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Original Research Article

Properties of Coir Fibre at Different Diameter, Gauge Length and Strain Rate

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ABSTRACT

Mechanical properties of coir fibre were investigated using stress-strain curves. Properties such as initial tensile modulus, breaking strength, and strain at break were evaluated as a function of fibre diameter, gauge length, and speed of deformation. The breaking strength and breaking strain decreased with increasing gauge length. Breaking strength and strain were within the range of 271 and 108 MPa, and within 120 and 29% respectively. The reverse was the case for Young's modulus which increased from 0.72 to 1.17 GPa as gauge length increased. Breaking strength and breaking strain of coir fibres increased as the speed of deformation increased from 50 mm/min to 200 mm/min and 50 mm/min to 250 mm/min respectively. At 250 mm/min, there was a drop in strength. The increase between adjacent speeds was insignificant. The highest percentage increase was 4.5% for breaking strength and 9.8% strain at 100 mm/min but suddenly dropped to an average of 3.88% for the rest of the speeds. The reverse was the case for the Young's modulus. It decreased with increase in speed of deformation. A maximum decrease of 1.45% was observed between 100 and 150 mm/min and between 200 and 250 mm/min. There was a significant change in mechanical properties within 0.2- and 0.5-mm diameters range investigated. Both tensile strength and moduli decreased as diameter increased. The reverse was the case for the strain. The percentage change, increased from 3.8% at 0.25 mm to 26.8% at 0.5 mm diameter for the strength.

1. INTRODUCTION

The use of fibres with high content of lignocellulose as reinforcements has been on the increase. The major reason is to replace synthetic fibres in the formulation of composite materials. The application of these reinforced composite cut across the packaging industries (Le Digabel and Averous, 2006; Kyrikou and

Briassoulis, 2007), automobiles industries (Wambua *et al.,* 2003) and the building sector (Khedari *et al.,* 2003). Other reasons for the interest include low density, abundance in nature, non-toxic materials, biodegradability, less abrasiveness to processing equipment, low cost and good mechanical properties (Khedari *et al.,* 2003; Facca *et al.,* 2006). In addition to the above advantages, ecological worries mainly from the automobile industries due to stringent enforcement of European laws, is also a source of concern (Satyanarayana *et al.,* 2005).

Fibres whose content are mostly cellulose, hemicellulose and lignin are extensively used as a reinforcement to produce bio-composite (Li *et al.,* 2007; Silva, et al., 2008; Saba *et al.,* 2017; Sahu *et al.,* 2017). The percentage composition of the fibres used for reinforcement depends among others on the plant and other agricultural conditions such as age, source and time of harvest. Natural fibres are composed of mainly cellulose, hemicellulose and lignin at different percentage (Muensri *et al.,* 2011; Mathura and Cree 2016). The percentage composition of coir fibre will affect the mechanical properties (Muensri *et al.,* 2011). The report of the composition of coir fibre shows a variation in cellulose content (39–53%), but close range of lignin content (38–41%). Notwithstanding, these values are different from those from other plant fibres. Cellulose and hemicellulose are the crystalline regions of the fibre while lignin is a three-dimensional amorphous or non-crystalline region. For a plant fibre the moduli of the crystalline and amorphous regions are 45 and 3 GPa respectively (Mclaughlin and Tait, 1980). The average weight fraction of lignin in coir fibre is estimated to be 0.46 % (Khedari *et al.,* 2004; Muensri *et al.,* 2011)

Coir fibres are extracted from either immature or mature fruits of the coconut tree. As stated earlier, they are lignocellulosic fibres gotten from the mesocarp of the coconut fruit. Coir fibre is one of the least expensive fibres. It is not brittle, non-toxic and is easily amenable to chemical treatment; but the waste from its disposal can cause environmental problems (Chowdhury and Fatema, 2016). Processing and availability of these fibres, along with narrative of their usage have been on the increase especially in countries where the yearly tonnage is high (Ramamoorthy *et al.,* 2015; Jayavani, *et al.,* 2016). Studies on the mechanical properties have revealed disparity of strength as a function of area of harvest, gauge length, diameter of fibre and strain rate (Kulkarni *et al.,* 1981; Tomczak et al., 2007; Muensri *et al.,* 2011; Mathura and Cree 2016). Surface treatment of coir fibre has equally shown different results (Prasad *et al.,* 1983; Pavithran *et al.,* 1983; Varma *et al.,* 1984).

Other factors that can lead to disparity in mechanical properties include plant species, type of soil, and climate of region, time of harvest and husk extraction process (Khalil *et al.,* 2015). Worldwide, studies on the mechanical properties of coir fibres have been on the increase. However, there is limited information on material characterization of Nigerian coir fibres in the literature. The mechanical properties assessed for single coir fibres from Brazil indicate that the Young's modulus, tensile strength, and strain at break were in the range of 1.3-2.7 GPa, 118-143 MPa, and 25-60%, respectively (Tomczak *et al.,* 2007). Coir fibres from India had Young's modulus, tensile strength, and strain at break to be 4–5 GPa, 112–161 MPa, and 18–43%, respectively (Kulkarni *et al.,* 1981). Another report indicates that Vietnamese coir fibres attained mechanical properties of Young's modulus, tensile strength, and strain at break in the range of 4-6 GPa, 186–343 MPa, and 26–64%, respectively (Defoirdt *et al.,* 2010). In the light of the above, the objective of this research was to appraise the mechanical properties of Nigerian coir fibres as a function of fibre diameters, gauge lengths and strain rates in comparison with results of those from other countries.

2. MATERIALS AND METHODS

Coir fibres used in this study were obtained from Marian market, a local market in Calabar, Nigeria. Fibres of different diameters ranging from 0.2 to 0.5 mm were sorted out using an optical microscope. For evaluating tensile properties, fibres were mounted on a piece of cardboard with a central window using cello tape (Figure 1) and pulled in an Instron testing machine. Fibres of 0.2 to 0.5 mm in diameter and 0.04 m long were tested at 200 mm/min test speed. Fibres of 0.4 mm in diameter but 0.01 to 0.1 m long were tested at a

test speed of 200 mm/min, and fibres of 0.4 mm in diameter and 0.04 m long were tested at test speeds of between 50 and 250 mm/min. For each set of tests, between 50 and 60 fibres were tested. All tests were carried out at 50% (relative humidity) at room temperature.
The crystallinity of cellulose coir fibres was appraised with Philips X'Pert PRO diffractometer with a Cu-Kα radiation (λ=1.54 Å). A current and voltage of 20 mA and 40 KV respectively were used, at a scanning rate of 2°/min. XRD spectra were collected over a 2θ angle of 5-80°. The crystallinity index (CI) of the coir fibres was estimated from the XRD spectrum based on Equation 1 (Sarikanat et al. 2014; Mulinari et al., 2009, Mathura and Cree 2016).

$$\text{CI } (\%) = [\{I_{002} - I_{am}\}/I_{002}]\ x\ 100 \quad (1)$$

Where I_{002} is the maximum peak intensity of the diffraction (002) at 2θ≈22-22.7° representing the crystalline region and. I_{am} is the minimum intensity at the amorphous region at 2θ ≈18-18.5°.

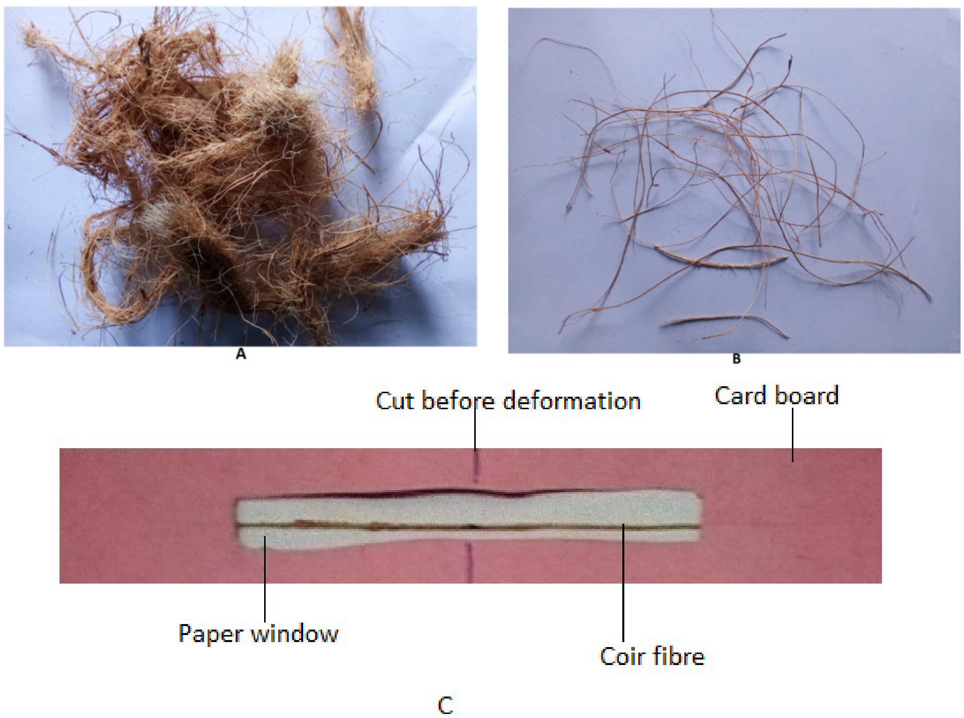

Figure 1: Coir fibre images (A) typical coir fibre section showing surface profile, (B) single fibre of different diameters before it was mounted on card board and (C) Illustration of image of tabs for mounting coir fibre into tensile grips

3. RESULTS AND DISCUSSION

3.1. Stress-Strain Curve of Coir Fibre

Figure 2 shows a typical stress strain curve of a single coir fibre of length 400 mm, diameter 0.4 mm, tested at a speed of 200 mm/min. The curve is characterized by a proportional straight line portion (where the slope is taken as the initial modulus) up to the yield strength of the material followed by a non-linear transition from elastic to plastic behaviour. From the start of the plastic deformation, the slope fell with a steady linear increase up to the failure point. The curve profile obtained was similar to other coir fibre tensile curves reported (Kulkarni *et al.,* 1981; Varma *et al.,* 1984; Tomczak *et al.,* 2007; Defoirdt *et al.,* 2010; Mathura and Cree 2016). Properties of fibres from plants depend on, among other things internal structure, the age and the source. Since the coir fibres used in this research are from one source and from the same coconut fruit, all the properties reported here are discussed in terms of the structure of coir fibre.

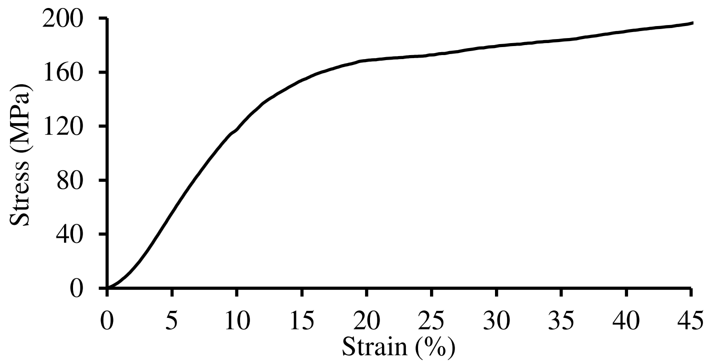

Figure 2: Stress strain curves of coir fibre of length 0.04 m, diameter 0.4 mm and tested at a speed of 200 mm/min.

Coir fibre is a multi-cellular plant fibre; the properties can be discussed via the cumulative effect of arrays of individual cells in the fibre subjected to tensile load. Plant fibres contain long chain molecules consisting of crystalline and amorphous (non-crystalline) regions (John and Thomas 2008). Helical spiral crystals surround the non-crystalline regions. Kinloch and Young (1995) have reported the mechanisms following the deformation of a material with the above structure subjected to tensile loading. Coir with a spiral-like structure may deform by the elongation of micro-fibrils alongside the amorphous regions, alternatively the uncoiling of the micro-fibrils with twisting and bending. It is not clear among the two which is dominant but both mechanisms are involved during deformation (Young and Eichhorn, 2007).

3.2. Effect of Gauge Length

To determine the effect of gauge length on the properties, coir fibres of different gauge lengths (0.01-0.1 m), diameter 0.4 mm, and speed of deformation of 200 mm/min were tested. Table 1 shows the mechanical properties with standard deviations. Figure 3 shows the tensile strength at failure as a function of gauge length. From the table and figure, breaking strength and strain decrease with increase in gauge length. There is a high standard deviation. The high standard deviations are typical of natural plant fibres. During removal or processing of the husk from the coconut fruit, surface flaws may occur.

Defects at the cellulose micro-fibril level are difficult to control. These large disparities in mechanical properties could be attributed to the flaws at cellulose micro-fibril level. As the gauge length increases, defects such as void, impurities minor cuts are on the increases there decreasing the strength. The reverse is the case at lower gauge length. It can be seen that both the tensile strength and strain at break decrease with increasing test length, while the Young's modulus increases with gauge length. A regression analysis between the tensile strength and gauge length shows a linear relationship given by Equation 2.

$$\sigma = 277.93 - 1796l \tag{2}$$

The correlation coefficient is $R^2 = 0.978$. The weak-link density calculated from the slope of this straight line is 1421.75 MPa, which is comparable with the earlier reported value of 1106 MPa (Tomczak *et al.,* 2007).

Table 1: Mechanical properties of coir fibres at different gauge lengths (Diameter = 0.40 mm, speed of deformation =200 mm/min)

GL(m)	% BST	YM (GPa)
0.01	67±13	0.71±0.41
0.02	54±11	1.17±0.29
0.03	46±9	1.31±0.21
0.04	33±8	1.37±0.31
0.05	30±7	1.36±0.44
0.06	28±6	1.42±0.49
0.07	27±9	1.37±0.33
0.08	26±5	1.28±0.13
0.09	25±8	1.21±0.82
0.10	23±6	1.13±0.32

GL = gauge length, BST = breaking strain, YM= Young modulus

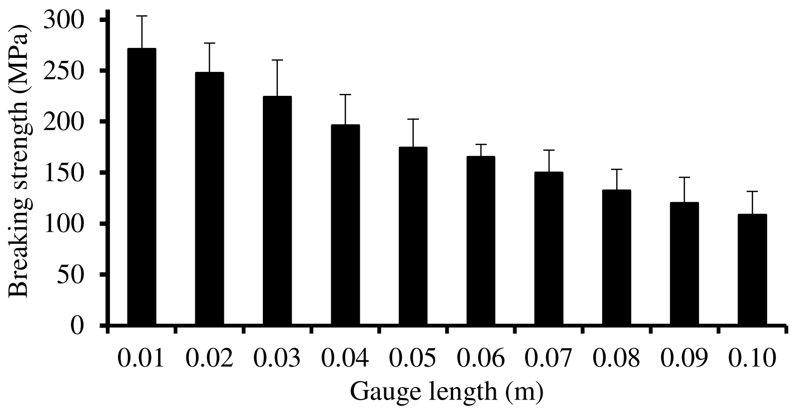

Figure 3: Variation of breaking strength with change in gauge length.

The coir fibre strengths for gauge lengths 10-100 mm ranged from 108-271 MPa. These values are in agreement with reported values in literature (Kulkarni *et al.,* 1981; Silva *et al.,* 2000; Tomczak *et al.,* 2007; Mathura and Cree, 2016). For instance, untreated coir fibres gauge length 20 mm and diameter 0.225 mm was deformed at a strain rate of 5 mm/min. An average tensile strength of 128±47 MPa was reported by Tomczak *et al.* (2007). When the gauge length was 25 mm, same diameter and strain rate, the tensile strength was 118±35. At a smaller gauge length of 5 mm a mean tensile strength of 142±70 MPa was reported. From the same source (Brazil), the report indicates that coir fibres with gauge length of 50 mm, average diameter 0.250–0.411 mm deformed at a strain rate of 5 mm/min had a tensile strength range of 59-91 MPa with a mean tensile strength of 76±15 MPa (Silva *et al.,* 2000). Also, coir fibres from Thailand with fibres diameter of 0.226-0.637 mm, test length 50 mm and strain rate 1 mm/min had a mean tensile strength, 123±34 MPa (Muensri *et al.,* 2011). The report of Mathura and Cree, (2016) was not different and results from their research showed that the tensile strengths decreased by 14% (from 139 to 120 MPa) as the gauge length increased from 20 mm to 50 mm at a diameter of 0.34 mm and strain rate of 20 mm/min. The differences in tensile strength could be attributed to fibre defects, diameter of fibre, rate of deformation, location of growth, coconut species, and age of the fibre.

From Table 1 the Young's modulus was observed to increase as the gauge length increased. The increase was gradual up to 0.06 m gauge length where it started decreasing. The maximum percentage increase between adjacent lengths was 65% between 0.01 and 0.02 m gauge length after which there is a sharp drop in percentage increase to 12%. The Young modulus ranged from 0.71 at 0.01 m gauge length to 1.13 GPa at

0.1 m gauge length. The maximum modulus was 1.42 GPa at 0.06 m gauge length. Mathura and Cree, (2016) reported a modulus of 1.74± 0.6 GPa and 2.31±0.49 GPa for gauge lengths of 20 and 50 mm respectively. A similar trend was reported by Tomczak *et al.* (2007). The modulus increased by 115% (from 1.27 to 2.73 GPa) when the gauge length was increased from 5 mm to 25 mm. The increase was attributed to larger amount of lignin in longer fibres, which may have contributed to a more rigid and stiffer fibre. Others reported modulus of 2.1±0.3 GPa, gauge length 50 mm (Silva *et al.,* 2000), 2.39±0.87 GPa, gauge length 20 mm (Silva *et al.,* 2000) and 2.29±0.47 GPa gauge length 50 mm (Muensri *et al.,* 2011). The increase in Young's modulus with increasing gauge length could equally be attributed to "multicellular structure and structural non-homogeneity of the fibres" (Mukherjee and Satyanarayana, 1984). Moreover, the longer the fibre's length, the higher its lignin content, which will invariably increase its resistance to stress applied resulting in higher stiffness or modulus (Tomczak *et al.,* 2007).

3.3. Effect of Speed of Deformation

Table 2 shows the breaking strains, and Young's modulus of coir fibres diameter 0.40 mm, test length 0.04 m, deformed at different strain rates (50, 100, 150, 200 and 250 mm/min). Graphical view of the breaking strength is presented in Figure 4. From the Table and Figure 4, the breaking strength and Young's modulus increased as the speed of deformation increased from 50 mm/min to 250 mm/min. The reverse was the case for the strain. It can be seen that the tensile strength increases from 175 MPa to 192 MPa. There were no significant changes in the strain at failure especially at higher strain rate (100-250 mm/min). The same pattern of insignificant change in Young's modulus was observed. While the strain is insignificantly decreasing, the Young modulus was insignificantly increasing. These observations are similar to those reported in literature (Kulkarni *et al.,* 1981; Tomczak *et al.,* 2007; Mathura and Cree, 2016).

Table 2: Mechanical properties of coir fibres at different speed of deformation (diameter =0.40 mm, gauge length =0.04 m)

SoD (mm/min)	% BST	YM (GPa)
50	36±4	1.34±0.24
100	35± 6	1.35±0.11
150	34±5	1.36±0.29
200	33±8	1.37±0.31
250	33±7	1.38±0.15

SoD = speed of deformation, BST= breaking strain, YM=Young's modulus

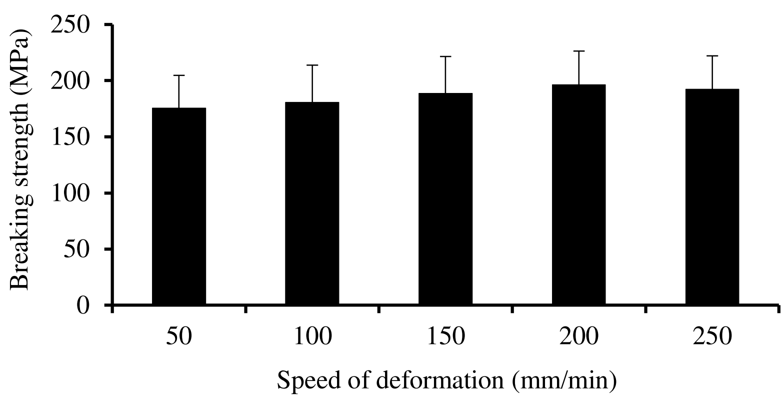

Figure 4: Variation of breaking strength with change in speed of deformation

The increase in tensile strength and insignificant change in modulus and strain at break with increasing strain rate can be elucidated in terms of the visco-elastic model of cellulose fibres (Kulkarni *et al.,* 1981; Mathura and Cree, 2016). When lignocellulosic fibres are subjected to mechanical loading, they behave as elastic body at higher speeds, with the crystalline region of the fibre sharing the greater part of the applied load, resulting into increased tensile strength and Young's modulus. At lower speeds, the fibre acts like a viscous liquid resulting to amorphous region of fibre taking greater part of the load, hence low modulus (Kulkarni *et al.,* 1981; Tomczak *et al.,* 2007; Samrat *et al.,* 2008).

3.4. Effect of Diameter

Table 3 shows the breaking strain, and Young modulus of coir fibre with gauge length 40 mm, strain rate 200 mm/min deform at diameters range from 0.2 mm to 0.5 mm while the graphical presentation of the breaking strength is presented in Figure 5. From the Figure and Table, there was a decrease in breaking strength and Young's modulus as diameter decreases. The reverse was the case for the breaking strain. This failure pattern is similar to the results obtained in similar investigations (Silva *et al.,* 2000; Tomczak *et al.,* 2007; Muensri *et al.,* 2011; Mathura and Cree, 2016). Tomczak *et al.* (2007) tested fibre of length 20 mm at strain rate of 5 mm/min, diameter range of 0.04 mm to 0.40 mm. Mathura and Cree, (2016) used diameter range of 0.16 mm to 0.56 mm at test speed of 20 mm/min. For the two gauge lengths tested, the tensile strengths decreased as the fibre diameter increased. In their report Kulkami *et al.* (1981) observed an increase in tensile strength for diameters of 0.1 mm to 0.2 mm, and between 0.2 mm and 0.45 mm diameters, tensile strength was constant.

Table 3: Mechanical properties of coir fibres at different diameter (Gauge length = 0.04 m, speed of deformation =200 mm/min)

DoCF (mm)	% BST	YM (GPa)
0.20	28±5	2.11±0.37
0.25	29±4	1.97±0.65
0.30	30±2	1.63±0.27
0.35	32±4	1.45±0.47
0.40	33±8	1.37±0.31
0.45	38±8	1.15±0.53
0.50	41±8	1.03±0.28

DoCF = Diameter of coir fibre, BST= Breaking strain, YM= Young's modulus

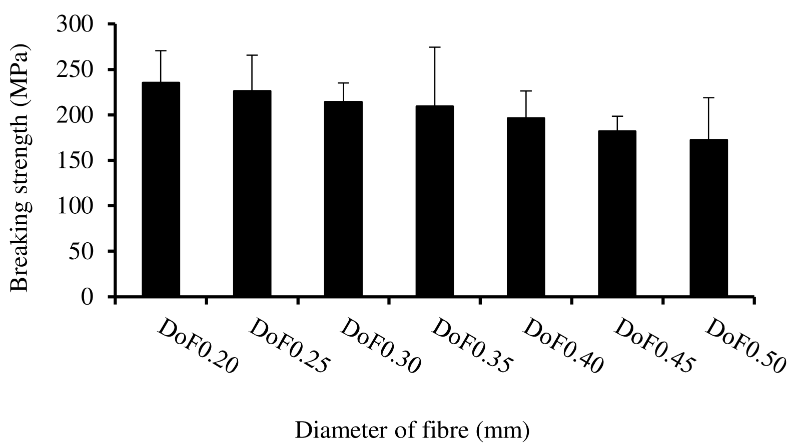

Figure 5: Variation of breaking strength with change in diameter

The percentage decrease in tensile strength between adjacent diameters in this research tends to increase as the diameter increases. The maximum decrease in breaking strength between adjacent diameters (0.20 to

0.25 mm or 0.25 to 0.30 mm) was 7.1 % while the maximum percentage decrease is 26.8 % (0.20 mm-0.50 mm). When compared with breaking strength, the percentage decrease in Young's modulus was appreciable. The percentage change between adjacent diameters is between 5.5 and 17.3%, while the maximum percentage decrease is 51.2 % (0.20 mm-0.50 mm). A decrease in tensile strength and modulus with increase in fibre diameter can be attributed to an increase in defects inherent in natural fibre materials especially during harvesting and processing (Mohan and Kanny, 2015). More importantly, the strength of fibres increases with increasing number of strength-rendering cells and decreases with increase in micro-fibril angle (Kulkarni *et al.,* 1983).

Table 4 shows the mechanical properties of coir fibre as reported in literature in comparison with those from this work. From the Table it is clear that there is a variation in mechanical properties of coir 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 crystallinity will result in high initial modulus and less strain. Micro-fibril angle also plays a dominant role in changes in mechanical properties.

Table 4: Mechanical properties of coir fibre from literature

D	GL	BS	BST	YM	SoD	Ref
0.16	20	≈178±24	NIL	NIL	20	Mathura and Cree, 2016
0.16	50	≈140±15	NIL	NIL	20	Mathura and Cree, 2016
0.34	20	139±19	50.35±7.19	1.74±0.60	20	Mathura and Cree, 2016
0.34	50	120±18	29.26±5.75	2.31±0.49	20	Mathura and Cree, 2016
0.225	20	128±47	29.9±12	2.3±0.7	5	Tomczak *et al.,* 2007
0.225	25	118±35	25±12	2.7±0.9	5	Tomczak *et al.,* 2007
0.25-0.41	50	59-91	29±5	2.1±0.3	20	Silva *et al.,* 2000
0.22-0.63	50	123±34	33.39±7.01	2.29±0.47	1	Muensri et al., 2011
0.25	20	265.98	60	NIL	250	Kulkami *et al.,*1981
0.25	50	169.02	36.94	5.83	250	Kulkami *et al.,*1981
0.40	20	247±29	70±11	1.17±0.29	200	This work

D =diameter (mm), GL = Gauge length (mm), BS=Breaking strength (MPa), BST = Breaking strain (%), YM=Young's modulus (GPa), SoD =Speed of deformation (mm/min)

3.5. X-Ray diffraction Analysis

The X-ray diffraction peaks of coir fibre are given in Figure 6. Two peaks are well defined in the Figure. The peaks are located at 2θ=15.7° and 2θ=22.6°. These peaks are attributed to cellulose I and IV (Mathura and Cree 2016; Abraham et al., 2013).

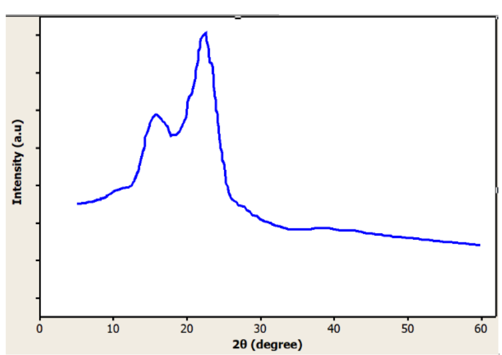

Figure 6: X-ray diffractogram of coir fibres

These peaks have been reported elsewhere (Varma et al., 1984; Abraham et al., 2013; Mathura and Cree 2016). The crystallinity index of the fibres was estimated using Equation 1 as reported by Sarikanat et al. (2014), Mulinari et al. (2009) and Mathura and Cree (2016). Based on the equation, the crystallinity index of coir fibres was found to be 54.4% compared to 57% (Tomczak et al. 2007), 44 % (Razera and Frollini, 2002) and 68% (Mulinari et al., 2011), 29% (Carvalho et al., 2010) and 24% (Rajini et al., 2013). The wide differences could be attributed to region of the fibre and age during harvest.

4. CONCLUSION

The stress-strain curve of coir fibre is characterized by a proportional straight line portion (where the slope is taken as the initial modulus) up to the yield strength of the material followed by a non-linear transition from elastic to plastic behaviour. From the start of the plastic deformation, the slope fell with a steady linear increase up to the failure point. The value of the experimentally observed Young's modulus, breaking strength, and percentage breaking strain are in the range 0.71 to 1.13 GPa, 271 to 108 MPa and 120 to 29 %, respectively, for fibres between the gauge length 0.01 to 0.1 m. The breaking strength of coir fibre increased from 175 to 192 MPa with an increase in the speed of deformation from 50 mm/min to 250 mm/min. Within the same range of speed deformation, the Young's modulus decreased from 1.39 to 1.35 GPa while percentage strain at break increased from 38 to 46 %. A decrease in breaking strength was observed with increase in diameter of fibre. The same pattern was observed for Young's modulus, while the percentage breaking strain increase as fibre diameter increases.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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