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Effect of Diameter, Gauge Length and Speed of Deformation on the Properties of Banana Fibre

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Abstract: *The mechanical properties of banana fibres were investigated using stress-strain curves. Properties such as breaking strength (BS), initial tensile modulus (YM) and percentage elongation at break (BST) were evaluated as a function of gauge length, fibre diameter, and speed of deformation. The BS and BST decreases as the gauge length increases from 20 to 200 µm. BS lie within the range 930.73 and 504.85 MPa, and within 6.74 and 1.83 % for BST. The reverse is the case for YM which increased from19.12 to 38.16 GPa as gauge length increases. BS and YM of banana fibres increase as the speed of deformation increases from 5 mm/min to 100 mm/min. The increase between adjacent speeds is insignificant; the highest percentage increase is 0.71% for BS and 9.26 % for YM. The reverse is the case for the breaking strain; it decreases with increase in speed deformation. There was no appreciable change in mechanical properties within 10 and 100 µm diameters range investigated, the maximum percentage change of 0.86 occurred between 70 and 80 µm diameter. In conclusion better mechanical properties can be achieved at low gauge length, low diameter and high speed of deformation.*

Key words: *Gauge Length, Diameter, Speed of Deformation, Strength, Modulus, Strain*

INTRODUCTION

Natural fibres are gaining attention in research, reason been that they are renewable, environmentally tolerable, decomposable and are material for industrial applications. Other advantages of natural fibres include low density, suitable toughness and mechanical properties. Most importantly, they are biodegradable and recyclable. From source point of view, natural fibres are categorized into animal, plant, and minerals fibres (Ramamoorthy *et al.,* 2015; Jauhari *et al.,* 2015; Brischetto, 2017; Khan *et al.,* 2018). Plant fibres are further classified into six types; these are bast, leaf, straw/stalk, wood, seed/fruit and glass fibres (Ramesh *et al.,* 2017; Rohan *et al.,* 2018). Natural fibres produced as by-product are referred to as secondary plant fibres example of which are pineapples, oil palm, and coir, while banana, jute, hemp, kenaf, and sisal are primary plant fibres because they are grown for their fibre contents (Ramamoorthy *et al.,* 2015; Rohit *et al.,* 2016). Bast fibres example of which is banana fibre are extracted from the outer layer of stems of the plants by the retting method (Ramesh *et al.,* 2017; Mukherjee *et al.,* 2011). Due to their greater strength and low density, their applications are found in automotive industries (Ashori *et al.,* 2008; Mukherjee *et al.,* 2011; Hassan *et al.,* 2017). Other areas include textiles, pulp and paper, as well as in civil and building engineering.

Mechanical properties of natural fibres vary from one plant fibre to another and can differ among the same fibre depending on the source of fibre (Rohit *et al.,* 2016), processing techniques (Ramamoorthy et al. 2015; Jagadeesh et al.2017), surface treatment (Jauhari *et al.,* 2015), the state as at the time of harvest (Ramamoorthy *et al.,* 2015; Jagadeesh *et al.,*2017), storage (Ramamoorthy *et al.,* 2015), hydrophilic nature and moisture content (Ramamoorthy *et al.,* 2015; Faruk *et al.,* 2012) and most importantly the internal structure (Jauhari *et al.,* 2015; Faruk *et al.,* 2012) among others. Physical properties also play crucial role in defining the overall performance of natural fibres. Among the physical properties include diameter, length, crystallinity, strength, structure, and defects. Aspect ratio (fibre length/width or diameter) of fibre which plays a prominent role in determining the strength of fibre could determine its application (Jawaid *et al.,* 2011; Faruk *et al.,* 2012). High strength means low fibrillar angle, small fibre diameter, and higher aspect ratio (Ramamoorthy *et al.,* 2015).

More research into composites from natural fibres is due to the acceptable mechanical properties at low density. Composites from nature offer a wide range of advantages among which are; lower density, availability, harmless, renewable, biodegradable, less abrasive to the processing equipment and low cost (Facca, *et al.,* 2006). The mechanical properties can be comparable to those of inorganic fibres (Bledzki and Gassan 1999; Plackett *et al.,* 2003; Ratajska and Boryniec, 1999). Agricultural fibrous crops plants like banana are available in abundance here in Nigeria. At present banana fibres is a waste agricultural product, without any additional cost input, it can be obtained for industrial use. The banana fibres (Musa Sepientum) being one of the largest herbaceous plant in the world is grown abundantly in several developing countries. After wheat, maize and rice, banana is the most important food crops (Waliszewski *et al.,* 2003). Banana fibre is obtained from the pseudo-stem of banana plant. It is a bast fibre with comparatively good mechanical properties. Like every other bast fibre, banana fibres are lignocellulosic made of helically coiled cellulose micro-fibrils in misty matrix of lignin and hemicellulose. The mechanical property is determined by the content of the cellulose and micro-fibril angle (Kulkarn *et al.,* 1983). A high cellulose content and low micro-fibril angle will convey required mechanical properties for banana fibres. In this research the mechanical properties of banana fibre (BF); Young modulus, breaking strength and percentage breaking strain, were reported as functions of diameter, gauge length and speed of deformation.

MATERIAL AND METHODS

2.1 Materials

Banana fibres with different gauge lengths and diameter, cardboard, sellotape,

A. Equipment
Instron 1121 tensile testing machine, optical microscope (OLYMPUS BH2 UMA).

2.2 Method

Banana fibres used in this study were obtained from a local banana garden in Nigeria. Fibres of different diameters ranging from 10 to 100µm were sorted out using an optical microscope (OLYMPUS BH2 UMA). For evaluating tensile properties, fibres were mounted on a piece of cardboard with a central window using sellotape and pulled in an Instron testing machine. Fibres of 10 to 100 µm in diameter and 100 mm long were tested at 100 mm/min test speed. Fibres of 100 µm in diameter but 20 to 200 mm long were tested at a test speed of 100 mm/min, and fibres of 100 µm in diameter and 100mm long were tested at test speeds of between 5 and 100mm/min. For each set of tests mentioned above between 40 and 50 fibres were tested. All the tests were carried out at 50% relative humidity at room temperature, after conditioning the fibres under these conditions. The fibres were dried in the sun until the weight is constant.

Results and Discussion

3.1 Stress-Strain Curve of Banana Fibre

Fig. 1 show a typical stress strain curves of banana fibre of length 100µm, diameter 100 µm and tested at a speed of 100 mm/min. The curve is characterized by a proportional straight line portion where the slope which is the modulus is taken, followed by a very small curvature indicating uneven increase in strain with stress until the banana fibre breaks. The tensile stress of BF is 731.16±110.24 MPa while the strain at break is 4.21±1.23%, and the Young Modulus is 24.64±4.37GPa.

These values are consistent with reported values in the literature (Biagiotti, *et al.*, 2004, Joseph *et al.*, 2002; Mohan and Kanny 2015; Pothan and Thomas 2003). The difference is attributed to the gauge length, diameter of fibre, and the speed of deformation. Mohan and Kanny (2015) reported tensile strength of 602 MPa, modulus of 17 GPa and elongation at break of 4.3% for untreated banana fibre. These values increased to 713 MPa, 22 GPa, and 3.5% respectively when treated with NaOH.

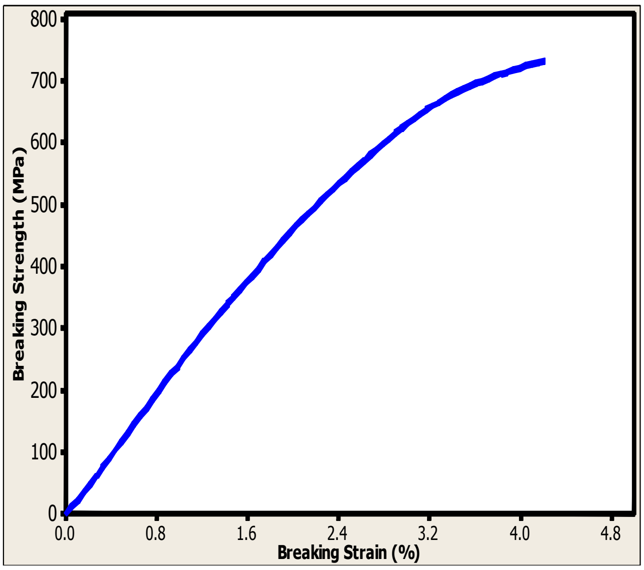

Fig. 1 Stress strain curves of banana fibre of length 100µm, diameter 100 µm and tested at a speed of 100 mm/min.

The mechanical properties of plant fibres depend among other factors on the source of fibre, processing techniques, the variety of fibre, the state as at the time of harvest, and most importantly the internal structure. The results of the present research will be interpreted in terms of the difference in structure of the fibre. It is well known that plant fibres have both non-crystalline and crystalline constituents. When a fibre is subjected to tension, both the crystalline and non-crystalline parts of the fibre undergo deformation (Young and Eichhorn, 2007). For spiral-like structures either the non-crystalline and micro-fibrils regions may elongate, or the micro-fibrils only may simply uncoil. These two mechanisms operate in the initial stage of the deformation thus contributing to the modulus of the fibre. At this stage of deformation referred to "initial modulus region" the fibre displays high resistance to deformation. The high resistance to stretch is owed to the meddling among the movements of adjoining molecular chains as well as inter-molecular ancillary bonding between the chains.

The degree of fibre resistance to deformation at the low strain region is known as initial modulus of fibre. As stated earlier both the crystalline and non-crystalline regions will deform on application of load, this load is shared between the two components as in composite materials. The effective modulus of fibre is given in terms of the two components as shown in equation 1 (Mclaughlin and Tait, 1980).

$$E_f = W_c E_c COS^2\theta + W_{nc} E_{nc} \quad (1)$$

Where, Ec, Enc, are the modulus of the crystalline and non-crystalline regions respectively and Wc, Wnc are the weight fractions of crystalline and non-crystalline regions. θ is the helix angle of fibre and is as 12 ± 1^0 or 11 ± 2^0 depending on the diameter of fibre (Kulkarn *et al.,* 1983). For a plant fibre, Ec, Enc, are assumed to be 45 and 3 GPa respectively (Mclaughlin and Tait, 1980), the weight fractions of Wc and Wnc for a banana fibre is 0.65 and 0.35 respectively (Kulkarni *et al.,* 1983). The effective modulus using the above equation at a helix angle of 12^o is 29.03GPa. This value is comparable with 24.64GPa obtained in this research

3.2 Effect of Gauge Length

To determine the effect of gauge length on the properties, banana fibres of 100µm diameter were tested at a strain rate of 100 mm/min with gauge lengths of 20 to 200µm. Table 1is the mechanical properties (standard deviations in brackets) at different gauge lengths and presented in Fig. 2. From the table the breaking strength and strain decrease with increase in gauge length

Table-1 Mechanical properties of banana fibres at different gauge lengths. Diameter = 100 µm, speed of deformation =100 mm/min

GL (µm)	BS (MPa)	% BST	YM (GPa)
20	930.73(160.54)	6.74(1.24)	19.12(3.29)
40	863.65(130.65)	6.02(1.11)	19.81(4.59)
60	797.43(106.65)	5.12(1.18)	21.54(4.35)
80	754.65(156.63)	4.99(1.24)	22.26(4.37)
100	731.16(110.24)	4.21(1.23)	24.64(4.37)
120	701.54(145.22)	3.41(0.76)	26.85(4.41)
140	647.98(121.93)	3.02(0.88)	27.84(2.52)
160	583.54(134.65)	2.55(0.98)	31.66(4.93)
180	542.42(125.87)	2.41(1.02)	35.56(4.47)
200	504.85(156.23)	1.83(0.54)	38.16(3.69)

The gradual decrease in tensile strength is an indication of the presence of strength limiting defects (Zhu *et al.,* 2012; Lim *et al.,* 2011). Some of these defects include voids, cracks, and minor cuts at the edges of fibres. The percentage decrease as gauge length increases is between 3.11 and 9.95 % with an average of 6.55%. The lower percentage value at gauge length between 60 and 80 µm is an indication of fewlimiting defects. The percentage decrease in strain as gauge length increases is between 2.54 and 24.06 % with an average of 13.26 %. From Fig. 2 the Young Modulus increases as the gauge length increases. The increase is between 3.34 and 13.72 % with an average of 8.04 %. Linear relationships between breaking strength (σ), percentage breaking strain, Young modulus of the fibre and gauge length$(l)$are given in equations 2-4 respectively.

$$\sigma = 955.82 - 2.273l \quad (2)$$

with correlation coefficient R^2 = 0.9893

$$\varepsilon = 6.99 - 0.027l \quad (3)$$

with correlation coefficient R^2 = 0.9889

$$E = 15.04 - 0.106l \quad (4)$$
with correlation coefficient $R^2 = 0.955$

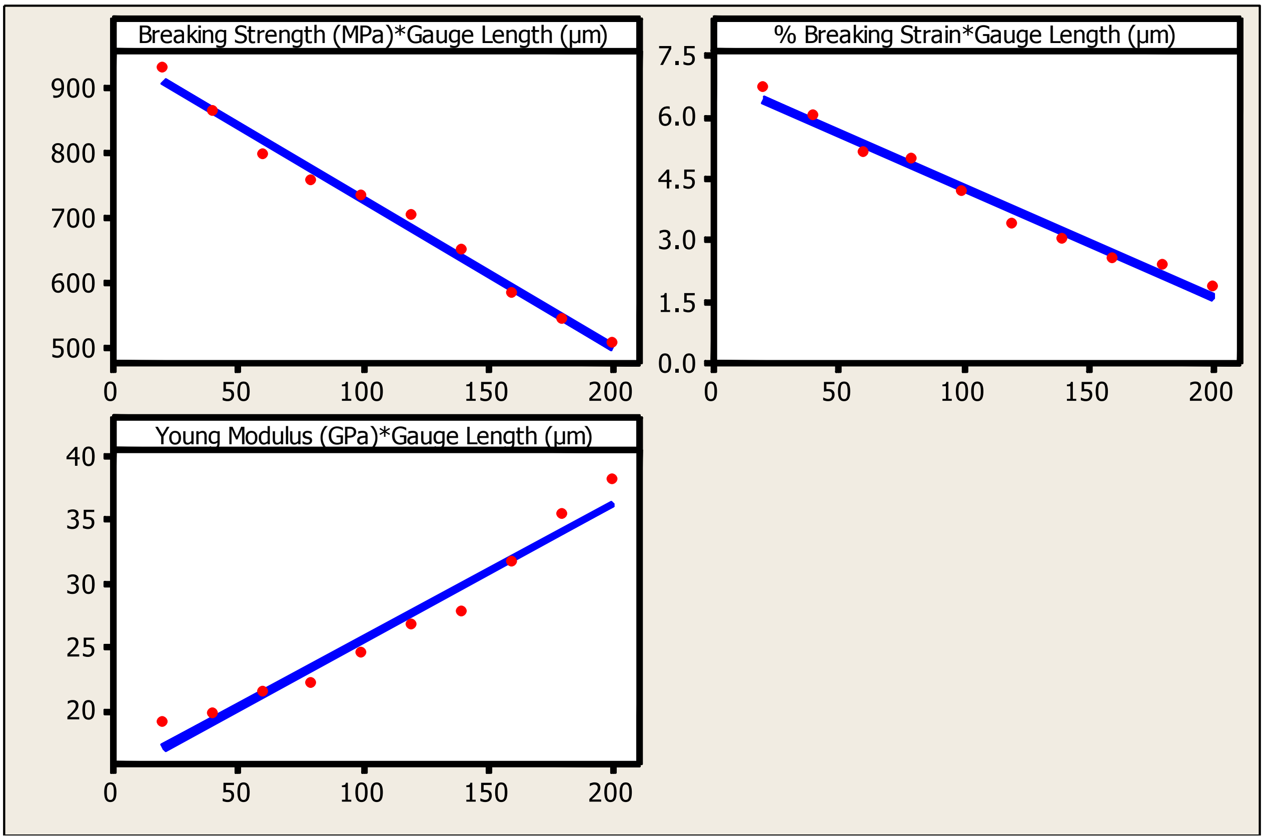

Fig. 2 Disparity in breaking strength, % breaking strain, and Young modulus with gauge length.

3.3 Effect of Speed of Deformation

Table 2 shows the breaking strength, breaking strains, and Young modulus of banana fibres diameter 100µm, gauge length 100µm deform at different strain rates (standard deviations in brackets). The values are presented in graphical forms in Fig. 3. From the table, the breaking strength and Young modulus of fibre increases as the speed of deformation increases from 5mm/min to 100 mm/min. The reverse is the case for the breaking strain. The increase between adjacent speeds is insignificant as the highest percentage increase is 0.71% for breaking strength and 9.26 % for Young modulus. The strain decreases with increase in speed deformation. The highest percentage decrease is 5.61%. The result obtained here is a reverse of what was reported by Samrat *et al.,* (2008) and also different from the performance of coir fibres (Kulkarni *et al.,* 1981) which showed slight disparity in breaking strength when tested at different test speeds. With increased strain rate the fibre acts more of a stiffer elastic material, suggesting that the crystalline region of the fibre shares the major applied load resulting in high values breaking strength and modulus (Samrat *et al.,* 2008). Linear relationships between breaking strength (σ), percentage breaking strain, Young modulus of the fibre and gauge length(l) are given in Equations 5-7 respectively.

$$\sigma = 710.09 + 0.191l \quad (5)$$
with correlation coefficient $R^2 = 0.9408$

$$\varepsilon = 5.86 - 0.016l \quad (6)$$
with correlation coefficient $R^2 = 0.9503$

$$E = 15.66 + 0.076l \quad (7)$$
with correlation coefficient $R^2 = 0.9153$

Table- 2 Mechanical properties of banana fibres at different speed of deformation, Diameter = 100 μm, Gauge length =100μm

SoD	BS (MPa)	% BST	YM (GPa)
5	710.45(104.46)	5.73(1.32)	16.63(2.28)
10	712.99(211.21)	5.66(1.45)	16.89(1.86)
20	715.84(115.48)	5.35(0.98)	17.94(2.51)
30	716.18(161.43)	5.53(1.12)	17.37(2.08)
40	717.27(127.82)	5.22(1.16)	18.45(3.58)
50	719.36(185.43)	5.29(1.02)	18.22(2.46)
60	718.45(138.23)	4.88(1.2)	19.75(1.99)
70	721.54(122.32)	4.75(0.87)	20.32(2.25)
80	726.64(123.54)	4.45(1.22)	21.92(1.98)
90	727.73(126.22)	4.33(1.18)	22.55(2.36)
100	731.16(110.24)	4.22(1.23)	24.64(4.37)

SoD =Speed of Deformation, BS=Breaking Strength, BST= Breaking Strain, YM=Young Modulus

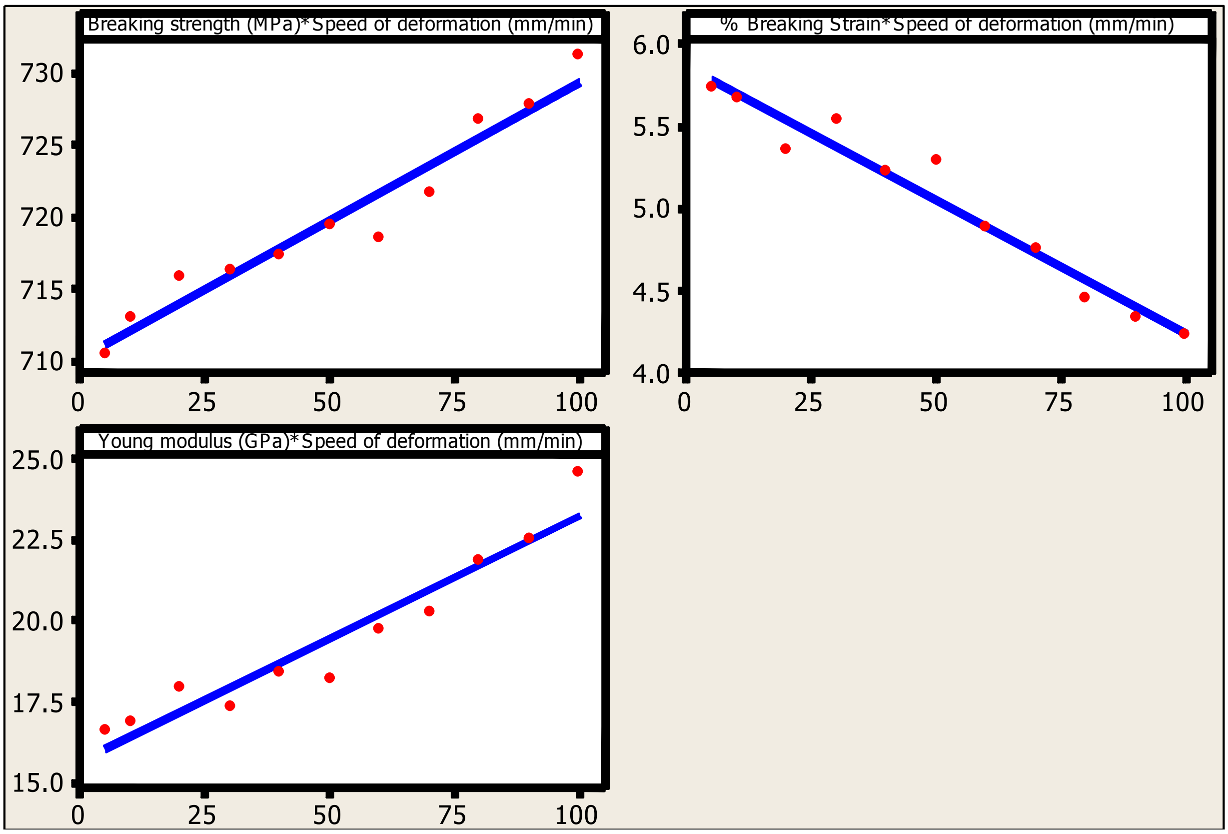

Fig. 3 Disparity in breaking strength, % breaking strain, and Young modulus with Speed of deformation

3.4 Effect of Diameter

Table 3 shows the breaking strength, breaking strains, and Young modulus of banana fibre gauge length 100µm, strain rate 100 mm/min deform at different diameters (standard deviations in brackets) and presented in Fig. 4. From the table there is a decrease in breaking strength and Young modulus as diameter decreases. The reverse is the case for the breaking strain. Notwithstanding, the decrease in breaking strength is not appreciable within the 10 and 100 µm diameters range investigated. The maximum percentage change of 0.86 occurred between 70 and 80 µm diameter. When compared with breaking strength, the decrease in Young modulus is appreciable. The percentage change is between 0.81 and 12.37 with one large value of 22.90 which may be attributed to experimental error. A reverse pattern of increase is observed for the breaking strain.

Breaking strength and strain are predominantly dependent on gauge length and the number of defects in the fibre (Mohan and Kanny, 2015). The strength of fibres equally increases with increasing number of strength rendering cells and decreases with increase in micro-fibril angle (Kulkarn *et al.*, 1983). Without prejudice to the absence of SEM images, none appreciable change in mechanical properties with fibre diameter could be attributed to lack of substantial variation in the micro-fibril angle, and fraction of strength rendering cells in the fibres.

Table-3 Mechanical properties of banana fibres at different diameter. gauge length = 100 µm, speed of deformation =100 mm/min

DoBF	BS (MPa)	% BST	YM (GPa)
10	758.27(124.76)	2.21(1.13)	45.97(6.21)
20	757.59(195.23)	2.34(1.03)	43.42(7.73)
30	755.72(187.24)	2.62(0.99)	38.64(5.65)
40	750.52(145.32)	2.72(0.86)	37.09(5.89)
50	745.43(143.24)	3.31(1.12)	30.18(4.69)
60	742.46(145.66)	3.52(1.15)	28.29(5.13)
70	740.72(127.34)	3.64(0.92)	27.29(4.42)
80	734.43(142.32)	3.73(1.13)	26.39(3.66)
90	730.74(142.45)	4.13(1.02)	24.44(3.46)
100	731.16(110.24)	4.21(1.23)	24.64(4.37)

DoBF = Diameter of Banana Fibre, BS=Breaking Strength, BST= Breaking Strain, YM= Young Modulus

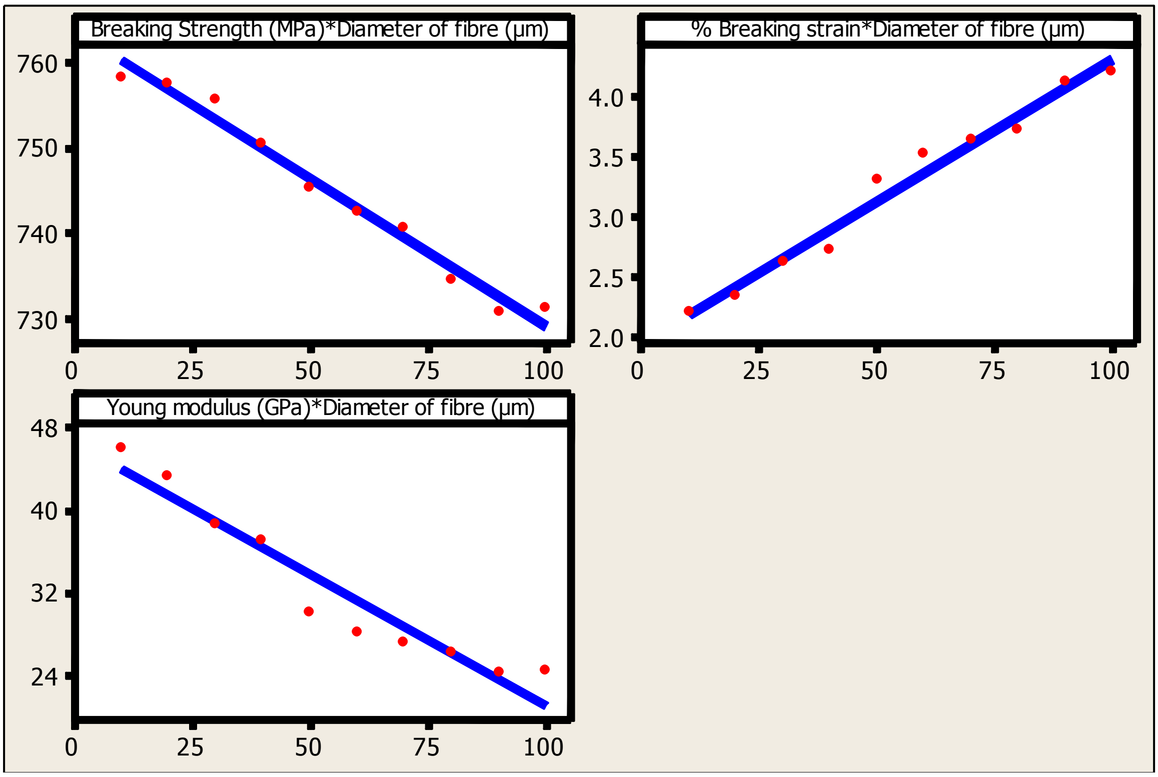

Fig. 4 Disparity in breaking strength, % breaking strain, and Young modulus with change in diameter

Table 4 is the mechanical properties of banana fibre as reported in literature. From the table it is clear that there is a variation of mechanical properties of banana fibre. As stated earlier the variation is attributed to source of fibre, processing techniques, the variety of fibre, the state as at the time of harvest, and most importantly the internal structure which as has to do with percentage weight of crystalline and amorphous constituents. Higher crystalline will result in high initial modulus and less strain.

Table-4 Mechanical properties of Banana fibre from literature

D (μm)	GL (mm)	BS (MPa)	BST (%)	YM (GPa)	SPD mm/min	Ref
-	20	500	7	12	10	Joseph *et al.* (2002)
205	30	550	5-6	20	1	Idicula *et al.* (2005)
50	30	779	2	32	-	Pothan and Thomas (2003)
100	30	711	3	30	-	Pothan and Thomas (2003)
150	30	773	3	29	-	Pothan and Thomas (2003)
200	30	789	3	27	-	Pothan and Thomas (2003)
250	30	766	3	29	-	Pothan and Thomas (2003)
-	-	99	-	7.0	0.5	Jordan and Chester (2017)
125-250	-	500-600	1-3.5	29-32	-	Biswal *et al.* (2011)
12-30	0.4-0.9	529-914	5-6	27-32	-	Gurunathan *et al.* (2015)
20	6	400–980	3-10	12	-	Chauhan *et al.* (2019)

CONCLUSION

The stress-strain curve for banana fibre is characterized by a proportional straight line portion where the slope which is the modulus is taken, followed by a very small curvature indicating uneven increase in strain with stress until the banana fibre breaks. The value of the experimentally observed Young modulus, breaking strength, and percentage breaking strain are in the range 24.64 to 43.43 GPa, 731.16 to 757.59 MPa and 2.34 to 4.21%, respectively, for fibres in the 10 to 100 μm diameter range. The breaking strength of banana fibre increases from 710.45 to 731.16 MPa with an increase in the speed of deformation from 5 mm/min to 100 mm/min. Within the same range of speed deformation, the Young modulus increases from 16.63 to 24.64 GPa while percentage strain at break decrease from 5.73 to 4.22 %. An increase in breaking strength is observed with decrease in gauge length. The same pattern is observed for percentage breaking strain, while the Young modulus increase as gauge length increases. Within the test range of 20 to 200 μm gauge length, there is a significant change in mechanical properties. In conclusion better mechanical properties can be achieved at low gauge length, low diameter and high speed of deformation.

CONFLICT OF INTEREST

The research work is original and there is no conflict of interest

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