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Mechanical properties of Napier grass fibre/polyester composites



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ABSTRACT

The mechanical properties of Napier grass fibre-reinforced composites were characterised. Napier grass fibres were extracted through water retting process. The effect of alkali-treatment on the tensile properties and morphology of the fibres was investigated. The fibres were alkali-treated using NaOH solutions of various concentrations and subjected to single fibre testing. The morphology of the fibres was observed using scanning electron microscopy. The 10% alkali-treated Napier grass fibres yielded the highest strength. To fabricate the polymer composites, Napier grass fibre and polyester resin were used as the reinforcing material and polymer matrix, respectively. The tensile and flexural properties of the composites were studied. In general, up to a certain threshold value, the tensile and flexural strengths of the composites increased as the fibre volume fractions increased, following which, there was a reduction in strength. The maximum tensile and flexural strengths of the composites were obtained at 25% fibre loading.

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1. Introduction

Artificial polymer composite materials are broadly utilised in many industrial areas to accommodate the light-weight and high-strength property requirements for certain applications. However, with the current growing use of synthetic fibre materials, environmental issues such as waste disposal, waste removal services, and pollution from incineration are becoming more important [1]. The utilisation of natural fibres as substitutes for traditional synthetic fibres, such as glass and carbon, has recently received increased attention to overcome these environmental issues [2]. However, there are still concerns regarding the use of natural fibres in reinforced composites, such as poor interfacial bonding between the cellulose fibres and the thermoplastic matrix, restricted thermal properties of the composites, and poor fibre partition and dispersion within the composites.

Elzubair and K.L. Pickering reported that the low melting point of natural fibres and the poor moisture resistance between the polymer matrix and the natural fibre often restrict their potential use as reinforcing agents [3,4]. A.K. Bledzki and J. Gassan found that the mechanical and physical properties of natural fibres are extre-

mely variable and can be influenced by certain factors, such as the ligno-cellulosic structure, climate conditions, and preparation methods [5]. With regard to engineering applications, there are serious concerns regarding the compatibility of the natural fibre and polymer matrix owing to a lack of interfacial bonding within the matrix [6,7].

H.L. Bos et al. studied the compressive properties of flax fibres. In that paper the compressive properties of composites with different natural fibres was measured and compared with their tensile properties [8]. Joseph et al. and De Rosa et al. both studied long and short sisal fibre-reinforced composites. Longitudinally and randomly orientated fibre composites were studied. They demonstrated that continuous fibres can be used for applications requiring high strength and stiffness in a single direction. However, randomly oriented short fibres offer lower strength but improve the isotropic properties of the composite [9,10]. R. Kumar examined the potential of banana fibre-reinforced composites utilising soy protein resin as a binding material, and suggested that the mechanical properties of the composites were highly dependent on the volume fraction of the fibre [11]. S. Ochi et al. investigated the mechanical properties of kenaf fibres and demonstrated that the tensile and flexural strength of kenaf reinforced PLA composites, increase linearly with fibre contents up to 50% [12].

X. Li et al. demonstrated that the structural stability and bonding properties of natural fibre-reinforced composites were improved by applying a chemical treatment to the fibres [13].

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The tensile strength of banana plant fibres was investigated by A.V. Kiruthika and K. Veluraja. The authors compared the results with those of non-treated fibres and fibres treated with various chemical compositions [14]. K.G Satyanarayana et al. discussed the physical and chemical properties of various natural fibre composites with epoxy resin matrices [15].

Using alkaline treatments and other numerous chemical modifications were performed to improve the bonding between the natural fibres and matrix [16,17]. F.E. El-Abbasi obtained results stated that the alkali treatment increases significantly the Young's modulus and tensile strength of the Alfa fibre reinforced polypropylene composites and reduces their loss during water ageing. [18]. K.M. M. Rao reported that the physical properties of natural fibres are primarily determined by their chemical and physical compositions, such as the fibre structure, cellulose content, cross-sectional shape and the density [19]. The characterization of flax fibre-reinforced composites has shown that the fibre arrangement and bonding within the polymer matrix are key factors to achieve high-performance composites [20,21]. A. Valadez reported that the adhesion characteristics of natural fibre surfaces were enhanced by the application of a chemical treatment [22]. H. Abral et al. reported the effects of moisture absorption for untreated and treated water hyacinth fibres. They observed that alkaline treatment did not significantly reduce the moisture absorption [23].

Currently, the utilisation of natural fibres as reinforcing materials in specific applications has great importance for composite engineering industries. Therefore, it is essential to continue research on natural fibre resources to enable simple and practical extraction that does not impair the properties of the fibres. The natural fibres must be thoroughly analysed to determine their physical, chemical, and tensile properties as well as their morphol-

ogy [24,25]. During the current study, a common natural fibre was extracted from an abundant, locally-available plant, Napier grass. Napier grass, scientifically known as '*Pennisetum purpureum*', is a newly-identified plant which forms robust bamboo-like clumps and is highly sustainable throughout Malaysia. These fibres were extracted using a simple manual water retting process before being subjected to an alkaline treatment. Subsequently, this study examined the fabrication of Napier grass fibre-reinforced polyester laminates and investigated their tensile and flexural properties. The obtained results were subsequently analysed and compared with other prevalent natural fibre-based composites.

2. Experimental procedure

2.1. Fibre materials

The Napier grass was harvested from a local farm near Bukit Kayu Hitam, Kedah, in northern Malaysia. These Napier grasses are easily grown, particularly in drier areas. The Napier grass fibres were extracted by using a conventional water retting process. Retting is a microbial procedure that separates the compound bonds that hold the stem together, and allows the bast fibres to detach from the woody centre. Water retting produces homogenous, high-quality fibres. The stems were immersed in water tanks, and their progress was monitored daily. Prior to retting, the Napier leaves were removed from the internodes of each stem. Subsequently, the stems were crushed with a mallet and immersed in a water tank filled with tap water for approximately three to four weeks, as shown in Fig. 1(a). Subsequently, the soaked Napier grasses were thoroughly cleaned and each fibre strand was

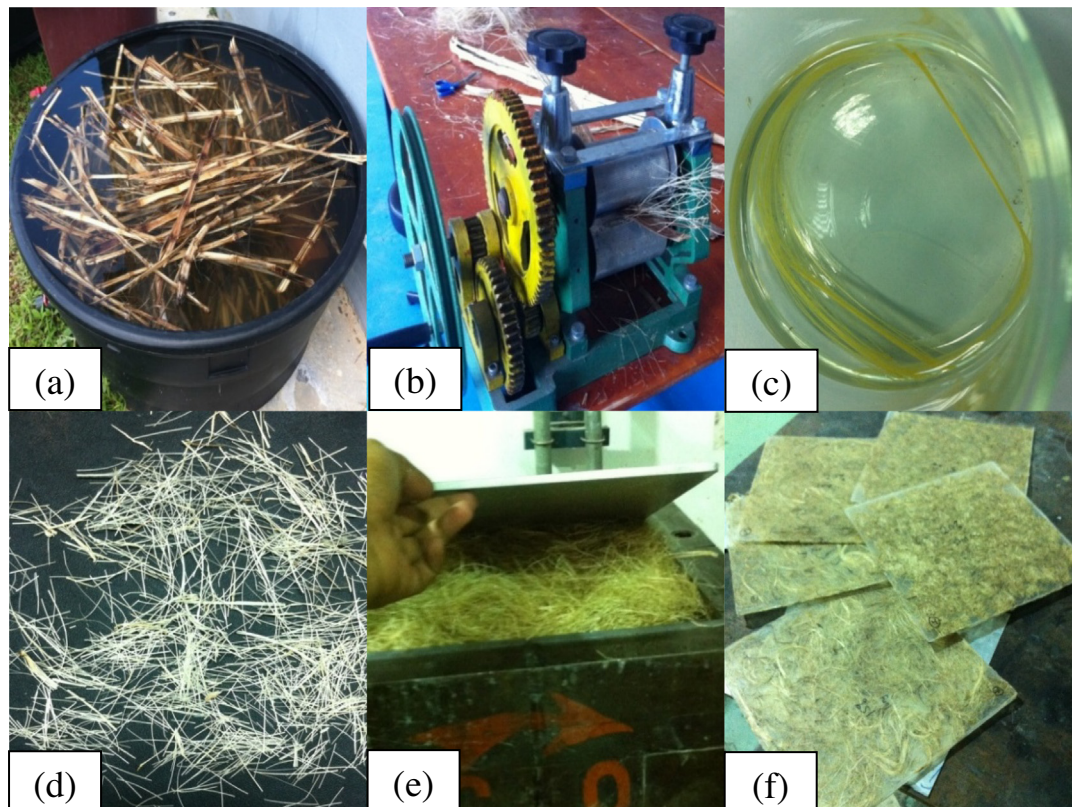


Fig. 1. (a) Soaked Napier grass fibres in tank, (b) roll-out machine for fibre extraction, (c) chemical treatment (NaOH) of Napier fibres, (d) short Napier grass fibres, (e) fabrication of Napier/polyester composites, (f) Napier/polyester composites with different fibre volume fractions.

extracted using a roll-out machine, as illustrated in Fig. 1(b). Finally, the extracted raw fibres were sun-dried for a few days to remove excess moisture.

2.2. Alkaline (NaOH) treatment

A sodium hydroxide (NaOH) solution was used to chemically treat the Napier grass fibres. The treatments were conducted using NaOH concentrations of 5, 10, 15, and 20%, and we investigated their effect on the immersed fibres. The ratio of Napier grass fibre to the soaking solution was maintained at 1:10. A treated sample is shown in Fig. 1(c).

2.3. Composite fabrication

The composite laminates were prepared at the Advanced Materials Research Composites (AMREC) facility at Kulim High Tech Park, Kedah, Malaysia. Prior to the laminating process, the extracted raw Napier grass fibres were oven dried at 50 °C for 30 min to remove excess moisture. To prepare the random short fibre-reinforced composites, the oven-dried Napier grass fibres were cut into lengths of 1–3 cm, as shown in Fig. 1(d). Polyester resin and methyl ethyl ketone peroxides (MEKP) were used and mixed at a weight ratio of 100:3. The Napier grass fibres were subsequently added to the mixture which was evenly mixed before being placed in a 5.0-ton hydraulic compression moulding machine, as shown in Fig. 1(e). The fibres and resins were compressed at 80 °C for 40 min and allowed to cure. The process was repeated for long Napier grass fibre with length ranging from 5 to 8 cm. The volume fraction percentages were determined according to ASTM D3171 standards. The Napier grass fibre/polyester

composite laminates were produced with fibre volume fractions of 10, 15, 20, 25, and 30%, as shown in Fig. 1(f).

2.4. Analysis

2.4.1. Digital scanning calorimetry (DSC)

During this investigation, 2.2 mg of Napier grass fibre was placed in a DSC diagnostic system. Using a heating rate of 10 °C/min, this diagnostic system was able to provide data up to a temperature of 350 °C. The glass transition temperature (T_g) and melting temperature (T_m) were obtained.

2.4.2. Thermo-gravimetric Analysis (TGA)

Thermo-gravimetric analysis (TGA) was conducted using 0.471 mg of untreated Napier grass fibre. Using a heating rate of 20 °C/min, the thermal properties of the fibres were observed at temperatures of 30–700 °C; the nitrogen gas flow was pre-set at 50 mL/min.

2.4.3. Tensile testing of a single fibre

The tensile properties of single Napier grass fibres were determined according to ASTM D3822-07 standards using an INSTRON micro-tester. The gauge length of each fibre was specified as 50 mm and a 2 kN load cell was used for the testing. The crosshead speed was pre-set at 1 mm/min and maintained throughout the testing. The test specimens were prepared according to the aforementioned standard, as shown in Fig. 2(a). Twenty samples were tested and the average tensile strength, tensile modulus, and elongation at failure/break were calculated. The fibre diameters were measured using a digital optical microscope and used to calculate the breaking tenacity, linear density, and tensile strength.

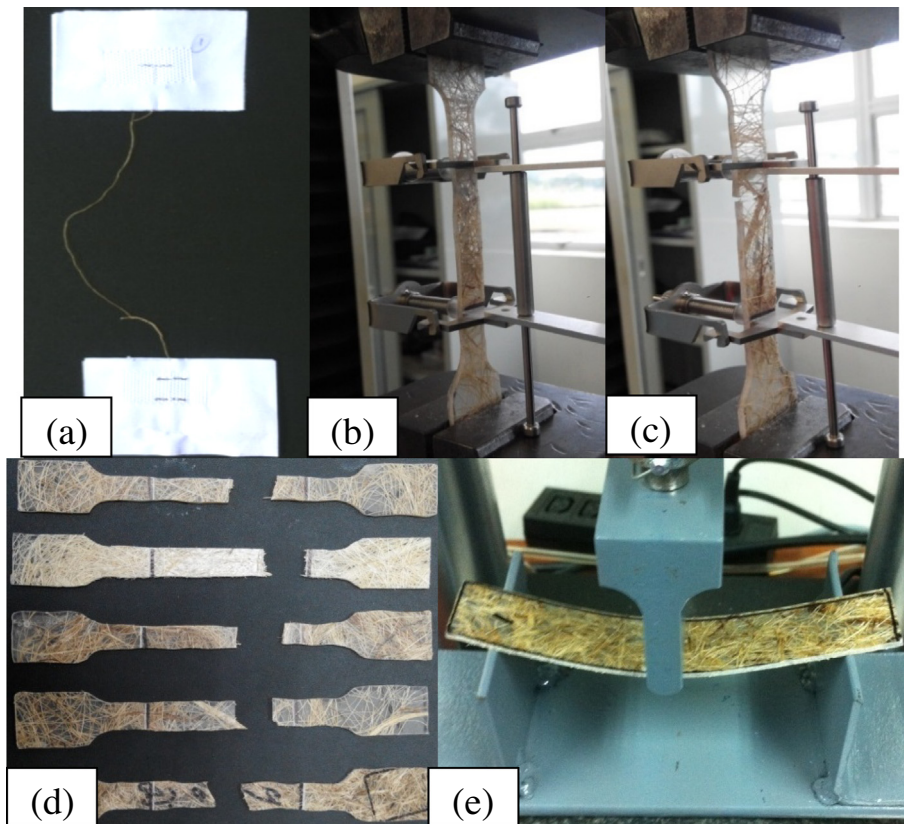


Fig. 2. (a) Tabbing of single fibre, (b) tensile test set-up using the INSTRON micro tester, (c) specimen breakage along the gauge length, (d) tensile tested specimens, (e) flexural testing.

2.4.4. Fibre surface morphology

The morphology of the Napier grass fibre was observed using a scanning electron microscope (SEM). The magnification was the range of 300–1000 \times .

2.4.5. Tensile testing of the composites

The composites were tensile tested using an electronic extensometer to measure the tensile properties. The specimens were prepared according to ASTM D638 standards. The specimens were machined to dimensions of 165 mm \times 20 mm \times 2.4 mm with a gauge length of 50 mm. Five identical test specimens were used for each volume fraction and the specimens were denoted as NT1, NT2, NT3, NT4, and NT5. An INSTRON micro-tester with a 2 kN load cell was used, and the samples were tested at a cross-head speed of 0.5 mm/min. The properties of the composites, such as the tensile strength, tensile (elastic) modulus and tensile load were determined from the results. Fig. 2(d) shows the breakage of the tested specimens.

2.4.6. Flexural test of the composites

Three point flexural tests were conducted according to ASTM D790 standards using the same INSTRON micro-tester. The specimens were machined to dimensions of 125 \times 20 \times 2.4 mm. The span length to depth ratio was set as 16:1. The specimens were tested at a crosshead speed of 2.5 mm/min. Five specimens were used for the each volume fraction and the specimens were denoted as NF1, NF2, NF3, NF4, and NF5. The set-up for the flexural testing is shown in Fig. 2(e).

3. Results and discussion

3.1. Digital scanning calorimetry (DSC)

The results of the DSC test for the untreated Napier grass fibre are shown in Fig. 3. The thermal degradation of the Napier grass proceeded through three distinctive stages separated into temperature ranges of 0–100 $^{\circ}$ C, 100–250 $^{\circ}$ C, and 250–350 $^{\circ}$ C. This change in the thermal properties is due to contrasts in the segments of the fibre cell structure, which signifies deterioration within specific temperature ranges. The first stage refers to low-temperature degradation which transforms the moisture into vapour. The lowest peak for this stage indicates that the T_g is \sim 66.6 $^{\circ}$ C. The second stage represents the decomposition of the hemicellulose and a portion of the lignin. Hemicellulose is a polysaccharide similar to cellulose, but consists of many singular sugars that build blocks of

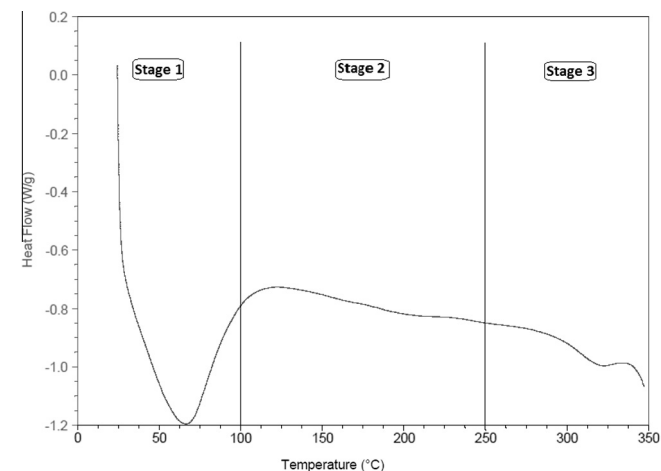


Fig. 3. Heat flow versus temperature ($^{\circ}$ C) for untreated Napier Grass fibre.

monomers in short chains. It also acts as a flexible support for the cell-wall in the plant. The last stage refers to a high-temperature region which indicates the complete degradation of the α -cellulose and the removal of the majority of the lignin from the Napier grass fibre [9].

3.2. Thermo-gravimetric analysis (TGA)

The TGA results of the Napier grass fibre are illustrated in Fig. 4. The TGA curve shows a number of degradation stages for the untreated Napier grass fibre. The changes during the first stage were observed above 250 $^{\circ}$ C. At this particular temperature, the weight of the sample is approximately 95% of the total weight of the sample (0.471 mg). At this stage, the Napier fibre undergoes moisture vaporisation, as reported in previous research [25]. The decomposition temperature was determined following an obvious weight reduction in the Napier fibres during the test. The TGA thermogram suggests that the decomposition temperature is \sim 250 $^{\circ}$ C. At 345 $^{\circ}$ C, the weight of the fibre is approximately 20% of its initial weight. This is due to the thermal de-polymerization of the hemicellulose. Above 500 $^{\circ}$ C, the fibre was completely decomposed with only residues of the Napier grass fibre remaining. Conversely, the results from the differential thermal analysis (DTA) demonstrated that the differential weight loss as a function of time is 1.3% at 250 $^{\circ}$ C. Above 250 $^{\circ}$ C, the sample exhibited an exothermic nature. From the analysis, it can be concluded that the crystallisation temperature of the Napier grass fibre is 320 $^{\circ}$ C. The lowest peak at 345 $^{\circ}$ C indicates the T_m of the Napier grass fibre. Above T_m , the fibre exhibits an endothermic nature as it will absorb heat and increase to a maximum peak level.

3.3. Single-fibre tensile test

Table 1 summarizes the single fibre test results for the untreated and treated Napier grass fibres. The tensile strength of the fibre was calculated for the 20 identical samples, using a ratio of the average load to average area. The fibre diameter varied between \sim 150 μ m and 250 μ m. The results show that the 10% NaOH-treated fibre exhibited the highest breaking tenacity of >7000 N/tex. The untreated fibre exhibited the lowest breaking tenacity of 462 N/tex. The fibres were enhanced by the alkaline treatment because it increased their surface roughness and decreased their moisture content, particularly for the 10% NaOH-treated specimens. Subsequently, the breaking tenacity decreased from 7093 N/Tex to 6480 N/Tex and further reduced to 2117 N/Tex for the 10%, 15%, and 20% NaOH-treated samples, respectively. The results suggest that the non-cellulose part of the Napier fibre deteriorates as the NaOH concentration increases, as illustrated in Fig. 7(d and e).

Fig. 5 shows the plotted stress–strain responses from the single-fibre tensile tests of the untreated and treated fibres at various alkaline concentrations. Based on the figure, the maximum strength of 106.2 MPa was achieved by the 10% NaOH-treated Napier grass fibre, with an elastic modulus of 2.2 GPa. However, the minimum strength was recorded at 12.4 MPa, for the untreated Napier grass fibre specimens, with an unchanged modulus of 2.2 GPa. This indicates a strength increase of almost 80% between the untreated fibre and the 10% NaOH-treated fibre. This is expected since the alkalization process results in fibrillation that breaks the fibre bundles into smaller bundles, increasing the effective surface area of the fibre strands [18,26,27]. This increase in surface area enables efficient contact between the fibre and the matrix, which should improve the interfacial bonding between the fibre and the matrix in the fabricated composites. From the test results, we can determine that the 10% NaOH treatment is optimal to enhance the properties of the Napier grass fibres.

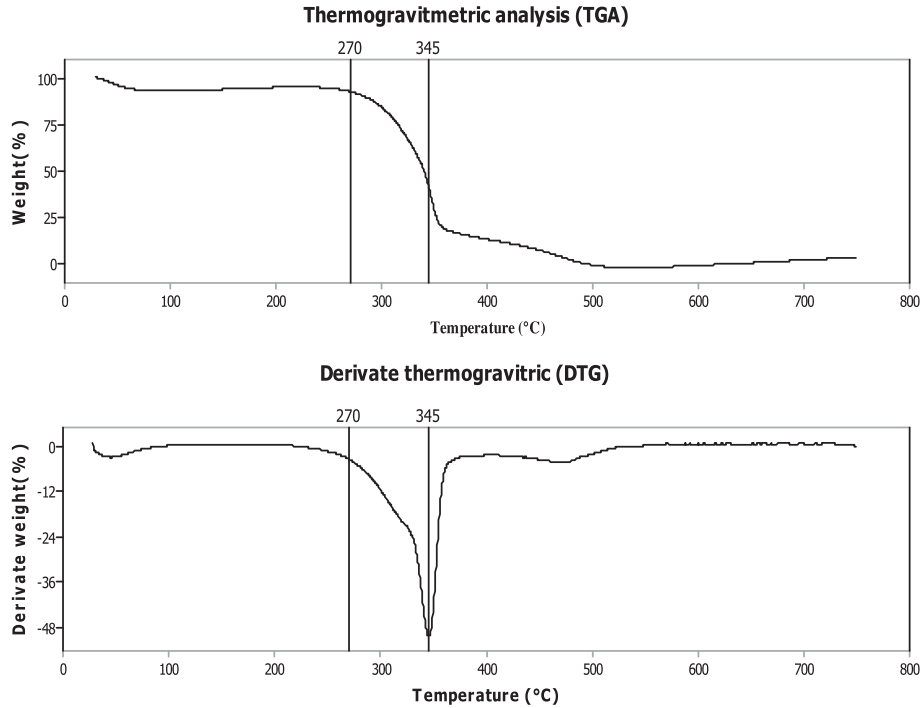


Fig. 4. Thermogravimetric and differential thermal analysis for untreated Napier grass fibre.

Table 1
Single fibre test results for untreated and alkaline-treated single Napier grass fibres.

| Specimen condition | Mass (mg) | Length (mm) | Diameter (μm) | Area (mm^2) | Linear density (kg/m) | Unit break (N/Text) |
|--------------------|-----------|-------------|----------------------------|------------------------|-----------------------|---------------------|
| Untreated | 4.1 | 121.2 | 198.4 | 0.031 | 0.000332 | 462 |
| 5% | 7.8 | 130.1 | 258.4 | 0.055 | 0.000589 | 1622 |
| 10% | 4.0 | 140.4 | 154.3 | 0.019 | 0.00028 | 7093 |
| 15% | 4.1 | 135.5 | 191.6 | 0.029 | 0.000298 | 6480 |
| 20% | 5.3 | 140.2 | 249.3 | 0.049 | 0.000371 | 2117 |

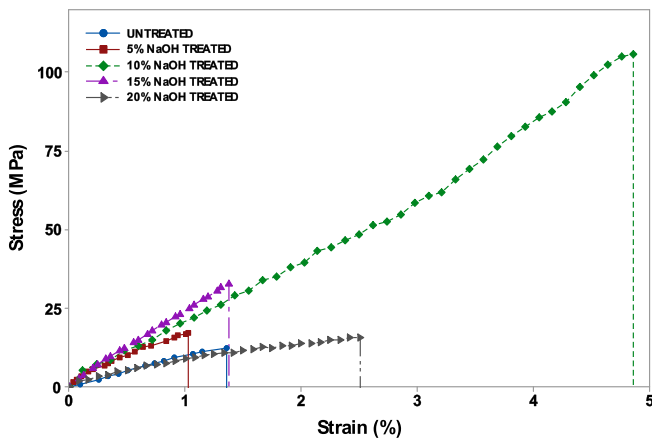


Fig. 5. Results of the single-fibre tensile test for untreated and NaOH-treated.

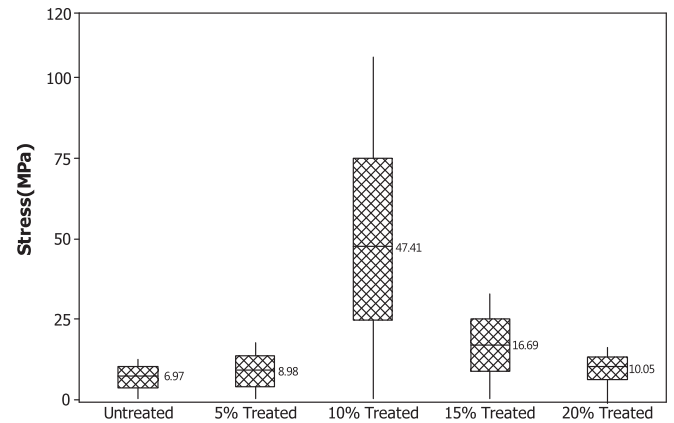


Fig. 6. Box plot of the single-fibre tensile test results for untreated and NaOH-treated Napier grass fibres at various concentrations.

Fig. 6 illustrates the box plot analysis for the untreated and NaOH-treated Napier grass fibres at various concentrations. It can be observed that the 10% NaOH-treated specimen exhibits the largest interquartile range with the greatest maximum and minimum values. Its median value is 47.41 MPa, which is the highest

amongst all the quartiles. The interquartile range of each of the other boxes is approximately a quarter of that of the 10% NaOH-treated specimen. The second largest interquartile range is for the 15% NaOH-treated specimen, followed by the 20% and 5% NaOH-treated specimens and the untreated specimen.

Table 2 shows a summary of the density and tensile properties of the Napier grass fibres along with those of more prevalently available fibres. The density of the fibres is critical, particularly for lightweight applications. The Napier grass fibre has one of the lowest densities (358 kg/m^3) compared to those of other conventional natural fibres. However, it is slightly higher than those of jute, sisal, and pineapple fibre. The average tensile strength of the Napier grass fibre was greater than those of bamboo and coir fibres. Although the Napier fibre yielded a lower strength than flax, hemp, jute, kenaf, and banana, it can be used as effective reinforcement for lightweight composites because of its low density of 0.358 kg/m^3 .

Table 2

Comparison of the tensile properties of Napier grass fibre with that of other natural fibres.

| Fibre name | Density (kg/m ³) | Diameter (µm) | Tensile strength (MPa) | Tensile modulus (GPa) |
|------------------|------------------------------|---------------|------------------------|-----------------------|
| Flax [9,13] | 1500 | – | 500–900 | 27.6–80 |
| Hemp [13] | 1480 | – | 300–800 | 70 |
| Jute [13,28] | 160 | – | 258–306 | 10–30 |
| Sisal [9,28] | 150 | 50–300 | 227–400 | 9–20 |
| Pineapple [15] | 144 | 20–80 | 413–1627 | 34.5–82.5 |
| Kenaf [13] | 1440 | 81 | 250 | 4.3 |
| Banana [11,28] | 1350 | 80–250 | 529–759 | 8.2 |
| Coir [28] | 1150 | 100–460 | 90 | 4–6 |
| Bamboo [28] | 910 | – | 16–38 | 35.9 |
| Snake grass [29] | 887 | 45–250 | 78 | 9.7 |
| Napier grass | 358 | 150–550 | 106 | 39–47 |

3.4. Influence of NaOH treatments on the surface morphology of the fibres

The effect of the alkali treatment on the tensile test results of the single Napier grass fibres can be further explained by examining the fibre surface. The SEM photographs of the surface morphology of the fibre following the alkaline treatments are presented in Fig. 7. According to S. Shibata et al., the fibres within the untreated fibres were packed together but splits were observed following the treatments [17].

This study demonstrates that the alkaline treatments resulted in obvious disparities in the morphology of the fibre surface. Fig. 7(a) shows that the surface of the untreated Napier grass fibre consisted of lignocelluloses covered with hemicellulose, waxy substances, and impurities. Fig. 7(b and c) shows that fibre fibrillation was observed for the 5% and 10% NaOH-treated fibres; the structure of the fibre deteriorated and the fibre bundles were split into ultimate fibrils. Fibrillation enhances the tensile strength because a larger amount of stress can propagate through the fibres owing to the larger surface area available for energy dissipation. Furthermore, as shown in Fig. 7(d and e), the fibrillation was much more aggressive than that observed for previous treatment concentrations. This causes a number of cavities to develop within the fibrils, resulting in insufficient energy transfer throughout the fibrils under loading, which consequently affects the tensile strength [28].

Overall, the 10% NaOH-treated fibres yielded the highest tensile strength, along with optimal removal of the hemicellulose layer. This is because the density and rigidity of the inter fibrillar region is likely to decrease as the hemicellulose is removed and the fibrils can subsequently rearrange along the direction of the stress loading. When the treated fibres were subjected to tensile loading, the arrangement of the fibrils resulted in a better loading arrangement and hence greater strength. Although rougher, the 15% and 20% NaOH-treated fibres have lower tensile strengths than the 10% NaOH-treated fibre. The SEM observations suggested that severe fibrillation occurred in the 20% and 25% NaOH-treated fibres, which resulted in lower tensile strength.

Table 3

Tensile properties of short and long Napier grass fibre composites.

| | Tensile properties | | | | | | | | | |
|------------------------|--------------------|-------|-------|-------|------|------------|-------|-------|-------|-------|
| | Short fibre | | | | | Long fibre | | | | |
| | 10% | 15% | 20% | 25% | 30% | 10% | 15% | 20% | 25% | 30% |
| Volume fraction (VFF%) | 10% | 15% | 20% | 25% | 30% | 10% | 15% | 20% | 25% | 30% |
| Tensile strength (MPa) | 8.13 | 13.22 | 13.50 | 15.64 | 7.59 | 5.79 | 10.16 | 11.91 | 18.17 | 12.65 |
| Tensile modulus (GPa) | 2.20 | 2.40 | 2.70 | 3.02 | 2.30 | 1.83 | 1.86 | 1.90 | 2.00 | 1.50 |

3.5. Tensile properties of the Napier fibre/polyester composites

The tensile properties of the long and short Napier fibre-reinforced polyester composites were investigated for the various fibre volume fractions, as presented in Table 3. Figs. 8 and 9 also illustrate the above results. Both the tensile stress–strain curves show similar characteristics to those of brittle materials [15]. For both composites, the elongation at break increased as the fibre volume fraction increased. The tensile strain also increased as the fibre volume fraction increased. The maximum tensile strength was observed with 25% fibre loading, suggesting the optimum volume fraction of the fibre. The reduced strength of the composite with a 30% fibre volume fraction could be attributed to the fibre entanglements that form in longer fibre lengths. The elastic moduli of the specimens were calculated by considering the slope of the elastic region of the stress–strain curve; a similar trend to that of the tensile strength was observed.

Fig. 10 shows the tensile strength against the various fibre volume fractions for both the long and short Napier fibre composites. The tensile strength increased from 5.79 MPa to 18.17 MPa as the fibre volume fraction increased from 10% to 25%, respectively. The strength decreased to 12.65 MPa at a fibre volume fraction of 30%, yielding a strength reduction of >30%. The results confirm that the optimum fibre volume fraction for the long Napier fibre-reinforced composites is 25%. The reduced strength of the long fibre composite with a fibre volume fraction of 30% suggests that the load and stress transfer between the fibre–resin interfaces were impaired because of poor matrix bonding in the composite laminates. Furthermore, the quantity of Napier grass fibre is greater in the composites with high fibre volume fractions, and this resulted in weak matrix bonding because there were fewer binders to hold the fibre intact. Similar trends were also observed for the tensile strength of the short Napier fibre-reinforced composites. For these tests, the short fibre lengths ranged from 10 to 30 mm. The tensile strength of the short Napier fibre composite increased as the fibre volume fraction increased. The tensile strength for the composites with the 10% and 25% fibre volume fractions were 8.14 MPa and 15.64 MPa, respectively; demonstrating a strength increase of almost 48%. As previously shown, the composite with a short Napier fibre volume fraction of 30% exhibited a strength reduction of >50%.

Fig. 11 shows a plot of the tensile modulus against the various fibre volume fractions for both the short and long Napier fibre/polyester composites. The results indicate that the short Napier fibre composites consistently yield higher tensile moduli than the long fibre composites. Similarly, the tensile modulus gradually increases as the fibre volume fraction is increased to 25%. The tensile moduli for the composites with a 10% volume fraction of short and long Napier grass fibre are 2.2 GPa and 1.83 GPa, respectively. The composite with a 25% volume fraction of short fibre yields a maximum tensile modulus of 3.02 GPa, whilst the composite with the same volume fraction of long fibre only exhibited a tensile modulus of 2.0 GPa. The results seem to suggest that fibre length has a dominant effect on the tensile modulus of Napier fibre/polyester composites.

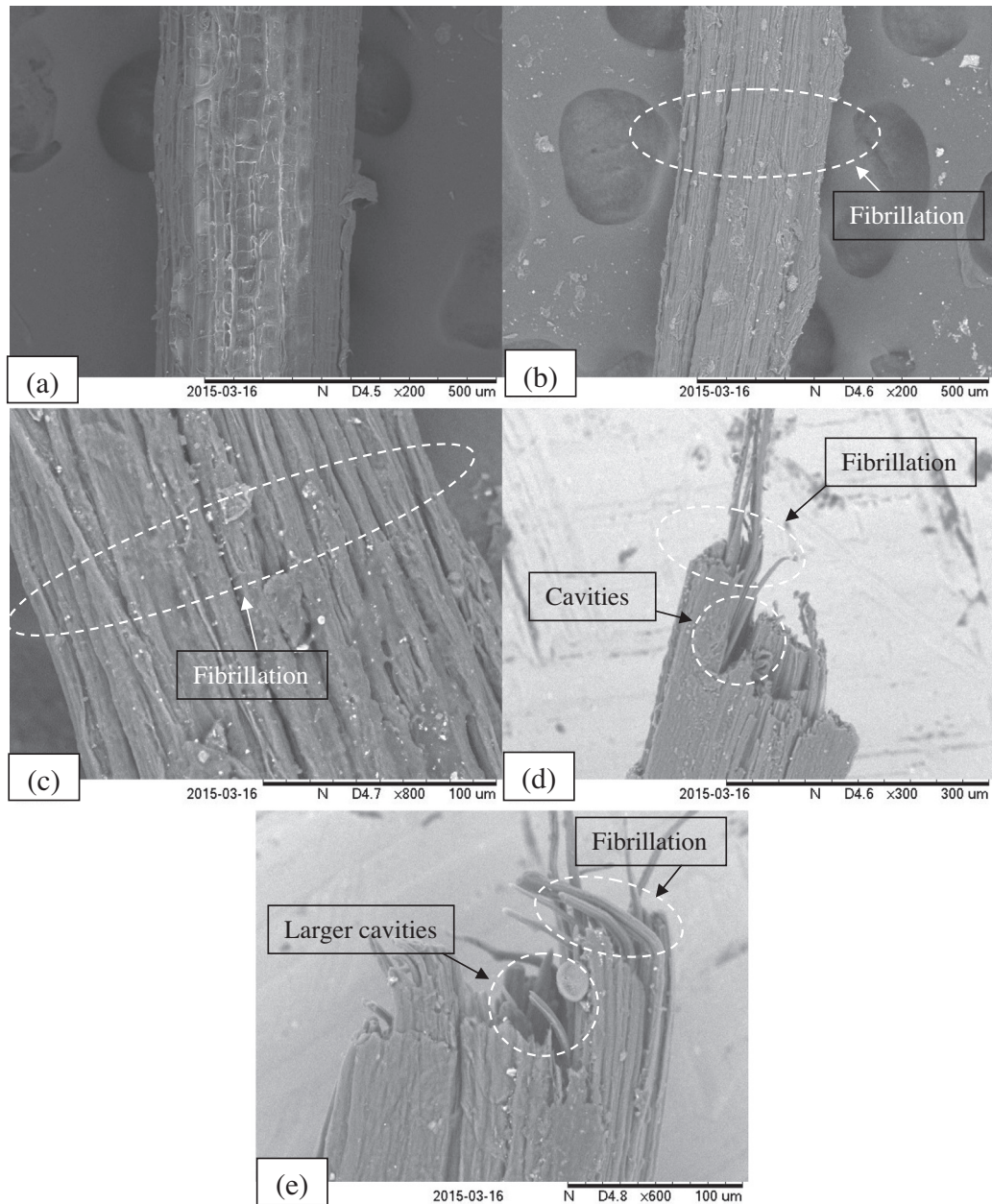


Fig. 7. SEM photographs of Napier grass fibre (a) untreated Napier grass fibre, (b) 5% NaOH-treated fibre, (c) 10% NaOH-treated fibre, (d) 15% NaOH-treated fibre, (e) 20% NaOH-treated fibre.

3.6. Flexural properties of the Napier fibre/polyester composites

A summary of the flexural properties of the composites with various fibre volume fractions is presented in Table 4. The flexural strengths of the short and long Napier grass fibre-reinforced polyester composites with various fibre volume fractions are displayed in Fig. 12. In general, the short Napier grass fibre composite exhibits a higher flexural strength at all fibre volume fractions than the long Napier fibre-reinforced composites. The short and long fibre composites both exhibit an increase in the flexural strength as the fibre volume fraction increases. Amongst the composites, the short and long fibre composites both yielded the maximum flexural strengths at a fibre volume fraction of 25%, which indicates the optimum volume fraction for the composites.

The results also suggest that the short and long fibre composites both exhibit similar trends with regard to flexural strength; the

composites with the short fibres demonstrate higher flexural strengths than those with the long fibres. This could be attributed to several factors, such as efficient load transfer, random fibre orientation, and ease of sample preparation [11]. Similarly, a further increase in the fibre volume fraction to 30% causes a severe reduction in the flexural strength for both the short and long fibre composites. The long fibre composites were most affected, with a flexural strength reduction of >20%. At higher fibre volume fractions, the reduction in flexural strength is suspected to be due to insufficient filling of the resin matrix that holds and binds the fibres, which results in weakened interfacial bonding between the fibre and resin.

Fig. 13 shows the flexural modulus results for the various fibre volume fractions of the Napier grass fibre polyester composites. The short fibre composites consistently yielded greater flexural moduli than those of the long fibre composites; this is less evident

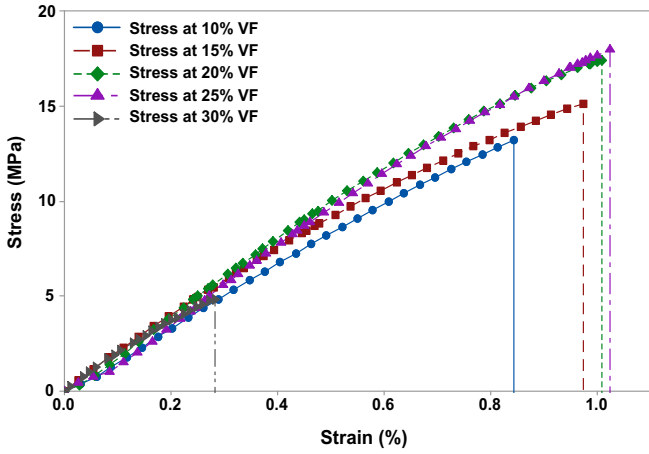


Fig. 8. Stress–strain responses for long Napier fibre/polyester composites with various fibre volume fractions.

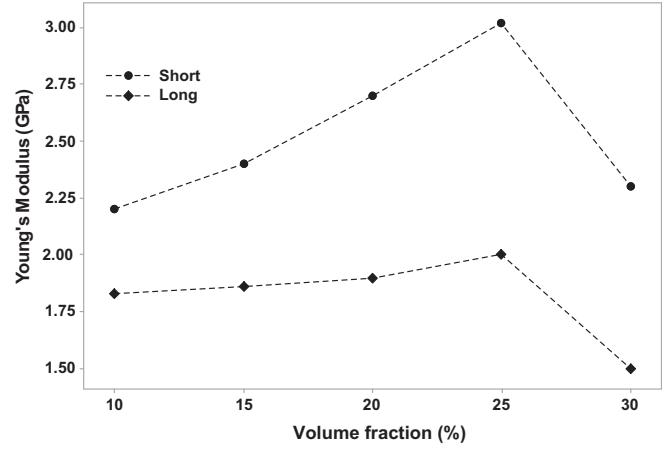


Fig. 11. Young's modulus versus fibre volume fraction for short and long Napier fibre composites.

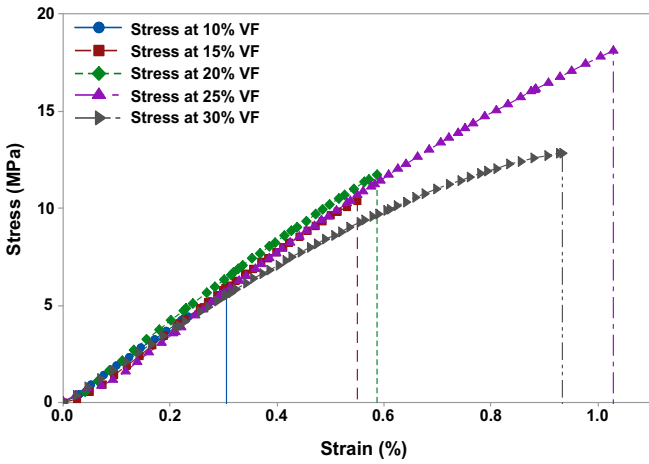


Fig. 9. Stress–strain responses for short Napier fibre/polyester composites with various fibre volume fractions.

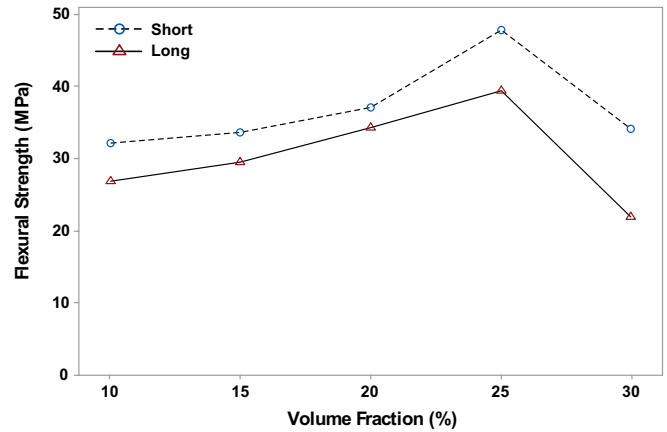


Fig. 12. Flexural strength versus fibre volume fraction for long and short Napier grass composites.

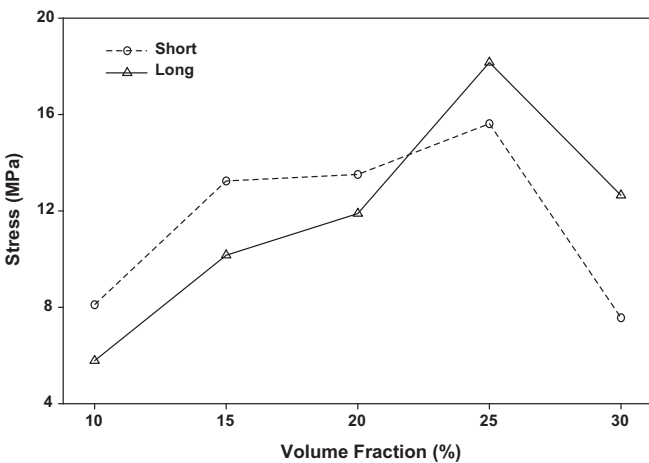


Fig. 10. Tensile strength versus fibre volume fraction for short and long Napier fibre composites.

compared with the tensile modulus results. The plot also suggests that the flexural moduli increase as the fibre volume fractions increase. At a fibre volume fraction of 25%, the maximum flexural

moduli of the short and long Napier fibre composites were 1.85 GPa and 1.81 GPa, respectively. A further increase in the fibre volume fraction to 30% resulted in reduced moduli of 1.38 GPa and 1.32 GPa for the short and long Napier fibres composites, respectively; a reduction of almost 30%.

3.7. Surface morphology of fractured Napier/polyester composites

SEM analysis was conducted to observe the failure mechanism of the composites. Fig. 14(a) exhibits the tensile fracture surface of the long Napier fibre/polyester composites. Relatively long extruding fibres can be observed, which is indicated by the fibre pull-out. This phenomenon can be explained by the deflection of matrix cracks by the fibres, which are subsequently redirected toward the fibre surface, resulting in fibre debonding. As cracks propagate between the fibre–matrix interfaces, matrix separation occurs around the fibres because of debonding, eventually causing fibre pull-out. The energy is dissipated through a shear mechanism. Similar conclusions were formed by D. Ray et al. for their bamboo fibre/polyester composites [28].

The figure also illustrates that the fibre experienced fibre splitting and end damage which suggests that upon debonding, energy dissipation occurs along the fibre prior to fibre pull-out. Fibre splits separate the fibre bundles into individual bundles of ultimate fibres. This consequently dissipates some energy as well as

Table 4
Flexural properties of short and long Napier grass fibre composites.

| | Flexural properties | | | | | | | | | |
|-------------------------|---------------------|------|------|------|------|------------|------|------|------|------|
| | Short fibre | | | | | Long fibre | | | | |
| Volume fraction (VFF%) | 10% | 15% | 20% | 25% | 30% | 10% | 15% | 20% | 25% | 30% |
| Flexural strength (MPa) | 32.1 | 33.6 | 37.1 | 47.9 | 34.1 | 26.9 | 29.6 | 34.3 | 39.5 | 21.9 |
| Flexural modulus (GPa) | 1.49 | 1.62 | 1.74 | 1.85 | 1.40 | 1.30 | 1.52 | 1.70 | 1.80 | 1.32 |

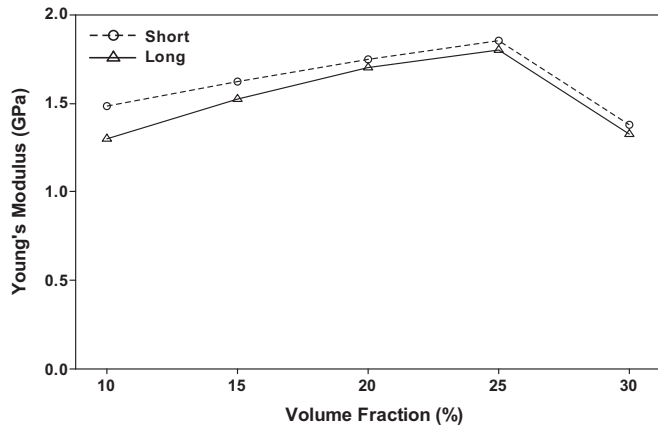


Fig. 13. Flexural modulus versus fibre volume fraction for long and short Napier grass composites.

improves the tensile strength. Moreover, Fig. 14(b) shows that some fibres were aligned parallel to the surface [6,7]. This indicates that those fibres played less significant roles in energy dissipation. However, the fibres normal to the fracture surface played a vital role in arresting the matrix crack propagation. This explains the superior performance of the Napier fibre/polyester composites with the optimum fibre volume fraction of 25%.

Fig. 15(a and b) shows the morphology of the tensile fracture surface of the short Napier fibre composite with the optimum fibre volume fraction of 25%. It could be observed that the fibres were very distant from one another. A greater number of holes and extruding fibres were observed, suggesting that a greater number of fibre pull-out failures occurred. K.J. Wong et al. explained that this could be due to the reduced surface area of the fibres; fibres could be pulled out without absorbing sufficient fracture energy [29]. Moreover, less fibre damage was observed, suggesting less effective energy dissipation. Thus, the morphology suggests that there is less favourable, weaker interfacial adhesion between the short Napier fibres and polyester resin during tensile loading.

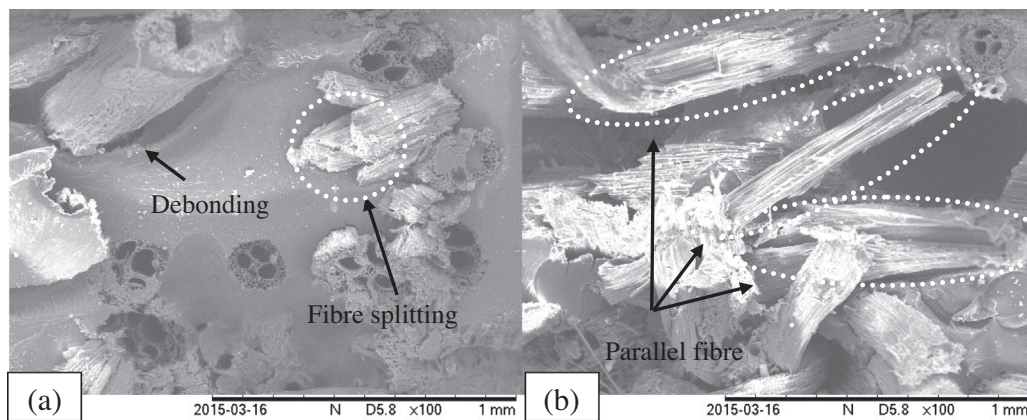


Fig. 14. Morphology of the tensile fracture surface of the long Napier grass fibre at 25% fibre volume fraction.

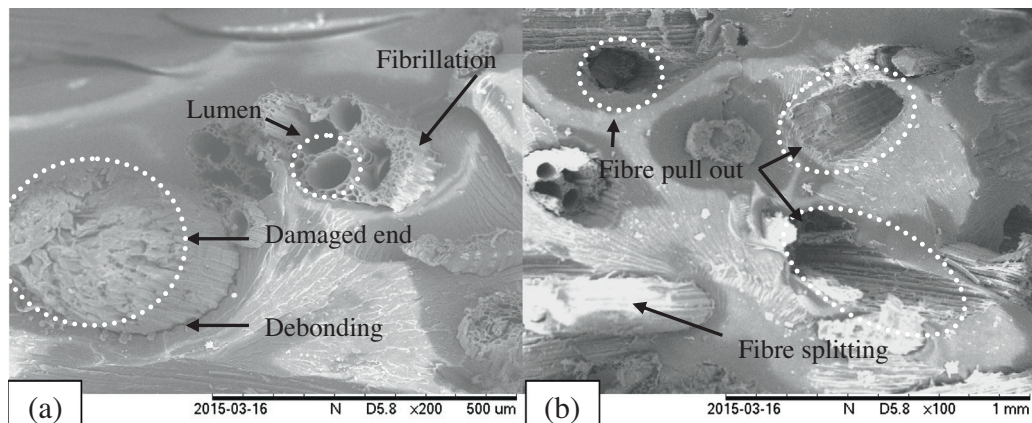


Fig. 15. Morphology of tensile fracture surface of short Napier grass fibre at 25% fibre volume fraction.

Fig. 15(a) shows the fibre fibrillation within the short Napier fibre composites, where the fibre bundles were split into ultimate fibrils due to the stress concentration at the ends of the short fibres. Fibrillation causes lateral deformation, which results in debonding between the matrix and fibres and consequently, more fibre pull-out. Similar observations were also reported by D. Ray et al. [28].

4. Conclusions

This study concerns the characterization of the mechanical properties of Napier grass fibre and its polyester composites. The conclusions obtained from this investigation are as follows:

1. The alkaline-treated Napier grass fibres demonstrate superior strength compared to that of the untreated fibres; the 10% alkaline-treated fibres yielded the highest tensile strength with an improvement of >80%.
2. The tensile and flexural strength of the untreated Napier fibre/polyester composites increased as the fibre volume fraction increased. Overall, it can be concluded that the composite with a 25% volume fraction of Napier fibre yielded the optimum tensile and flexural properties.
3. A further increase in the volume fraction, up to 30%, resulted in reduced strength and modulus for both the long and short Napier fibre-reinforced composites.
4. Fibre pull-out failure was observed in the morphology of the tensile fracture surfaces of both the long and short fibre composites. However, owing to their reduced surface area, this was more evident in the short fibre composites because the fibres could be pulled out without absorbing sufficient fracture energy.

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