Quantitative analysis of hollow lumen in jute

Md. Rashnal Hossain,*, Md. Aminul Islam, Aart Van Vuure, Ignaas Verpoest

Department of Materials and Metallurgical Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000

Department of Metallurgy and Materials Engineering, Katholieke Universiteit Leuven, Kasteelpark Arenberg 44, 3001 Heverlee, Belgium

Abstract

In the era of smart materials the natural fiber composites has been of extreme importance. Nevertheless, most natural fiber contains some empty spaces known as lumen or lacuna, which never contribute to the mechanical properties and remain as it is inside the composites. As processing techniques of NFRP composite fabrication varies the properties of composites so this restricts its application. In this research work, initiative has been taken for quantitative analysis of the hollow lumens so that they could be considered in the composite manufacturing process. For doing this, hollow lumen of Bangla white grade B (BWB) jute was analyzed with the help of scanning electron microscopy along with image processing software. Experimental results revealed that proper analysis of the hollow lumens and their consideration can effectively reduce the percentage error of the tensile strength and stiffness values of natural fibers.

Keywords: Bangla white; lumen; normal distribution; fiber diameter.

1. Introduction

Present world focuses on the composite materials where the properties can be tailored according to specific requirement. Among these composite materials the fiber reinforced especially natural fiber reinforced composite materials gained importance due to the environmental concern.

However natural fiber characterization has been the major area of research during the last few years as these fibers physicochemical behavior is totally different from their artificial peers.

* Corresponding author. Tel.: +88-01720-433364; fax: +88-02-8826257.
E-mail address: hrashnal@gmail.com
Moisture sensitivity irregular distribution of fiber forming material and their compositional variability renders these natural fibers to behave erratically under mechanical force [1, 2]. Additionally characterization of these fibers under various loading condition is still under research. [3, 4, 5].

However normal distribution, single parameter, multiple parameter data set Weibull distribution has been tried by the researcher to reduce the percentage error of the fiber characterization. Weakest link theory was also applied to reduce the characterization error [6, 7, 8, 9].

But most natural fibers have lumens or lacuna which is an empty space that never contributes to the fiber property but has a large interior area in the context of an elementary fiber [8]. Also excluding this area from cross section of fiber reduces error percentage to a great extent. So the current research is to see the effect of these lumens and their ability to reduce the error percentage.

2. Experimental Method

Bangla White Grade B jute (BWB) was procured from Bangladesh Jute Research Institute. The procured jute was cleaned with distil water followed by ethyl alcohol and acetone wash and dried in an oven overnight at 60°C temperature.

Jute fiber diameter was calculated with “width measurement method” by means of Leica MZ8 image processing software based stereo optical microscope. “Weight measurement method” was also tried to calculate jute fiber average diameter. To compare the procedures for jute fiber diameter measurement a number of 20 fibers of same 50mm length were taken from the same bunch of fiber from which single fiber tensile test specimens were made. At least 60 width data were randomly taken for each fiber through the entire length. Accordingly, to crosscheck the optically obtained average width value of these fibers and the weight of individual fiber was measured and the average diameter was calculated from the length and density value of jute fiber.

In another set of experiment the jute fiber lumen cross sectional area were also photographed under Scanning electron microscope XL30 SEM FEG and then it was processed with Leica MZ8 image processing software. Detailed graphical analysis and comparison of solid fiber and the lumen were done and the data aquatinted was used for correcting the tensile test data of BWB jute fiber.

Tensile test of single jute fiber was carried out (over 60 numbers for each span) and test data were corrected for span length with the help of normal distribution, Weibull distribution and the effect of percentage lumen exclusion is also studied and a comparison was made. Fiber failure morphology is also discussed.

3. Results and Discussion

3.1. Jute fiber diameter measurement and analysis

It was observed that the individual technical fiber has different perimeter for a same population of fiber. The cross sectional view of lumen is also different and has got little resemblance in shape and size to its neighboring lumen as shown in Fig 1a.

From Fig 1b it is clear that although the jute fiber is assumed to quasi circular along its length but the fiber diameter varies widely irrespective of its length. However, the validity of fiber cross sectional area measuring methodology is an area of debate, since jute fiber is very thin and irregular shaped. Some researcher follow optical root to measure fiber diameter, some follow measurement of weight of fiber and then calculate diameter of fiber from known density and fiber length value.

The drawback of the optical procedure of fiber diameter measurement is that the crosses sectional circumference of the fiber is considered as circular, and the hollow spaces within the lumens are not excluded.
Fig. 1. (a) Random lumen cross section of BWB jute; and (b) variation of circumference of BWB 54mm jute fiber in preceding 3mm fiber length.

Fig. 2. Comparison of BWB jute fiber diameter measurement via weight measurement and optical measurement route.

| Diameter (µm) | Weight Measurement | Optical Measurement |
|--------------|--------------------|---------------------|
| 1            | 46.8               | 66.0                |
| 2            | 41.5               | 54.6                |
| 3            | 45.1               | 59.1                |
| 4            | 53.1               | 58.3                |
| 5            | 46.8               | 56.7                |
| 6            | 50.1               | 60.8                |
| 7            | 74.1               | 58.4                |
| 8            | 51.6               | 62.6                |
| 9            | 50.1               | 65.4                |
| 10           | 70.8               | 54.5                |
| 11           | 53.1               | 40.2                |
| 12           | 48.5               | 41.6                |
| 13           | 56.0               | 36.4                |
| 14           | 48.5               | 45.3                |
| 15           | 45.1               | 42.6                |
| 16           | 54.6               | 56.8                |
| 17           | 53.1               | 39.9                |
| 18           | 58.7               | 59.7                |
| 19           | 48.3               | 44.9                |
| 20           | 50.1               | 46.7                |

Fig. 2 shows that weather the diameter measurement method is either weight measurement based or optical based there will be always some discrepancy. The advantage of weight measuring to get the fiber diameter is that the hollow spaces of the fiber are always excluded. In accordance with this, for any single technical fiber of any types of
shape, if a large number of values of fiber width are taken through the length then the average may closely resemble to the diameter measured via weight measurement method as shown in Fig 2.

More over it was observed that the interior of lumen is not uniform, which is shown in Fig 3. This matter indicates that as the interior of BWB jute fiber lumen is non-uniform so whatever the diameter measurement procedure of BWB jute there always will be some statistical percentage of error. One must keep in mind that these values of diameter can vary widely and without following any statistical nature.

![Image](image.png)

Fig. 4. Lumen cross sectional area (a) lumen percentage and (b) solid fiber percentage

From the Fig 4 a & b it was observed that the lumen percentage may vary widely without following any statistical pattern but during our study on an average 20% of lumen area was found within an elementary BWB jute fiber. With the application of statistics or % lumen correction we can minimize the error but we will not be able to remove it totally. Therefore it can be stated that the discrepancy between the two diameter measuring procedures are influenced mostly by natural causes, rather than the methodology implemented.

### 3.2 Jute fiber mechanical property assessment and statistical evaluation

Table 1 indicates the data summary of the tensile test of Bangla white jute fiber. Regarding the fiber diameter there is no statistical resemblance with increasing span length. The property trend is clearly observed in the table. But one must notify from the table that the effect on mechanical property data of the fiber is far more different as % lumen is considered. Strain to failure shows decreasing trend with increasing span but as lumen like empty space has no contribution to the mechanical strength or strain so it remained unchanged for all the analysis.

However, since there are amorphous region and crystallite region within jute fiber (“α” – cellulose) itself so regarding the weakest link theory the fiber failure at the weakest link may not be fully acceptable fact. This is since microscopic elongation is possible everywhere within the fiber under tension. The amorphous zone that elongates
and becomes narrower than the narrowest crystallite region can fail immediately as the stress concentration is increased. The standard deviation of the strength value of the %lumen excluded fiber is higher than the normal distribution, since lumen interior is also irregularly distributed in an elementary fiber. This phenomenon higher standard deviation indicates more error is excluded from the tensile test data set of jute fiber. the similar procedure can be implemented for other natural fiber like jute.

Table 1. Tensile test data summary of BWB jute fiber.

| Span (mm) | Fiber diameter (μm) | Tensile strength (Mpa) | Tensile strength % lumen excluded | Strain To failure (%) | Modulus (Gpa) | Modulus % lumen excluded |
|-----------|---------------------|------------------------|-----------------------------------|----------------------|---------------|-------------------------|
| 5 ± 0     | 64.41 ± 11.36       | 712.87 ± 288.23        | 896.70 ± 362.55                  | 1.70% ± 0.59%        | 45.15 ± 6.58  | 56.79 ± 8.28            |
| 10 ± 0    | 70.86 ± 14.82       | 524.84 ± 138.86        | 616.22 ± 180.89                  | 1.26% ± 0.38%        | 43.14 ± 2.00  | 54.26 ± 2.51            |
| 20 ± 0    | 83.47 ± 8.89        | 507.86 ± 93.03         | 638.81 ± 123.61                  | 1.19% ± 0.24%        | 42.79 ± 2.64  | 53.82 ± 3.32            |
| 35 ± 0    | 69.25 ± 6.57        | 452.27 ± 102.55        | 528.32 ± 128.99                  | 0.98% ± 0.13%        | 46.32 ± 9.40  | 58.26 ± 11.82           |

Table 2. Variation of Weibull shape parameter.

| Span length (mm) | Ultimate Cell Dimension (taken from literature) [3, 10] | Weibull Shape parameter “m” | % Lumen excluded |
|------------------|----------------------------------------------------------|-----------------------------|------------------|
| 5 ± 0            | Length                                                   | 2.5973                      | 2.5973           |
| 10 ± 0           | 2 – 5.5mm                                                | 3.6989                      | 3.6989           |
| 20 ± 0           | Diameter                                                 | 5.3279                      | 5.3279           |
| 35 ± 0           | 5 - 20μm                                                 | 4.6110                      | 4.6110           |

From Table 2 it is clear that the calculated Weibull shape parameter remains unchanged whether or not the percentage lumen is considered. This information indicates that the percentage error, which has been excluded with the help of normal distribution and the exclusion of %lumen from the diameter data, remains insensitive [6, 7, 8].

3.3. BWB Jute fiber fracture morphology

![Fiber fracture morphology of BWB jute under tensile load (a) delamination; and (b) microfibriller failure.](image)

The failure morphology of BWB jute is given in Fig 5a. Additionally from the failure morphology it can be said that the failure of BWB jute is not uniform but localized. The failure may also yield some delaminated lumens indicated by arrow.
As jute itself is a natural composite composed of lignin and pectic materials and main reinforcing element is cellulose [10, 11]. So we can now understand that the pectic material fails first, followed by alignment of microfibril of amorphous zone with the loading axis, which is followed by the formation of narrow stress concentration zone and then final failure after some elongation. As the final failure of the fiber will occur by rupture of microfibril so the surface will be rough leaving the ligament like structure on the failure surface. This phenomenon is confirmed by Fig 5b.

4. Conclusion

Conclusive remarks from the above study are stated below:

- Whatever the diameter measurement procedure i.e. optical or weight measuring basis there will always remain some error, which will be statistically extraneous.
- Exclusion of lumen percentage from cross sectional area of BWB jute yields higher mechanical value and tensile test data error is reduced
- Weibull shape parameter remains insensitive to the exclusion of the percentage lumen present in the fiber. This indicates the statistical modeling of natural fiber shows the cumulative effect of defect on the tensile strength rather the interaction of individual type of defect.
- For BWB jute the cellulose microfibril always fails last.

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