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Development of a Method for Characterization of the Fibre Length of Long Staple Carbon Fibres Based on Image Analysis

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Abstract
For the manufacturing of load-bearing carbon fibre reinforced plastics (CFRP) made from staple carbon fibres (CF) , statements of the CF fibre length in the composite are essential. However, no suitable fibre length measuring method is currently available for long staple CF over 60 mm. The aim of this study is the development of an effective method for characterization of the fibre length distribution of long staple CF. For this method, a fibre beard specimen is extracted from a sliver manufactured from 80 mm staple CF, which is then scanned. Greyscale values densities (GD) of the individual length classes are determined from the scanned images, which correspond to the number of fibres per length class. From the proportion of all length classes, a span length diagram and staple fibre length diagram can be compiled. The results show the good potential of the method developed for the fibre length measurement of long staple CF.

Key words: *carbon fibre, fibrogram, span length diagram, staple length.*

Introduction

Due to the increasing use of carbon fibres (CF), production waste obtained during the manufacturing of carbon fibre reinforced plastics (CFRP) has to be disposed of, and the re-use of recycled CF from end-of-life components has to be considered. One innovative approach is the production of yarn constructions from recycled or waste CF. To use the very high strength potential of the CF in CFRP, long fibre lengths from 40 mm are necessary [1]. Since CFs are brittle in nature and sensitive to shear forces, they have to be processed as gently as possible in textile processes. Therefore in order to optimize the process parameters required for the gentle processing of CF into yarns e.g. in carding units, draw frames and spinning machines, an effective and reproducible measurement method for the fibre length measurement of CF is extremely important.

Although a number of methods for the length measurement of conventional natural and man-made fibres can be found from different literatures, a suitable measurement system especially for long staple CF is still not known or commercially unavailable. The test method required must be able to identify the CFs, with their small diameter (7 μm), high fibre lengths (up to 150 mm) and wide range of fibre length distribution as precisely as possible. This includes the correct distinction and evaluation of the CFs as individual fibres and in fibre bundles. Another necessary requirement is a gentle testing method to prevent additional fibre damage. The result of the tests should be reproducible and able to deliver statistically relevant values for fibre length characterisation.

The methods used for measurement of the fibre length can be classified into direct and indirect testing. In direct testing, each fibre is tested separately, while in indirect testing, a bunch of fibres are tested at the same time. Fibre length characteristics can then be obtained from the lengths and weights of the fibre group.

In the direct measuring methods, each fibre is sorted individually by length, and then the number or weight of fibres in each fraction is determined to give the data necessary for plotting a type of length frequency curve [2]. Since it is very difficult and time consuming to measure the length of each individual fibre, most test methods and instruments for fibre length analysis measure the length and weight of each group of fibres, generally classified in the length class [3]. This includes single fibre measurement according to test standard DIN 53808-1 [4], where fibres are removed by forceps and measured manually. This method does not include random sampling and hence is not suitable for statistical analysis due to the subjective/ biased selection of fibres by the tester. Furthermore due to the brittleness of CF, the length can be shortened more significantly if they are removed from the fibrous specimen individually than removed as bundles. CF bundles, on the other hand, contain up to several hundred individual fibres, and therefore a single fibre bundle would cover the entire testing size.

Another direct measuring method to test the length of fibres uses air canals and optical sensors (e.g. AFIS by USTER AG, Uster, Switzerland [5]). In this method, the fibres are individualised from a sliver by separation rollers, transported to an optical high-speed sensor by an air stream, and tested. However, the mechanical separation of the tapes into individual fibres damages the brittle CFs and influences the test results.

In the direct fibre length testing method presented by [6], pyrolyzed CF bundles from a thermoplastic component are separated within a solution by means of a high frequency generator. Finally a fibre length of 2,000 individual fibres is analyded with image processing software. Although the separation is performed gently, the test complexity is relatively high regarding the selection of a high number of individual fibres.

Direct fibre detection by means of image processing is a relatively new development in fibre length measurement. The software can detect the fibres and their course autonomously as well as calculate the fibre length from digital images. For instance, this is performed by digitising nonwovens made of CF with commercially available scanners [7], with adapted scanners or camera systems digitizing high-performance fibres in a solution [8], or using computed tomography in CFRP [9]. The disadvantage of this method is that if longer fibres

Table 1. *Comparison of methods for fibre length characterization.*

Measuring method	Test method	General suitability for measuring long CF	Brief assessment
Direct length measuring	Forceps method	No	High testing complexity
	AFIS		Fibre damage of CFs
	Individualization and digitalization		High testing complexity
	Direct detection		Not suitable for high fibre lengths
Indirect length measurement – end-aligned	Almeter		High testing complexity, capacitive measurement
Indirect length measurement – random-aligned	Pneumatic length measurement		Imprecise cut length due to fine CF
	Cutting		High testing complexity, imprecise
	HVI method	Yes	Not suitable for high fibre lengths (>60mm)

(around 40 mm) are used in a nonwoven, no accurate ordering of the beginnings and ends of the fibres is feasible, and the course of the individual fibre cannot be followed clearly. Therefore such systems are unsuitable for long fibres made from CF.

In indirect measurement, a specimen of paralleled fibres is measured at various positions by some scheme, and these measurements are converted into number of fibres to give the data necessary for plotting a length-frequency curve. The bunch of fibres can be arranged either end-aligned or random-aligned [2, 10].

Methods using end-aligning include a manually sorting of each fibre in the bunch to a reference line. Afterwards the fibres can be sorted manually by length class, and the amount of fibres per length class can be weighted for determination of their percentage. Alternatively computer-assisted testing technology can be used, which primarily includes a capacitive system (e.g. Almeter [11, 12]) where the aligned fibre bunch is scanned based on the capacitive method and sorted into length classes. The Almeter method is not suitable due to the electrical conductivity of CF.

Fibre length measurement from randomly aligned fibres used in different methods such as Fibrograph, High Volume Instrument (HVI), pneumatic length measurement and the cutting method significantly reduce the testing effort, being common for the length determination of cotton fibres. The Fibrograph, introduced by Hertel in 1940, is an optical instrument and employs photovoltaic cells for scanning specimens of parallel fibres to trace a type of length frequency curve [2]. It was intended to plot a seed cotton staple diagram by scanning the entire distribution of the specimen. The fibrogram theory introduced for a specimen of parallel fibres in which the fibres are positioned at random configures the fibrogram curve if they are arranged with their catching points along a line.

For pneumatic length measurement [13], the fibre beard is guided through a measuring slit under an air current for scanning. The opening of the measuring slit is changed in a manner that ensures a constant air current in relation to the amount of fibres in the scanned cross-section. Thus there is a relation between the measuring slit size and the amount of fibres, allowing determination of the quantity distribution of the fibres, similar to the optical process. However, the fineness of the CF complicates an accurate testing of the fibre length by pneumatic measurement.

In the cutting measuring principle [14], a fibre beard from cotton fibres is cut after each length class and the cut-off fibres are weighed. The result is the ratio of the weight of the fibres in each length class. In [15], the cut fibres of each length class are analysed using image processing software, and the amount of fibres are allocated to their specific length class. The tests require extensive effort and the cutting of the fine CFs is relatively imprecise.

HVI, which is the most important device for cotton fibres developed in the 1980's, uses the same principle of Fibrograph for length measurement and includes other features, such as micronaire, strength and elongation testing. A fibre specimen is extracted automatically and the fibres are clamped randomly, forming a fibre beard. The beard is then parallelised by means of brushes. Non-clamped fibres are then removed. Afterwards the fibre beard is inspected by an optical sensor which detects the number of fibres per scanned cross-section. However, commercially available HVI systems are not adapted to the length determination of CF long staple fibres as they work solely with a maximum fibre length of 60 mm.

In order to overcome the drawbacks of the methods as described above (also cf. ***Table 1***), a new testing method based on image analysis especially suitable for the length measurement of CF (> 60 mm) is introduced in this paper.

Conceptual explanation of the newly developed method for fibre length measurement

The approach of the length measuring method presented in this paper is based on the theory of fibrogram applicable for a random-aligned fibre beard. According to this theory, if the randomly selected fibres are arranged with their catching points as in ***Figure 1***, rather than their left ends, along the vertical axis, their right ends form the fibrogram function. Such a specimen is represented by $r(l)$, which is the second integral of $p(l)$, as shown in ***Equation 1*** [2]:

$$r(l) = \int_{l}^{l_m} \int_{l}^{l_m} p(l)\,dl\,dl \qquad (1)$$

where, $p(l)$ is the probability that a fibre of the population has a length between l and $l+dl$, and l_m denotes the longest fibre.

If all fibres in the specimen have the same length, an ideal diagram course, as in ***Figure 2.a***, will be the result. The fibres are homogeneously distributed in all length classes in the fibre beard, and hence there is no slope variation in the span length distribution curve.

The span length distribution and corresponding staple fibre length distribution are illustrated in ***Figure 2.b*** for the case of two fibre lengths. The slope in the span length distribution curve changes as a result of fibre length variation. Consequently the corresponding staple fibre length distribution also changes. ***Figure 2.c*** shows a real composition of cotton fibres for comparison.

In the method presented in the paper, the fibres are clamped along an orientation line (cf. A in ***Figure 3***), and the greyscale value densities (GD) of each length

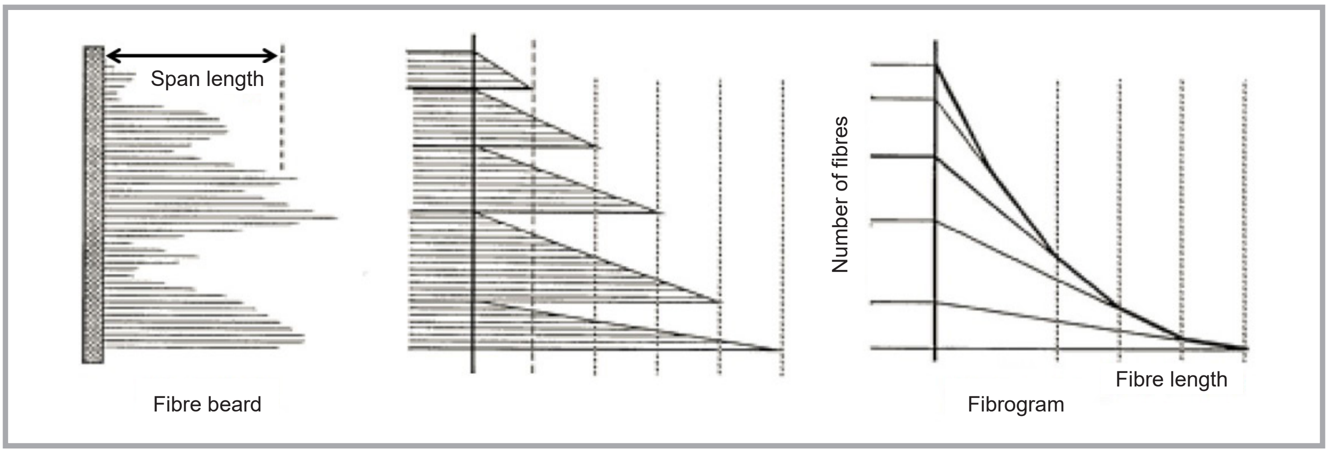

Figure 1. *Randomly caught fibres and the corresponding fibrogram curve [3]*

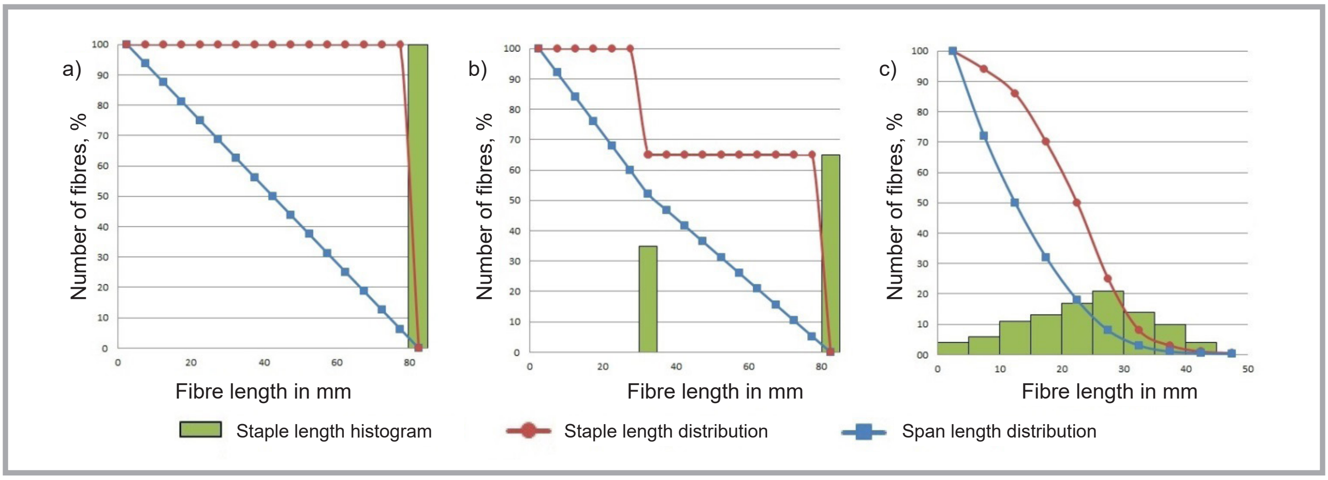

Figure 2. *Interrelation of span length distribution and staple length distribution in the case of (a): one fibre length, (b): two fibre lengths, and (c): real distribution of cotton fibres.*

class are determined from the scanned image of the clamped fibres. The GD is defined as the count of pixels and their corresponding grey scale values of a defined area in the image. Each pixel has a greyscale value between 0 (pure white) and 255 (pure black). For example in ***Figure 3***, the grayscale value of point B is 37 and the total GD in the length class of 25 - 30 mm is 432203.

From the relationship between the GD and number of fibres of every length class in the specimen, a span length distribution diagram (Fibrogram) can be compiled.

Experimental details

Test P1: Proof of suitability of the measuring method

The suitability of the method is first checked based on reference specimens prepared by cutting from virgin filament tow SIGRAFIL C50 T050 EPY (SGL, Germany) (50,000 filaments and linear density 3,300 tex). The objective of this test is to determine the relationship between the GD values and the actual number of fibres. Ten pre-defined specimen variations are tested (40 - 1000 fibres per bundle, five bundles per specimen), whose number of fibres is counted beforehand. The ten specimens and corresponding number of fibres used for Test P1 are detailed in ***Table 2***. Due to the very low diameter (7 µm) of the individual fibre, an approximately 10% error in the number of fibres can be considered.

The specimens are scanned using an HP PSC 1410 scanner (HP Inc., USA).

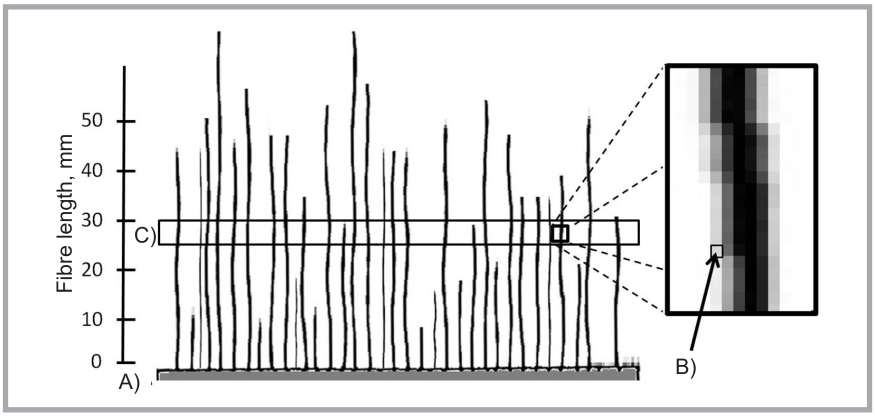

Figure 3. *Scheme of length measurement with a fibre beard using GD values; A) orientation line, B) GD of the marked pixel (= 37), and C) total GD in length class of 25 - 30 mm (= 432203)*

Table 2. Specimens with different numbers of fibres in the bundle for Test P1.

Specimen	Number of fibers / bundles
#1	40
#2	60
#3	80
#4	100
#5	150
#6	200
#7	300
#8	500
#9	700
#10	1000

Table 3. Settings of HP PSC 1410.

Parameters	Value
Colour format	Grey-scale
File format	JPG
Resolution in dpi	300
Brightness	-72
Contrast	57

The scan settings are summarized in ***Table 3***. The gray value 35 is defined as the border; all values below are specified as the background gray value and are not considered. The scan settings are selected from the results of pre-investigations carried out by varying the contrast, brightness and resolution to find out the best match with a defined number of fibres.

Scanned images of the specimens with 100 and 500 fibres per bundle are shown in ***Figure 4*** as an example. The images are then processed with Matlab R2014a (TheMathWorks, USA) software, where the GD is measured and averaged.

Test P2: Fibre length measurement of CF in a sliver

For measurement of the fibre length from a real specimen processed by textile machines, a sliver consisting of CF is used (cf. ***Figure 5***). For manufacturing of the sliver, cut fibres of 80 mm staple length from virgin filament tow SIGRAFIL C50 T050 EPY (SGL, Germany) are first processed on a laboratory long staple carding machine (Anton Gulliot, Germany) at the ITM [16]. The fineness of card webs that are produced is approximately 30 ktex. Afterwards drafting is carried out on the card webs using a high performance draw frame - RSB-D40 (Rieter, Ingolstadt, Germany). The fineness of the draw frame slivers produced is found to be approximately 3.5 ktex.

A specimen is taken from the sliver produced for the purpose of fibre length measurement (Test P2). The fibres are clamped between two metal plates and fixed together by screws. After fixation, the non-fixed fibres are gently removed by a comb, which also helps to parallelise the remaining fibres at the same time. The fibre beard prepared is then released from the clamp and glued on white paper with a printed orientation line.

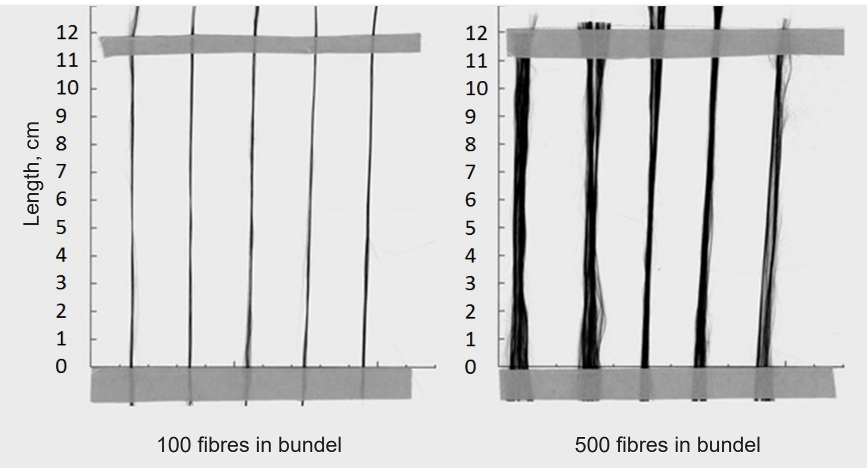

Figure 4. Scanned images of pre-defined specimens with 100 and 500 fibres per bundle.

Figure 5. Draw frame sliver manufactured from 80 mm staple CF.

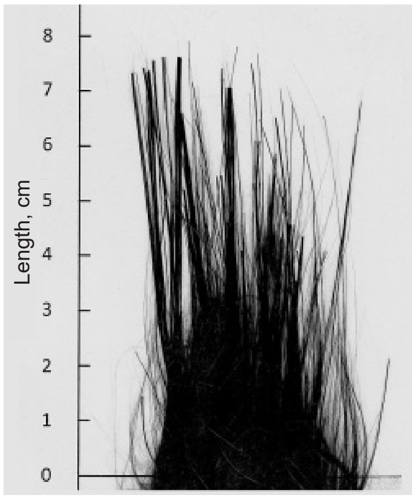

Figure 6. Scanned image of the fibre beard specimen used for fibre length measurement in the case of Test P2.

The fibre beard attached to the white paper is then scanned using the parameters detailed in ***Table 3***. A scanned image of the fibre beard is shown in ***Figure 6***, analyzed in the way mentioned in the case of Test P1. The GD of the individual length classes, which is defined as 5 mm according to DIN 53808-1 for 80 mm fibre length, is calculated automatically.

To verify the results of the image processing, the fibre length distribution of the CF in the fibre beard are additionally investigated by the forceps method according to DIN 53808-1. However, in order to reduce the testing effort and to cover all fibres of the fibre beard (approximately 20,000 fibres), the fibres are separated into two length classes only. Length class 1 includes all fibres with the original length (i.e. 80 mm) and length class 2 - fibres which are shorter than 80 mm, as a result of the textile processing. After this, both fibre classes are weighted by a scale - Bosche FW-K 600 2M (Bosche Waegetechnik, Germany).

Results and discussion

Test P1

The results of Test P1 are summarised in ***Figure 7***, where it can be seen that the GD increases linearly with the increasing fibre count. This indicates that the proportion of the number of fibres per length class can be determined by means of the GD measured. The high standard deviation in the case of a higher number of fibres can primarily be traced back to the error resulting from the manual counting of CF in the bundles, as already mentioned.

Test P2

GD values of each length class which are obtained from the analysis of the scanned image of the fibre beard are detailed in ***Table 4***. Since the proportion of GD values corresponds to the proportion of the number of fibres in a length class, the corresponding percentage of the cumulative span length is calculated from the proportion of the GD values for each length class. By plotting the percentage of the cumulative span length against each length class, the characteristic span length distribution diagram (i.e. Fibrogram) of the fibre beard specimen prepared from the sliver can be derived as illustrated in ***Figure 8***.

From the span length distribution, the corresponding histogram and staple length distribution are calculated, based on the slopes of the individual length class of the span length distribution curve. If the slope of the curves changes between length classes, the proportion of the staple fibre length distribution per length class also changes. For this, the percentile proportion of the slope differences per length class is calculated based on the span length distribution curve, starting from the highest length class. These slope differences are equivalent to the relative frequency of the staple fibre length per length class (Histogram). The resulting histogram and staple length distribution can be seen from ***Figure 8***.

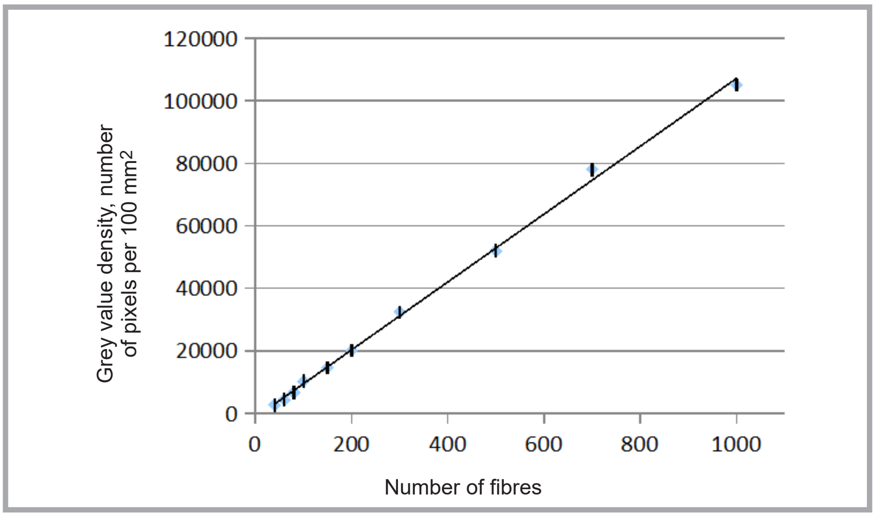

Figure 7. *Relationship between GD and number of fibres.*

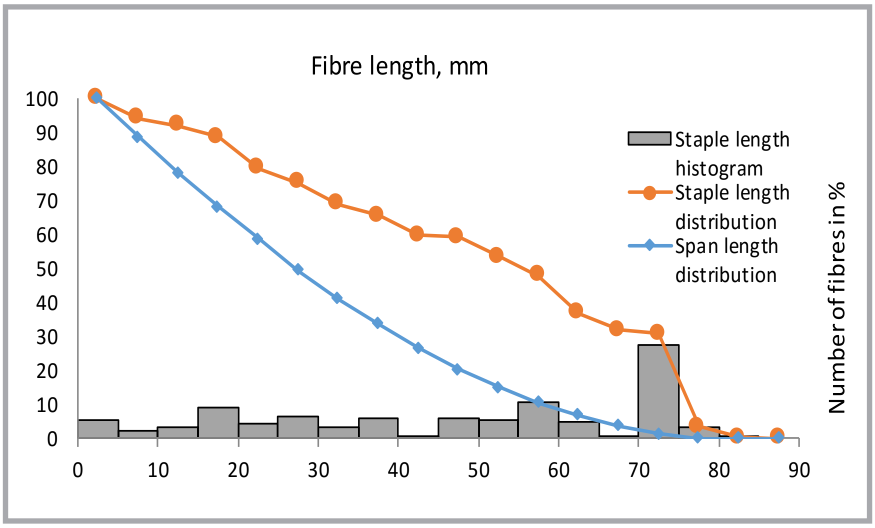

Figure 8. *Span length distribution and corresponding staple fibre length distribution as well as the staple length histogram obtained from Test P2.*

Table 4. *Results of Test P2.*

Length class	Class width in mm	Mean length in mm	GD values per class width	Proportion of GD in %	Corresponding cumulative span length in %	Relative frequency of staple length in %	Cumulative relative frequency of staple length in %
1	85-90	87.5	0	0.0	0.0	0	0
2	80-85	82.5	586	0.1	0.0	0.3	0.3
3	75-80	77.5	7006	0.1	0.1	3.2	3.5
4	70-75	72.5	63313	1.2	1.4	27.4	30.9
5	65-70	67.5	118010	2.3	3.7	0.9	31.8
6	60-65	62.5	163478	3.2	6.9	5.1	36.9
7	55-60	57.5	189029	3.7	10.6	10.9	47.8
8	50-55	52.5	224739	4.4	15.0	5.6	53.4
9	45-50	47.5	271256	5.3	20.3	5.9	59.3
10	40-45	42.5	318757	6.3	26.6	0.5	59.9
11	35-40	37.5	355811	7.0	33.6	5.7	65.6
12	30-35	32.5	386903	7.6	41.2	3.3	68.9
13	25-30	27.5	429661	8.4	49.6	6.4	75.3
14	20-25	22.5	464931	9.1	58.7	4.1	79.4
15	15-20	17.5	483342	9.5	68.2	9.3	88.7
16	10-15	12.5	508188	10.0	78.2	3.5	92.2
17	5-10	7.5	536947	10.5	88.7	2.1	94.3
18	0-5	2.5	576005	11.3	100.0	5.7	100.0
		sum:	5097962	100.00			

Table 5. Results obtained from weighting the fibres.

Length class	Weight in g	Proportion in %
Length class 1: original CF length	0.156	54
Length class 2: shortened CF length	0.132	46

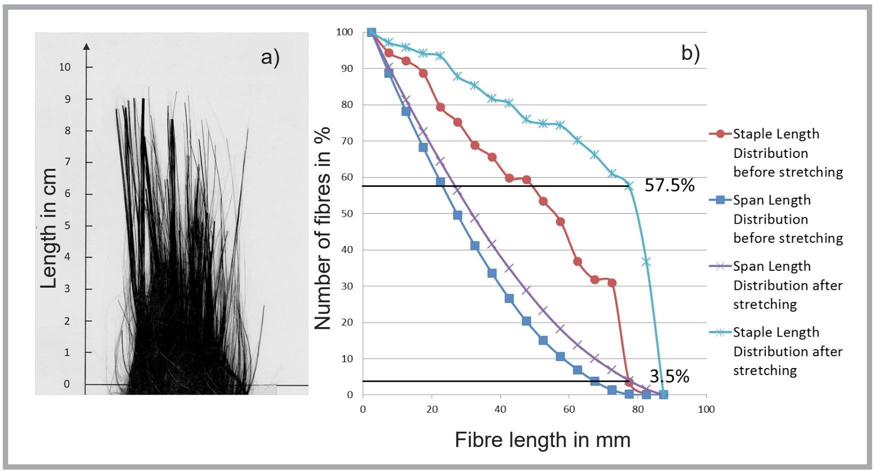

Figure 9. *a) Scanned image of Test P2 stretched by factor 1.19; b) comparison of span length and staple length curves before and after stretching with factor 1.19.*

It can be seen from ***Table 4*** that 3.5% of the fibres have an original staple length of 80 mm in length classes 2 - 3 (75 – 85 mm fibre length). However, validation of the results by weighing shows that 54% of the fibres have the original staple length (cf. ***Table 5***). This difference is mainly caused due to the beard sampling method itself, which was also revealed in [2] for cotton fibres. It was shown that fibrograms gave the best agreement with measurements of fibres when the length axes of the fibrograms were increased by a factor of 1.19. This was attributed firstly to the fibre waviness and tapering of the fibre ends and secondly to the displacement of the base line due to the clamping method.

In the case of CF, the orientation line (as shown in ***Figure 6***) needs to be extended back from the zero axis in order to clamp the fibre beard. Considering this distance as a constant fraction of the individual fibre length of each fibre, a factor is more suitable rather than a linear displacement of the zero axis. Because of this reason, the test is repeated, while the fibre beard in the image is stretched by different factors from the orientation line to the longest fibre. The image stretched by factor 1.19 correlates ("P2-1.19") well with that found by weight fibre classes (cf. ***Table 5***), as can be seen in ***Figure 9***. However, the results show that in this case measurement of the fibre length using image analysis deviates approximately 6.5% from the practical values.

Conclusion

In this paper, a new method based on image analysis for measurement of the fibre length especially suitable for long CFs is introduced. For this, a randomly aligned fibre beard is prepared from a sliver manufactured from 80 mm staple CF by carding and drawing. After scanning the fibre beard, GD values are determined from the individual length classes. From the analysis of the GD values, it can be revealed that those of a defined fibre length class are linearly proportional to the number of fibres of CF. This allows the creation of a span length distribution diagram (i.e. fibrogram) and calculation of a staple fibre length distribution diagram. However, the fibrogram obtained by stretching the scanned image by factor 1.19 gives the best agreement with results found by weighing the fibre length class of the fibre beard. It is expected that the method developed will help to characterise and quantify the fibre length of long staple CF more effectively, which would contribute significantly to the optimization of machine parameters required for the processing of staple CF.

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