# Yarn Diameter and Linear Mass Correlation

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**Abstract** This paper focuses on the determination of the
statistical correlation between yarn diameter and yarn linear
mass. The experimental methods employed are based on op-
tical analysis and on image processing techniques applied to
electron microscope images. Several different cotton yarns
were examined over a wide range of yarn linear masses. The
results indicate that diameters predicted by the relationship
commonly quoted in the literature can be as much as 62%
smaller than those experimentally observed.

**Keywords** Yarn diameter · Cotton yarn · Experimental ·
Linear mass

## 1 Introduction

A key parameter in the textile industry is the relation be-
tween a yarn's diameter and its linear mass. For example,
capacitive measurements are often used to characterize a
given yarn's linear mass and from this the average diame-
ter is deduced. If one assumes that the yarn has, on average,

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a cylindrical shape it is clear from simple geometrical con-
siderations that the yarn diameter should be proportional to
the square root of its linear mass. Following the industry
standard of expressing linear mass in g/km, call *tex*, one can
immediately arrive at the following expression [1, 2]

$$tex(\text{g/km}) = \phi \times \rho\,(\text{g/cm}^3) \times \pi \left( \frac{d\,(\text{cm})}{2} \right)^2 \times \left( \frac{10^5\,\text{cm}}{\text{km}} \right)$$

$$\Rightarrow \quad d\,(\text{cm}) = \sqrt{4 \times tex/(\pi \times 10^5 \times \phi \times \rho)}. \qquad (1)$$

Here $\phi$ represents the yarn "porosity", which is the fraction
of the yarn actually occupied by fibers, the rest being air. It
is curious that most literature values result from theoretical
considerations, assuming that the individual fibers are them-
selves cylindrical and closely packed within the yarn. To our
knowledge there does not seem to be any experimental con-
firmation of these assumptions. Theoretical literature values
for the porosity typically range from 0.55 to 0.70 [2–5]. If
we take as a characteristic value for the porosity the median
value of 0.63 then for 100% cotton yarns ($\rho = 1.5$ g/cm$^3$),
the expected relation between diameter and linear mass den-
sity is

$$d(mm) = 0.037\sqrt{tex}. \qquad (2)$$

Here we have included a simple units conversion and ex-
pressed the diameter in millimeters instead of centimeters
as in Eq. 1. This is the relation commonly encountered in
the literature. While the square-root dependence on linear
mass is simply a consequence of the assumed cylindrical
geometry, the appropriate value of porosity is not at all obvi-
ous. In an effort to experimentally determine this parameter,
we have analyzed several different cotton yarns with linear

masses ranging from 4.2 to 295 *tex* and fit the results to an equation of the general form,

$$d(mm) = K\sqrt{tex}. \qquad (3)$$

Our results show that the typical literature values, $K = 0.037$, are 62% lower than our experimental findings. This suggests that the actually porosity parameter, $\phi$, is roughly a third of what is typically assumed. While this seems intuitively to be extremely low, we have acquired electron microscope images which suggest that the actual volume occupied by cotton fibers is in fact quite low. In the following section we briefly describe the experimental analysis [6, 7] used to deduce the relation between yarn linear mass and diameter. Our experimental technique is in principle capable of determining diameters with a precision of a few microns.

## 2 Experimental Procedure

The main goal of the study was to experimentally obtain the correlation between yarn mass and yarn diameter validating Eq. 3 and in the process to experimentally determine the mean porosity factor of Eq. 1. The optical experimental set-up used in this study is shown in Fig. 2.

The main purpose of the optical setup is to produce an image that can be analyzed to provide information regarding the local degree of yarn hairiness (i.e. the amount of fibers which protrude significantly from the yarn core, as seen in Fig. 1) [8] and yarn core diameter in the final image plane (position of the photo detector in Fig. 2) (I/PD). Coherent light from the laser diode in a single transverse mode is incident on a collimating lens (L1) and directed to the yarn, placed in the object holder (O). The size of the final image detected by the photodiode array (I/PD) is controlled by the lenses L2 and L3.

A custom spatial filter with roughly 1 mm of opaque target (F) placed in the Fourier plane of L2, blocks all spatial frequencies below 10 mm$^{-1}$ (high pass spatial Fourier filter), corresponding to a characteristic size of 100 microns or larger in the object plane. Textile yarns typically have diameters ranging from a few microns up to millimeters, while the small hairs protruding from the yarn are single fibers with diameters typically less than 10 microns [9]. As there is a clear separation in the characteristic length scales of the yarns, this results in the contours of the edges of the yarn and associated hairs being highlighted while simultaneously eliminating the constant background illumination of the incident laser beam (Fig. 3).

Figure 4 shows the line profile result of a linear section of this image along the line profile highlighted in Fig. 3. Our actual data was acquired using a linear photodiode array (S8378-256Q from Hamamatsu, with a pitch of 25 μm) in the image plane. These devices are consist of multiple photo-sensitive areas (pixels), organized over a single line,
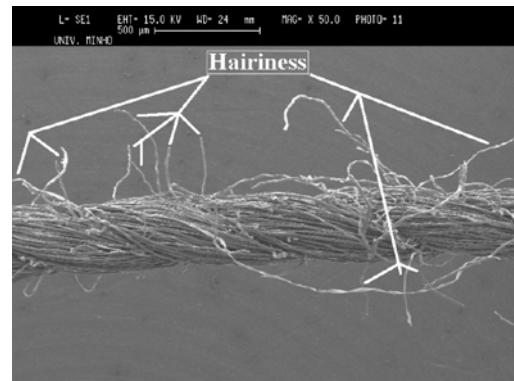


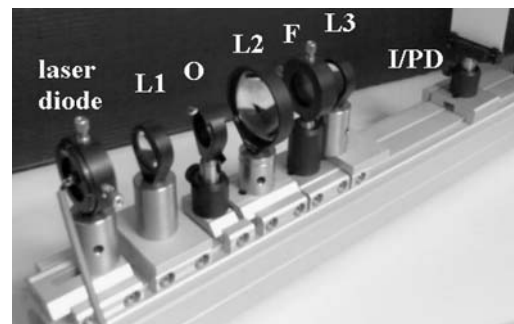**Fig. 1** Identification of yarn hairiness in an electron microscope photograph



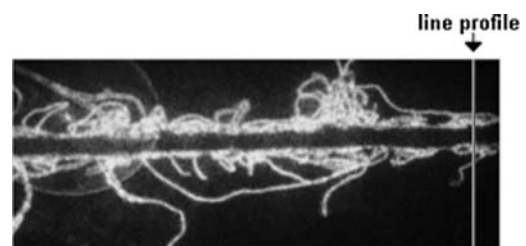**Fig. 2** Custom developed optical yarn measurement hardware



**Fig. 3** Example of an image resulting from coherent optical signal processing

which convert a spatial light distribution to a proportional current or voltage signal distributed sequentially in time. The yarn diameter in the image plane corresponds to the difference of pixels between the peak positions of the right and left yarn contours, multiplied by the pitch of each pixel. This can then be easily converted to obtain the actual yarn diameter in the object plane using the measured optical system magnification.

In addition, to increase the amount of available data, image processing techniques were applied to previously acquired electron microscope images. These images were digitized and the number of pixels between yarn contours on opposite sides of the yarn was determined. Using a similar technique for the magnification calibration bar of each image, the actual yarn diameter could easily be found with a

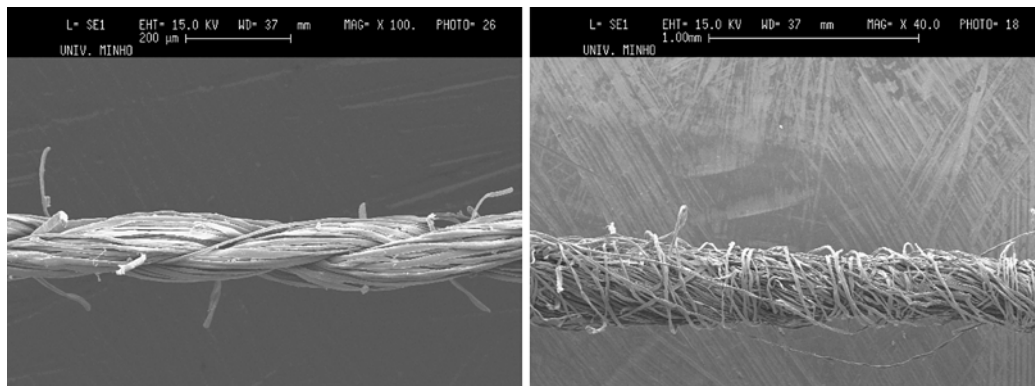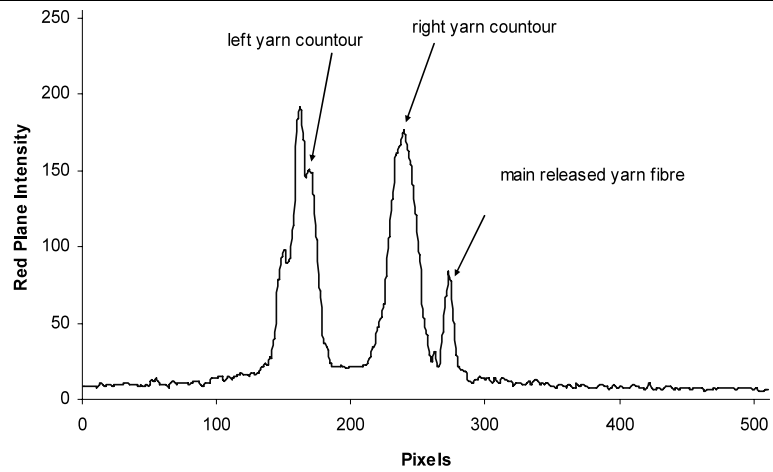**Fig. 4** Red plane line profile obtained for Fig. 2 with 512 pixels



**Fig. 5** Pictures obtained with the electron microscope for yarns 4.20 *tex* (*left photograph*) (folded or multi-cable yarn [10], two cables, anti-clockwise yarn orientation) and 48.44 *tex* (*right photograph*) (un-folded, spun or single cable yarn [11], one cable, clockwise fiber orientation) from which were considered individually ten different sections for average diameter characterization

precision of order of a few microns or better, depending on the magnification of the electron microscope image.

Several different analyses were performed:

- Four different 100% cotton yarns (19.67 *tex*, 36.88 *tex*, 62.00 *tex* and 295.00 *tex*), with an optical diameter characterization, using ten different sample positions for each yarn;
- Four different 100% cotton yarns (4.20 *tex*, 48.44 *tex*, 75.10 *tex* and 212.20 *tex*), with a diameter characterization based on image processing under electron microscope images, using also ten different locations for each yarn.

The pictures obtained using the electron microscope for the 4.20 *tex* and 48.44 *tex* yarns are shown in Fig. 5, while those for the 75.10 *tex* and 212.20 *tex* yarns are displayed in Fig. 6.

## 3 Results

The results of the various diameter measurements are summarized in Table 1. For each yarn analyzed ten individ-ual diameter measurements were carried out. Based on a nonparametric test the two procedures used in the diameter measurement (IMP, Image Procedure Measurement, and OM, Optical Measurement) are not statistically significant ($p > 0.05$) [12]. As a first step we thought it was important to fit simultaneously both the proportionality constant K and the power, a, of the linear mass (*tex*) in Eq. 4.

$$d(mm) = K.tex^a. \tag{4}$$

Figure 7 shows the results obtained employing a power dependence, where the best fit parameters determined to Eq. 4, where $K = 0.062 \pm 0.002$ and $a = 0.490 \pm 0.009$, with $R^2 = 0.973$.

Furthermore, we also tested the linearization of the power correlation model, where new adjustment parameters were calculated [12]. However, as the two models did not show significant differences and considering the parallelism to the theoretical literature model used as a reference for this study, the power correlation model was applied.

The results shown graphically in Fig. 7 confirm that the power law dependence is the expected result of 1/2 for
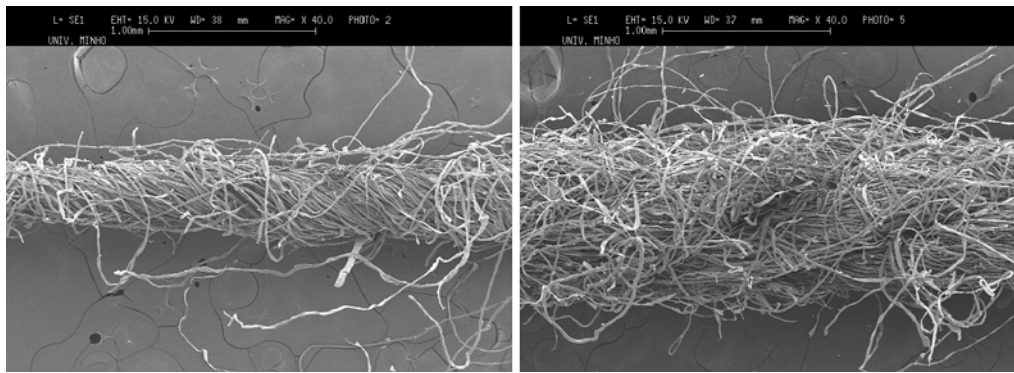
**Fig. 6** Pictures obtained with the electron microscope for yarns 75.10 *tex* (*left photograph*) (unfolded yarn [11], one cable, clockwise fiber orientation), and 212.20 *tex* (*right photograph*) (folded yarn [10], four cables, anti-clockwise yarn orientation). Ten different diameters were determined from separate positions along the fibers in these images

**Table 1** Experimental diameter and constant *K* results

| Yarn (tex) | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 | Average (mm) | SD (mm) | K (experimental) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **4.20** | 0.11 | 0.12 | 0.13 | 0.13 | 0.14 | 0.14 | 0.13 | 0.14 | 0.15 | 0.14 | **0.13** | ±0.01 | 0.065 |
| **19.67** | 0.25 | 0.25 | 0.21 | 0.32 | 0.32 | 0.25 | 0.25 | 0.32 | 0.28 | 0.29 | **0.27** | ±0.04 | 0.062 |
| **36.88** | 0.32 | 0.39 | 0.36 | 0.36 | 0.32 | 0.29 | 0.36 | 0.32 | 0.36 | 0.39 | **0.35** | ±0.03 | 0.057 |
| **48.44** | 0.45 | 0.43 | 0.41 | 0.36 | 0.37 | 0.32 | 0.32 | 0.36 | 0.4 | 0.38 | **0.38** | ±0.04 | 0.055 |
| **62.00** | 0.46 | 0.54 | 0.43 | 0.43 | 0.43 | 0.46 | 0.46 | 0.43 | 0.5 | 0.43 | **0.46** | ±0.04 | 0.058 |
| **75.10** | 0.51 | 0.51 | 0.46 | 0.50 | 0.49 | 0.48 | 0.47 | 0.48 | 0.50 | 0.49 | **0.49** | ±0.02 | 0.056 |
| **212.20** | 0.89 | 0.90 | 0.90 | 0.85 | 0.86 | 0.88 | 0.89 | 0.89 | 0.96 | 0.89 | **0.89** | ±0.03 | 0.061 |
| **295.00** | 1.04 | 1.25 | 1 | 1.07 | 0.96 | 1 | 1.07 | 1 | 1.14 | 1.21 | **1.07** | ±0.10 | 0.063 |

▨ Image processing measurements

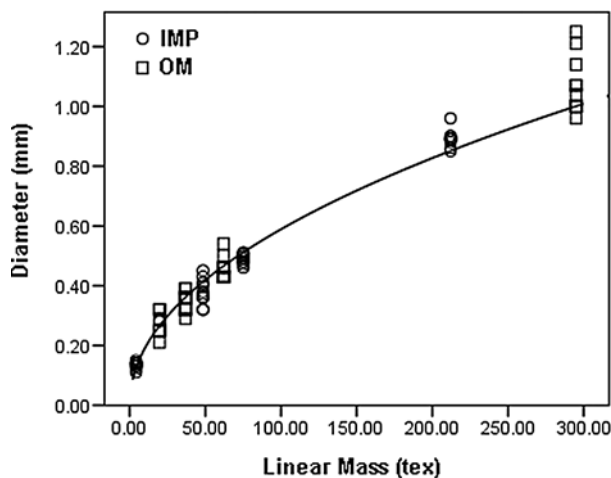▯ Optical measurements (photodiode array)

*K* average = 0.060



**Fig. 7** Fit to the experimental data of Table 1, where the solid line represents the best fit obtained to Eq. 4

cylindrical yarns. Given the strong physical basis for the square root dependence on linear mass (*tex*) we have subse-quently, assumed this as given and focused attention on ob-taining the best experimental fit to the proportionality con-stant *K*.

### 3.1 Experimental Determination of the Constant *K* Value

As a first step the average diameter values for each yarn in Eq. 3 were used to determine an "experimental *K* value" for each of the yarns analyzed. These values are reported in the final column of Table 1. The average of the 8 experimental *K* values is 0.060.

Figure 8 presents the best fit to the experimental data as-suming the functional form of Eq. 3. The resulting propor-tionality constant, $K = 0.060 \pm 0.001$ with $R^2 = 0.972$, is quite close to that found above (Fig. 7) and similar to that given by the average of the "experimental K values" in Ta-ble 1.

Based on these results, there is little doubt that the exper-imentally determined correlations point to a proportionality constant, $K = 0.060$ in Eq. 3. This value fits the experimen-

**Table 2** Comparative analysis between the theoretical and experimental diameters

| Yarn (tex) | Experimental $K$ diameter ($d_e$) (mm) | Theoretical $K$ diameter ($d_t$) (mm) | $\Delta d = d_e - d_t$ (mm) | $\Delta d = 100 - 100x(d_e - d_t)/d_e$ (%) | Average diameter (Table 1) $- d_e$ (mm) |
|---|---|---|---|---|---|
| 4.20 | 0.122963 | 0.07583 | 0.047136 | 61.67 | 0.007037 |
| 19.67 | 0.266105 | 0.16410 | 0.102007 | | 0.003895 |
| 36.88 | 0.364373 | 0.22470 | 0.139676 | | −0.014370 |
| 48.44 | 0.417593 | 0.25752 | 0.160077 | | −0.037590 |
| 62.00 | 0.472440 | 0.29134 | 0.181102 | | −0.012440 |
| 75.10 | 0.519962 | 0.32064 | 0.199319 | | −0.029960 |
| 212.20 | 0.874025 | 0.53898 | 0.335043 | | 0.015975 |
| 295.00 | 1.030534 | 0.63550 | 0.395038 | | 0.039466 |



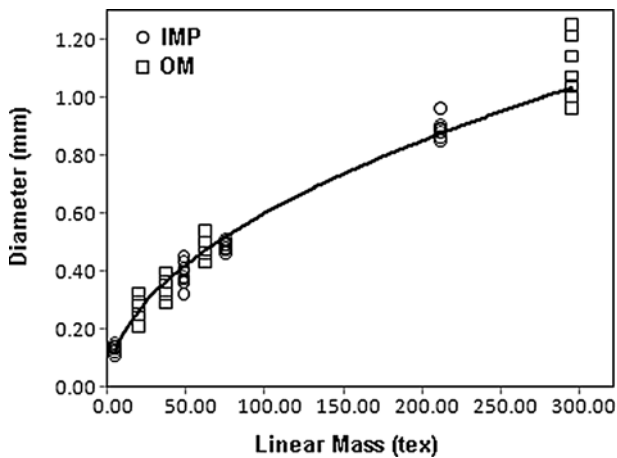**Fig. 8** Fit to the experimental data of Table 1, where the solid line represents the best fit obtained to Eq. 3



**Fig. 9** Comparison of the experimental K results with those predicted by the theoretical relationship reported in the literature

tal data for a wide range of *tex* values stretching from 4.2 up to 295 *tex*.

### 3.2 Experimental and Theoretical Diameter Values

Table 2 presents the diameter values obtained by using Eq. 3, considering the theoretical $K$ value found in the literature (0.037) and the experimental $K$ value (0.060).

Analyzing Table 2, the theoretically predicted diameters are approximately 62% lower than the diameters determined with the experimental $K$ value. Moreover, the difference between the average diameters (Table 1) and the diameters determined using the experimental $K$ value (Table 2) is minimal and, for almost all yarns, within the standard deviation (SD) range of the diameters measurements (Table 1), as shown in Table 2.

Figure 9 illustrates the distribution curves of the theoretical and experimental diameter values. It can be observed that, as expected, the theoretical diameter results are always inferior to the experimental results.
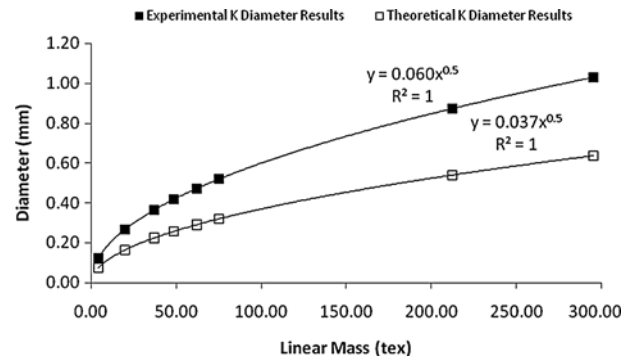
As stated in the introduction, the theoretical literature values typically assume cylindrical fibers put together in a closed packed geometry. The obtained experimental results call into question this assumption. Indeed, if the experimental $K$ values are translated into an effective porosity, using Eq. 1, it is found that 100% cotton yarns have a porosity of only 0.232, being quite low when compared to the theoretical values referred in the literature (between 0.55 and 0.70).

To lend additional support to this interpretation we have acquired electron microscope images of a transverse section of a 75.10 *tex* 100% cotton yarn. These images, presented in Fig. 10, show that there is a large amount of empty space in these yarns. Also observing other transversal pictures found in the literature [13, 14], the same phenomenon was verified. In addition the individual cotton fibers are far from cylindrical in shape, having a transverse profile that is more ribbon like. The $500\times$ magnification image appears to be roughly consistent with the conclusion that only 23% of the yarn volume is actually occupied by cotton fibers.

## 4 Conclusions and Future Work

Using two different and independent experimental techniques we have shown that the commonly quoted relation-
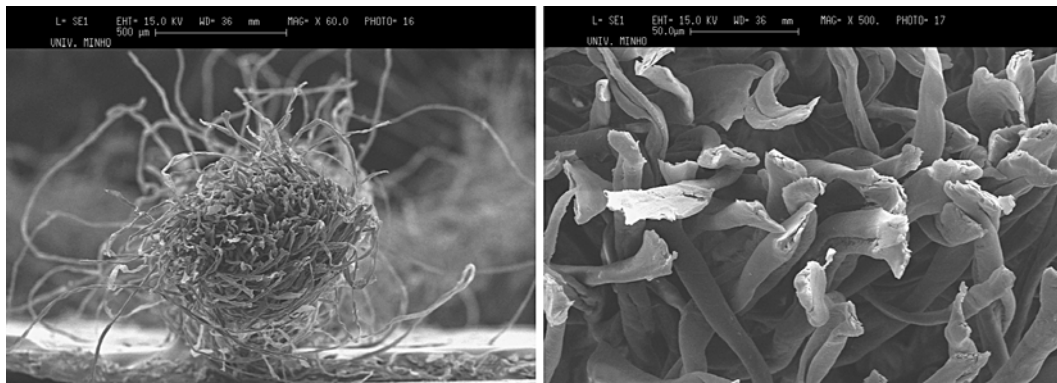
**Fig. 10** Transversal analysis of the 75.10 *tex* yarn for a magnitude of 60× and 500×

ship in the literature for diameter in function of the linear mass is in error by roughly 62% for the 100% cotton fiber analyzed. It would be interesting to discover if similar discrepancies exist for yarns made from other types of fibers. Indeed we plan to investigate this question in the near future.

Moreover, this study also shows that the diameters inferred from the capacitance measurement are in danger of being inaccurate if not properly calibrated by an appropriate porosity. This is because the capacitance measurements are sensitive only to the quantity of cotton fibers between the sensor plates and not to the empty space (air) between the fibers that constitute the yarn. There is therefore a strong need to accurately characterize the porosities of the various types of yarn commonly used in the textile industry.

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