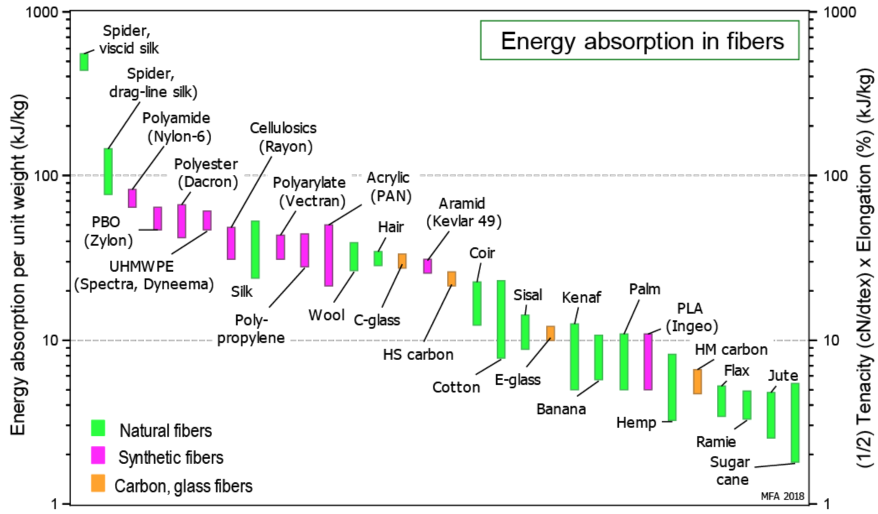


Figure 7. Energy absorption in fibers

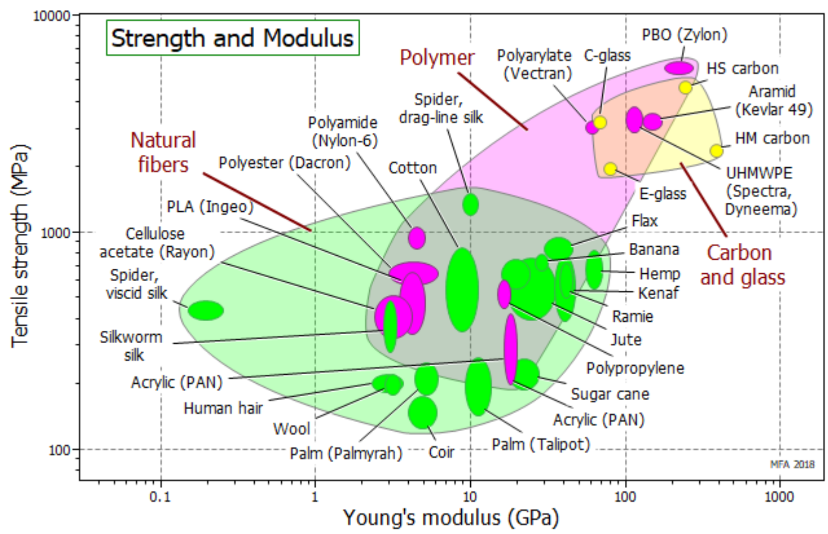


Figure 8. Strength and modulus of fibers

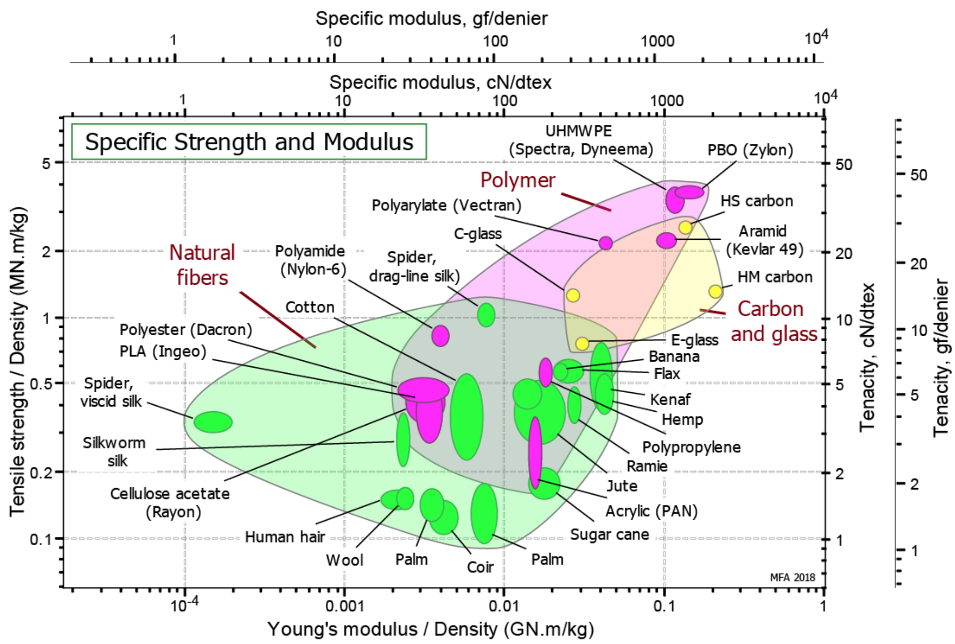


Figure 9. Specific strength and specific modulus of fibers

Economic properties

Some fibers are very cheap, costing less than $1/kg, and are produced in very large quantities. Others – particularly the newer super-fibers, are much more expensive, costing up to 100 $/kg and their production is at present small (Figure 10). The product of price and annual world production gives an approximate measure of the global market size; it is shown as diagonal contours on the figure. That for the three most-used natural fibers – cotton, jute and wool – is large, as is that for the four most-used synthetics – polyester, polypropylene, nylon and cellulosic. By contrast, the global market size for the super-fibers remains small.

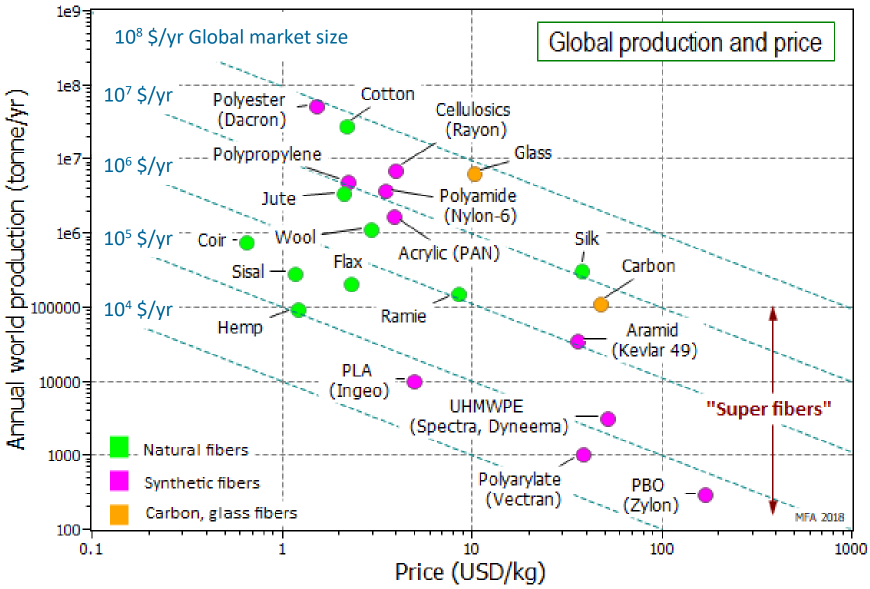


Figure 10. Approximate price and global production of fibers, with contours of global market value

Environmental properties

One might expect that the carbon footprint of natural fibers would be lower than that of the oil-based synthetics. Figure 11 shows that this is indeed the case, and that the carbon emissions associated with the super-fibers is particularly high. What is not shown is the associated water consumption, the data for which is imprecise; all indications are that natural fibers and semi-synthetics (PLA, Cellulosics) demand more water than the pure synthetics.

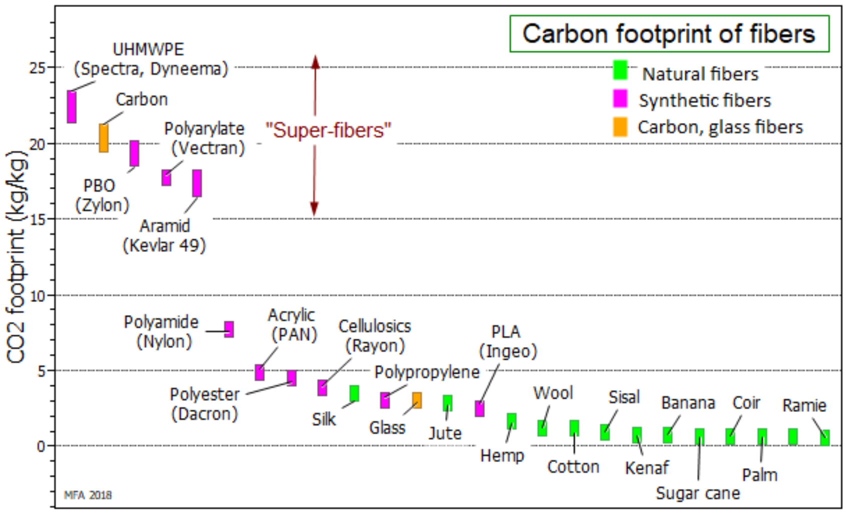


Figure 11. Approximate Carbon footprint of fibers in kg/kg

Aesthetics of fibers and fabrics

Most fabrics are made to be seen and touched: think of clothing, drapes, furniture covers, carpets. The appearance and feel of a fabric depend in part on the fiber or yarn from which it is made and in part on the way this is configured to make the fabric: a weave looks and feels different from a knit and both differ from a felt (a non-woven fabric). How are look and feel characterized and how do fiber properties influence them? [4].

Visual properties: color, luster, sheen

The appearance of a fabric include color, color consistency, luster and opacity (Figure 12). These are qualities that relate directly the fiber of which the fabric is made, but not this alone: the nature of the weave or knit influences the way that it reflects or absorbs light.

(a) (b) (c)

Figure 12. (a) Coarse cotton – low luster, coarse drape and hand. (b) Polyester –higher luster, intense color, finer drape and softer hand. (c) Silk – high luster, elegant drape and very soft hand.

Drape

"Drape" describes the way a fabric hangs under its own weight. The desired draping qualities depend on the planned use. Knitted fabrics are relatively floppy so garments made from them tend to follow body contours. Woven fabrics are stiffer, so they are used in tailored clothing where the fabric hangs away from the body and disguises its contours. Drapes (curtains) with attractive drape fall into graceful curves when closed and elegant folds when drawn back. It depends in part on the weight and shear properties of the fabric, and thus its weave, and partly the bending stiffness of the fibers it is made of.

Drape is measured in the way sketched[5] in Figure 13. A rectangular strip of material of standard size is clamped at one end and allowed to droop. The included angle of droop measures the drape for that angle of weave. Cutting strips at differing angles to the weave map out the drape profile.

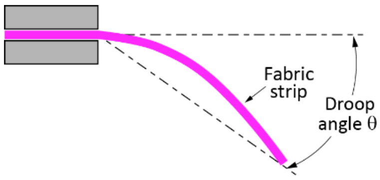


Figure 13. Measuring drape

Hand

Hand is a broad term for the kinesthetic or movement qualities of a fabric and the way it feels when touched: its softness, crispness, dryness and silkiness. A fabric with a soft hand is smooth to the touch. A hard hand describes a fabric with rough, coarse, harsh or stern feel. Hand encompasses flexibility and stretchiness, texture, area-density and thermal characteristics.

[4] http://www.textilevaluechain.com/index.php/article/technical/item/166-functional-and-aesthetic-aspects-in-apparel

[5] http://textilelearner.blogspot.com/2012/02/fabric-stiffness-testing-determination.html

4. Case Studies

Case study 1. How does the performance of fibers compare with their price?

In many applications fibers are valued for their tenacity, meaning strength per unit weight (specific strength): protective clothing, ropes, sails and awnings are examples. Specific strength is plotted against price in Figure 14.

Among natural fibers (green envelopes), flax, hemp, jute and cotton have high specific strength and low price. Many of synthetic fibers (fuchsia envelopes) compete directly with them; polyester (Dacron) has now replaced cotton as the fiber produced in the greatest quantities.

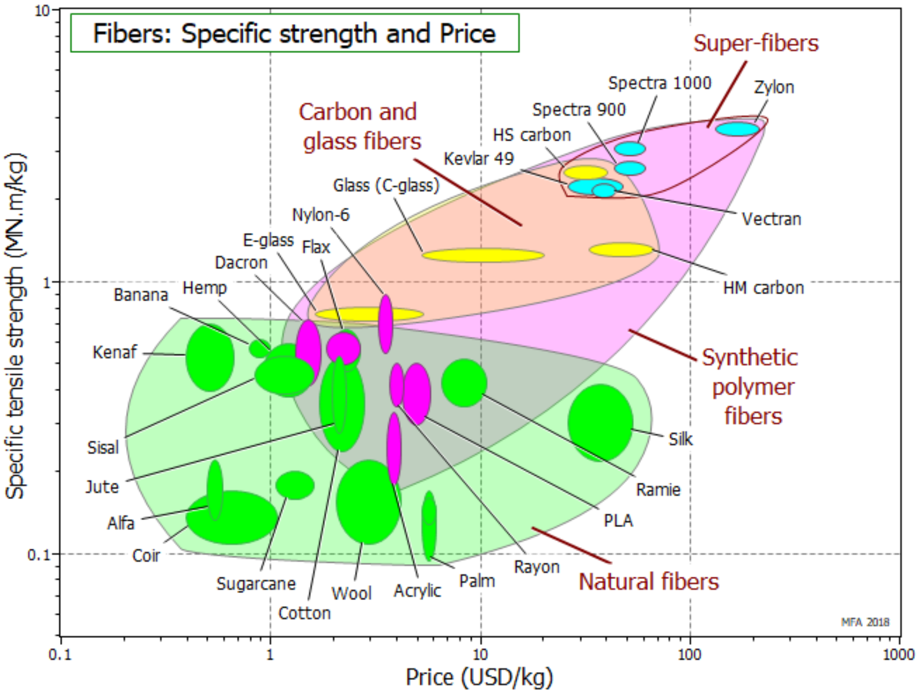


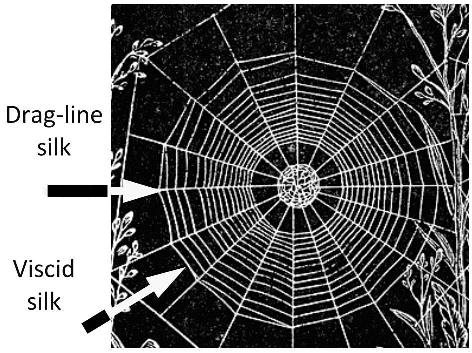
Figure 14. Specific strength and price of fibers

The specific strength of glass and carbon fibers (yellow bubbles) exceeds that of natural fibers and the commodity synthetics; HS (high-strength) carbon out-performs them all. The highest specific strengths are those of the “super-fibers” Kevlar, Vectran, Spectra, Dyneema and Zylon, but at a high price. With fibers you get what you pay for.

Case study 2. Is spider silk really stronger than steel?

Spider silk is a natural fiber. Spiders webs use strong, relatively stiff silk for the radial "drag-line" strands and a more compliant, resilient "viscid" silk for the circumferential strands. It is sometimes claimed that spider drag-line silk is stronger than steel. Is it?

The strength and modulus of fibers are plotted in Figure 15. The set includes "Patented" steel wire (piano wire), heavily drawn high-carbon steel; it is about as strong as steel can get. Spider drag-line is the strongest of the natural fibers but the steel wire is twice as strong and twenty times stiffer.



The drag-line and viscid threads of a spider

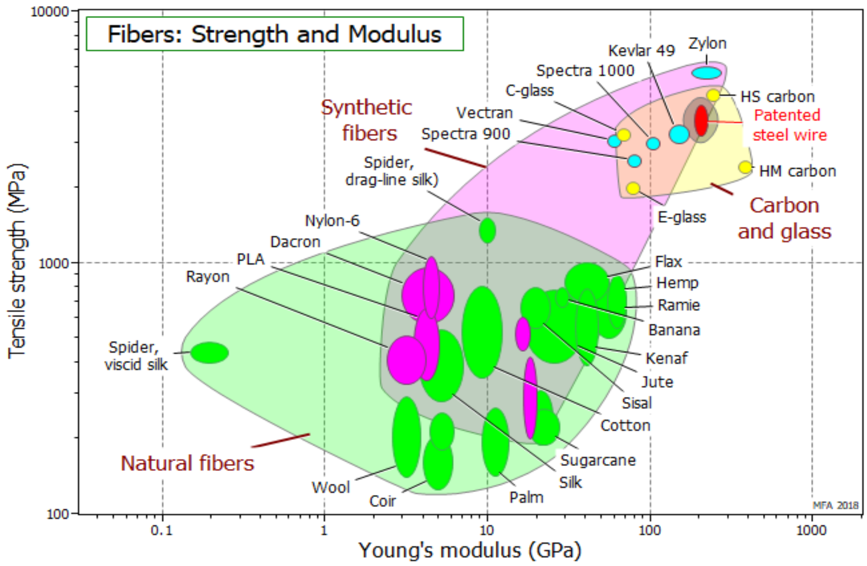


Figure 15. Tensile strength and modulus of fibers

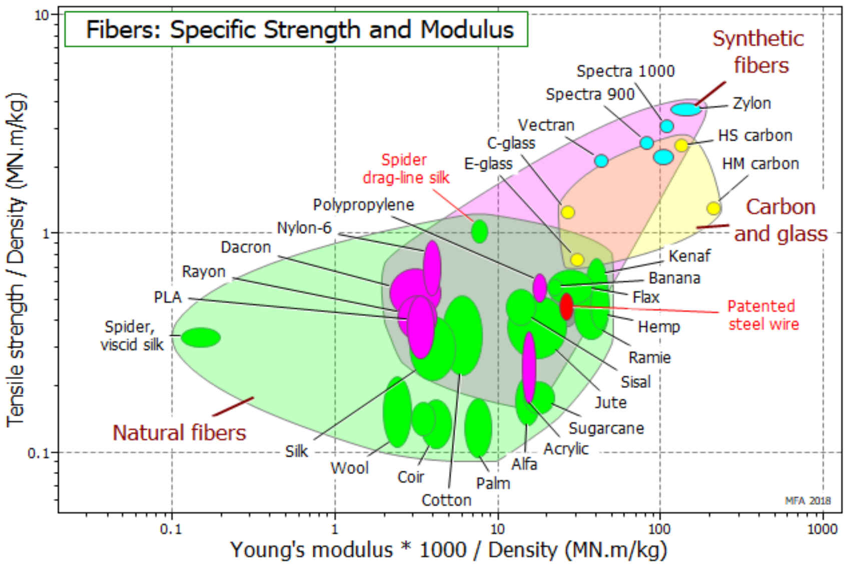


Figure 16. Specific tensile strength and specific modulus of fibers

Perhaps the more accurate statement is that spider silk is stronger than steel *per unit weight?* Figure 16 is a chart of specific strength, σ_{ts} / ρ, and specific modulus, E / ρ. Now the picture has changed. Drag-line silk, and even flax fibers, are stronger per unit weight than the strongest steel.

Case study 3. How have parachute materials have evolved over time?

A parachute

Parachutes are made of strong, stiff, light fibers. Long ago parachutes were made of cotton, then silk-worm silk, then nylon and Terylene, now Kevlar* or even Zylon, a polyoxazole[6]. How is this evolution explained?

Strong and light means high specific strength; stiff and light means high specific modulus. Figure 17 show these two properties for 32 natural and synthetic fibers. For clarity, only the mean values are plotted, not the ranges. The parachute materials are high-lighted in red; the black arrows follow the progression over time. The path reveals the way in which parachute makers have sought materials with ever higher specific strength, which increases from the first (cotton) to the last (Zylon) by a factor of 10. Specific modulus seems to be less of a driver, though here too there has been an increase by a similar factor.

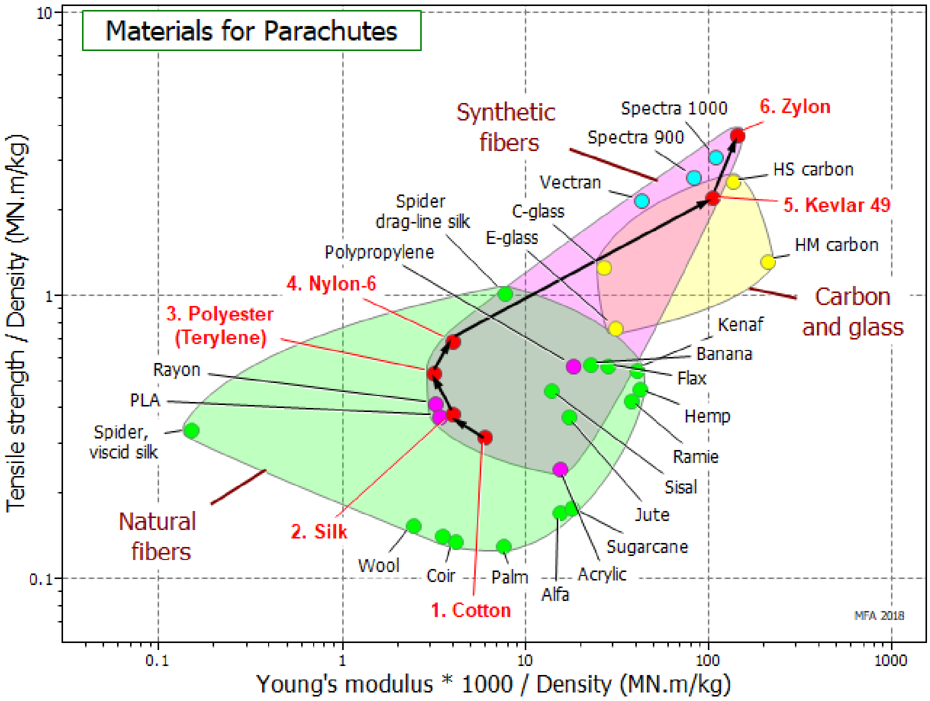


Figure 17. Specific tensile strength and Specific Young's modulus with parachute materials highlighted in red. The arrows show the progression over time.

6 https://www.azom.com/article.aspx?ArticleID=10429

Case study 4. Fibers for seat belts

A seat belt constrains the occupant of vehicle when it is involved in an accident. The belt itself is a woven webbing about 48 mm wide. The stated pre-requisites for the fiber of which it is woven are

Seat belt webbing

- high tenacity,
- good abrasion resistance and
- UV resistance
- at minimum price.

What is the best fiber for making seat belts?

Tenacity (strength per kg) and Price ($ per kg) are plotted in Figure 18. Constraints on durability in fresh and salt water, UV resistance and abrasion resistant have been applied using a Limit stage. The ratio (Tenacity / Price) has the dimensions of energy per $ (MJ/$), a measure of the cost-effectiveness of the fiber in this application; it appears as a set of diagonal contours. On the low-price side of the diagram (Price < $10 per kg) the fiber with the highest tenacity is Nylon 6, but it is not the most cost-effective. The winner here is polyester (Dacron, Terylene).

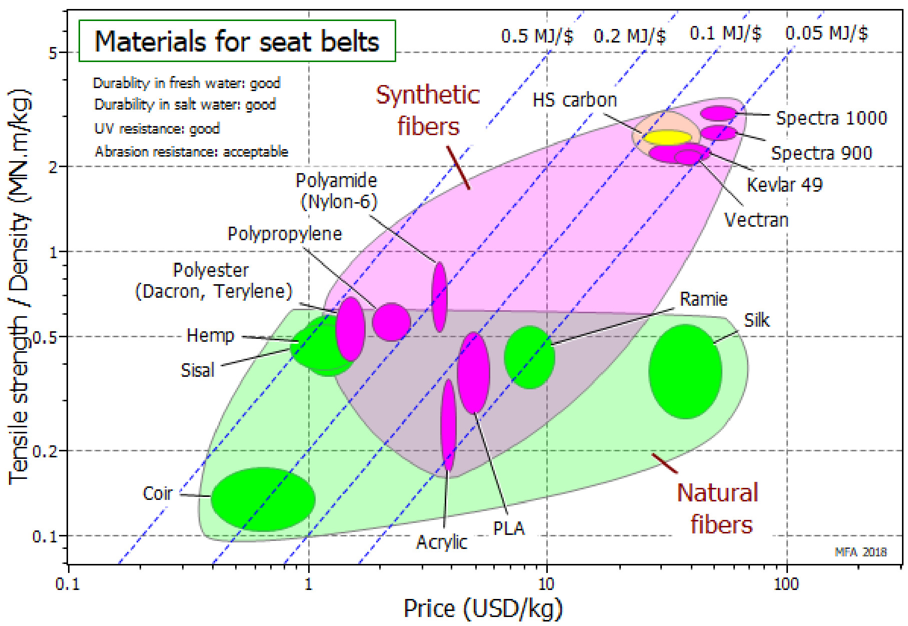


Figure 18. The tenacity and price of fibers subject to the constraints listed at the upper left of the figure.

What's the reality? Research[7] in the 1970s measured the static and dynamic response of nylon and polyester seat belts, correlating it with the geometry of the belt and the deceleration rate of the car. The results established polyester as the better choice. Today, polyester commands the greater share of the seat belt market whilst nylon holds a niche position. In 1995, about 35 million pounds of high-tenacity polyester was used in the US to make seat belts. By comparison, the consumption of high-tenacity nylon for seat belts was negligible.

[7] http://www.indiantextilejournal.com/articles/FAdetails.asp?id=4986

Case study 5. Fibers for climbing ropes

Polyester climbing

Ropes, in the past, were made from hemp, sisal, cotton, flax, or jute. Today, these natural fibers have largely been replaced by synthetics. The choice of fiber depends on the intended use of the rope. Tent-ties, awning tethers and bridge suspensions need ropes or cables that are able to carry load over long periods of time without re-tightening; for these, fibers with high stiffness, high strength and minimal creep fill the bill. Climbing ropes have a different purpose: to provide last-resort protection in the event of a fall. They only rarely carry much load, and when they do, elastic stretching is an advantage because it arrests the falling climber in a less abrupt way, rather as a bungee-jump tethers do. Climbers carry the rope with them, and the lead climber carries the weight of the rope below, so light weight is a priority; for these, fibers with great energy-absorbing qualities and the ability to stretch without breaking are what is wanted.

Consider selection of fibers for the climbing rope. The energy absorbed per kg of rope-weight with a rope is stretched is

$$\text{Energy (MJ/kg)} = \frac{1}{2}\,\frac{(Tenacity)^2}{Specific\ modulus}$$

It is shown as the Y-axis of Figure 19. Stretch is measured by the strain the rope can sustain when loaded – the bigger the stretch the better. It is measured by

$$\text{Stretch (\%)} = \frac{Tenacity}{Specific\ modulus}\ x\ 100$$

It appears as the X-axis of the figures. Fibers that make good climbing ropes lie towards the upper right. Spider silk excels but is impractical until a way can be found to synthesize it. The best choices are Nylon and Polyester. Surprisingly, the super-fibers Kevlar, Zylon, Spectra and Vectran rank less well; their high modulus allows them less stretch and limits their energy absorbing ability.

There is, of course, more to designing climbing ropes than this. There is abrasion resistance, resistance to embrittlement by UV radiation and to degradation by water, human sweat and other contaminants. And there is the weave or braid of the rope itself, which also plays a part in determining energy absorption and stretch. But our simple criteria have worked well: Nylon and polyester are indeed the fibers of choice for climbing ropes.

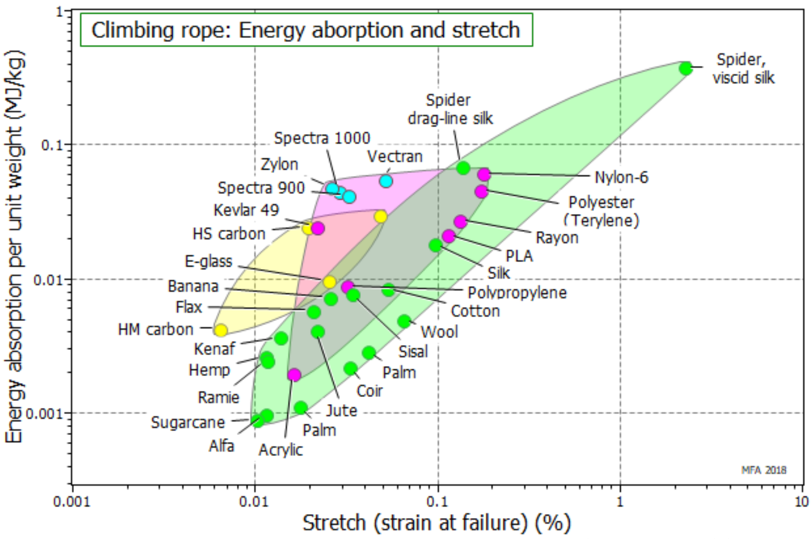


Figure 19. Energy absorption per unit weight and safe-stretch of fibers

Case study 6. Power from the wind: materials for sails

For centuries sails were made from linen. Linen was replaced by cotton during the 19th century because it was more durable. Both were replaced by synthetics the late 20th century.

Sails

The design requirements for sails are

- High specific modulus to limit elastic distortion, particularly when sailing up-wind.
- High tenacity.
- Durability: resistance to fresh and salt water.
- Creep resistance: a fabric may have a high modulus but can lose its shape over time by creep.
- Flex Loss: loss of strength lost from bending, folding, or flogging.
- Low moisture regain for quick drying and low weight.
- Cost: a set of racing sails can cost more than the boat, but most customers want something more affordable.

The database contains data for moisture regain and for durability in various environments, list on a 3-point scale (Good, Acceptable, Poor). Figure 20 shows the fibers that have moisture regain below 5% and rank as Good in fresh and salt water, and for UV resistance. Flax, the fiber of linen, is shown for reference, although it does not meet these cirteria. The figure suggests Dacron as the best inexpensive choice, but its modulus is low allowing stretch under pressure that may distort the shape of the sail. Vectran, Spectra and Carbon offer the best all-round combination of properties. Nylon does not appear because its moisture regain is too high; Kevlar and Zylon drop out because they fail the UV requirement.

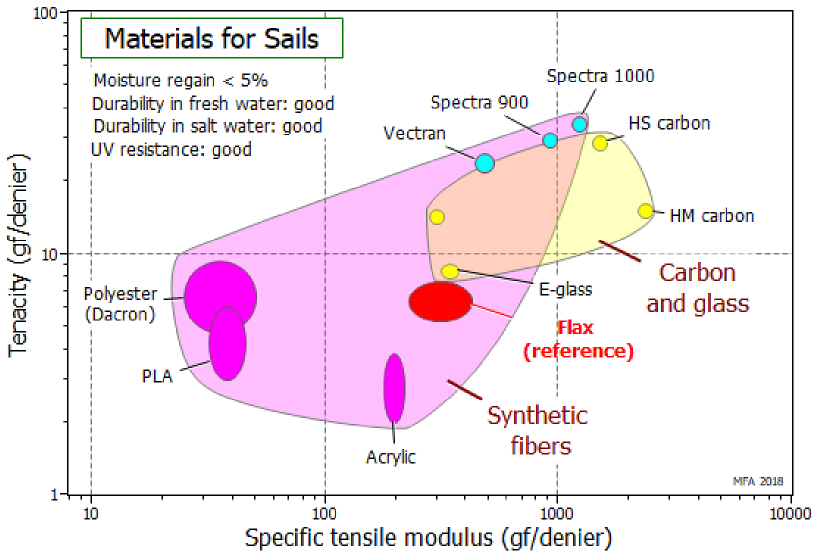


Figure 20. Tenacity and specific modulus with added constraints

What's the reality here?The choice of fiber for sails depends on sail and boat type and the type of sailing[8]. Dacron (polyester) is the standard sail fabric for cruising mainsails, genoas and jibs. It retains its shape over long periods of time and wind ranges and is mildew resistant. Nylon, which is inherently

[8] What Sails are Made of and Their Uses
https://www.getmyboat.co.uk/resources/tips-for-owners/291/what-sails-are-made-of-and-their-uses

stretchy and absorbs shock well, is typically used in spinnakers, but is not suitable for sails that must hold their shape. Laminated sail fabrics combine a Mylar film[9] with a reinforcing fiber, typically Dacron, Kevlar, or carbon. Laminated fabrics are lighter, stronger and have less stretch but are more expensive than simple Dacron so they are limited to competitive racing.

5. Concluding remarks

Of all the forms into which materials can grow or be made, that of fiber is perhaps the most intimate. Almost all clothing is woven from fiber. The paper on which this is printed is compacted fiber. The carpet on which my feet rest as I type this page is fiber. I wash with a face-cloth and dry my face with a towel – all fiber. Even the hair that keeps my head warm (though I haven't got much now) is fiber.

Fiber and textile science has evolved along a different historical path than that of the more familiar materials of engineering. The result: the metrics to describe even the simplest properties – density, modulus, or strength, for instance – so differ in the two fields that the one has trouble communicating with the other. The bi-lingual approach described here is an attempt to bridge the gap and delivering it at a level that would work in a 1st year Materials Engineering course.

It could, I'm sure, be much improved, better examples could be found, better illustrations made to illuminate the concepts. All critical comments and constructive suggestions towards these ends would be most welcome.

[9] Mylar is a polyester film made from polyethylene terephthalate (PET). Mylar is laminated into racing sailcloth, giving high tensile strength, dimensional stability, and transparency.

6. Data sources

"Engineering of High-performance textiles" Editors Menghe, Miao, John, Xin,Woodhead publishing (2017) (ISBN 979-008-101273-4)

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Water footprint of fibers https://waterfootprint.org/media/downloads/WFA_Polyester_and__Viscose_2017.pdf

Appendix 1. The fibers

Natural fibers	Synthetic polymer fibers	Carbon and glass fibers
Alfa	Acrylic (PAN)	Carbon (HS carbon)
Banana	Aramid (Kevlar 49)	Carbon (HM carbon)
Coir	Cellulose acetate (Rayon)	Glass (E-glass)
Cotton	HDPE (Spectra 1000)	Glass (C-glass)
Flax	HDPE (Spectra 900)	
Hemp	PBO (Zylon)	
Human hair	PLA (Ingeo)	
Jute	Polyamide (Nylon-6)	
Kenaf	Polyarylate (Vectran)	
Palm (Palmyrah)	Polyester (Dacron, Terylene)	
Palm (Talipot)	Polypropylene	
Ramie		
Silk (Silkworm silk)		
Silk (Spider drag-line silk)		
Silk (Spider viscid silk)		
Sisal		
Sugarcane		
Wool		

Appendix 2. Unit conversion matrices

Linear density

Linear density is mass per unit length. The choice of the "unit" of length is not universally agreed, so three measures are in use:

- *tex* — Mass in grams per 1,000 m (the Metric unit)
- *decitex* (*dtex*) — Mass in grams per 10,000 m (a unit of convenience)
- *denier* — Mass in grams per 9,000 m (the English unit)

To → / From ↓	denier (*den*)	tex (*tex*)	decitex (*dtex*)	Linear density kg/m
	Multiply by			
denier (*den*)	**1**	0.111	1.11	1.11×10^{-7}
tex (*tex*)	9	**1**	10	10^{-6}
decitex (*dtex*)	0.9	0.1	**1**	10^{-7}
Linear density kg/m	9×10^{6}	10^{6}	10^{7}	**1**

They are related to conventional density ρ (in kg/m^3), for a solid, single-strand filament with a cross section *A* mm^2, in the following way.

$$\rho = \frac{denier}{9A} = \frac{tex}{A} = \frac{dtex}{10A}$$

If the filaments have a circular cross-section with diameter *d*, the cross-section area is $A = \pi d^2 / 4$. Some filaments have a non-circular cross-section (oval, dog-bone, rectangular) and for these the area is well defined but the "diameter" is not.

Specific tensile modulus

The specific tensile modulus is the modulus divided by the density. The SI unit for this is MPa/(kg/m^3).
Three other measures are in common use:

gf/denier (gfd) (1gf = 0.981 cN)
cN/dtex
N/tex

The conversion between these units is shown in the table

To → / From ↓	gf/denier	cN/dtex	N/tex	MPa/(kg/m3)
	Multiply by			
gf/denier	**1**	0.883	8.83×10^{-2}	8.83×10^{-2}
cN/dtex	1.13	**1**	0.1	0.1
N/tex	11.3	10	**1**	**1**
MPa/(kg/m^3)	11.3	10	1	**1**

Tenacity (Specific Strength), Yuri and Breaking length

Tenacity is tensile strength per unit weight. It allows the strengths of fibers and yarns of different linear densities to be compared. There are a number of different measures

gf/denier (gfd)
cN/tex
cN/dtex (1gf = 0.981 cN)

The Breaking length L^* is the filber length in km that can just support its own weight.
L^* = 1000 x Tensile strength / (9.81 x Density) when tensile strength is MPa and density is kg/m^3 .

The Yuri (named after Yuri Nikolaevich Artsutanov, a Russian engineer) is specific strength in Pa/(kg/m^3).

The various measures of specific strength are related in the ways shown in the table.

To → *From ↓*	gf/denier	cN/tex	cN/dtex	Yuri Pa/(kg/m³)	MPa/(kg/m³)	Breaking length (km)
	Multiply by					
gf/denier	**1**	8.83	0.883	8.83×10^4	8.83×10^{-2}	9.09
cN/tex	0.113	**1**	0.1	1×10^4	0.01	1.02
cN/dtex	1.13	10	**1**	1×10^5	0.1	10.2
Yuri, Pa/(kg/m³)	1.13×10^{-5}	1×10^{-4}	1×10^{-5}	**1**	1×10^{-6}	1.02×10^{-4}
MPa/(kg/m³)	11.3	100	10	1×10^6	**1**	102
Breaking length (km)	0.11	0.98	0.098	9800	0.0098	**1**

Yarn tenacity

Yarns are made by spinning short fibers to give a continuous thread. The tenacity of the yarn is roughly half that of the individual fibers provided a sufficiently high number of fibers are available in the yarn cross-section (the Fiber count).

Appendix 3. Typical record

Cellulosics (Rayon)

The material

Malabrigo Rayon Vert Sock and rayon cowl

Cellulose acetate, diacetate and triacetate, collectively known as Cellulosics, are among the earliest synthetic fibers. They are based on cotton or tree-pulp cellulose. Diacetate “silk” was first produced in 1923 by an English company, Celanese. At the beginning of 1930, Celanese (U.S.), American Viscose, E.I. DuPont, and Eastman Kodak began to produce diacetate fiber in large quantities. Acetate and triacetate are very like rayon; the difference lies in the detailed chemistry of production. They differ slightly in properties, but not sufficiently to require a distinction here. Acetate fabric is used frequently in wedding gowns and other bridal attire. Its lustrous sheen and smooth, satiny texture make it a good synthetic alternative to silk. These cellulosic fibers have been replaced in many applications by cheaper petro-based fibers nylon and polyester, which are more durable and less flammable than Rayon.

The data shown here are for rayon monofilament

Composition (summary)

Cellulose acetate (CA) is made up of repeating glucose units, C6H7O2 (OH)3

General properties - SI System

Fiber diameter	0.085	-	0.092	mm
Fiber cross-section area	5.6e-4	-	6e-4	mm^2
Density	980	-	1e3	kg/m^3
Price	3.69	-	4.22	USD/kg
Annual world production, principal component	7e6			tonne/yr
Date first used	1923			

General properties - Textile System

Linear density (denier)	1.5	-	15	g/9km
Linear density (tex)	0.16	-	1.6	g/km

Mechanical properties - SI System

Young's modulus	2.4	-	4.1	GPa
Specific modulus (MPa.m/kg)	2.4	-	4.1	MN.m/kg
Shear modulus	* 0.6	-	0.62	GPa
Bulk modulus	* 2.5	-	2.8	GPa
Poisson's ratio	* 0.35	-	0.36	
Tensile strength	330	-	510	MPa
Specific tensile strength (MN.m/kg)	0.35	-	0.5	MN.m/kg
Elongation	17	-	20	% strain
Mechanical loss coefficient (tan delta)	0.027	-	0.032	

Mechanical properties - Textile System

Specific tensile modulus (gf/denier)	27	-	46	gf/denier
Specific tensile modulus (cN/dtex)	24	-	41	cN/dtex
Tenacity (gf/denier)	3	-	4.6	gf/denier
Tenacity (cN/dtex)	2.6	-	4	cN/dtex

Thermal properties

Melting point	258	-	262	°C
Maximum service temperature	53	-	67	°C
Minimum service temperature	-60	-	-50	°C

Thermal conductor or insulator?		Good insulator			
Thermal conductivity	*	0.13	-	0.16	W/m.°C
Specific heat capacity		1.39e3	-	1.44e3	J/kg.°C
Thermal expansion coefficient	*	119	-	121	µstrain/°C
Limiting oxygen index (LOI)		18.4	-	18.6	%

Durability (Poor, Acceptable, Good)

Moisture regain	6	- 6.5	%
Water (fresh)	Acceptable		
Water (salt)	Acceptable		
Weak acids	Poor		
Weak alkalis	Poor		
Organic solvents	Poor		
UV (sunlight) resistance	Acceptable		
Abrasion resistance	Poor		

Optical properties

Transparency	Optical Quality		
Refractive index	1.46	-	1.49

Primary material production: energy, CO2 and water

Embodied energy, primary production	*	85.4	-	94	MJ/kg
CO2 footprint, primary production	*	3.6	-	4	kg/kg
Water usage	*	228	-	252	l/kg

Material recycling: energy, CO2 and recycle fraction

Recycle	False

Supporting information

Design guidelines

Rayon is very drapable, with a silk-like hand. Rayon and other acetates are flammable. Acetate clothing requires hand washing – the fibers disintegrate in a tumble dryer.

Aesthetic properties

Cellulosic fibers are white in color with high luster. Cellulosic fabrics have a fine hand, and elegant drape and are cool to wear.

Typical uses

Viscose rayon fiber is used in dresses, linings, shirts, shorts, lingerie, coats, jackets, and other outerwear. It is also used in industrial yarns (tyre cord), upholstery and carpets and filters.

Tradenames

Acetate, CA, Triacetate, Rayon, Vicose, Modal, Lyocell, Acele, Avisco, Celanese, Chromspun, Estron, Tencel, Brocade, Satin, Taffeta.

Data sources

http://www.swicofil.com/products/200viscose.html
https://en.wikipedia.org/wiki/Rayon
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