Original Article

Effect of pineapple leaf (PALF), napier, and hemp fibres as filler on the scratch resistance of epoxy composites

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ABSTRACT

This article presents the effects of pineapple leaf (PALF), napier, and hemp fibres as filler on the scratch resistance of epoxy composites. In particular, it explores the effect of these natural fillers on the horizontal load, coefficient of friction (COF), penetration depth, fracture toughness, scratch hardness, brittleness index and scratch observation. The mixing method using magnetic stirrer was used to produce the natural fibre-filled epoxy composites with different wt%, namely, 5, 7.5, and 10 wt%. The test was performed using a CSM Revetest Xpress, which consisted of a cone of the half-apex angle of $60°$ ending with a sphere having a tip radius of $200\,\mu m$. The indenter scratch distance and speed were 7 mm and 1.5 mm/min, respectively. The results show that the napier fibre-filled epoxy composites have the highest peak load and COF. It was also noted that the napier fibre-filled epoxy composites have the lowest penetration depth for each wt% of filler. Lastly, the fracture toughness (K_c) for the napier fibre-filled epoxy composites with 10 wt% of filler yielded the highest value of $4.33\,MPa.m^{1/2}$. It can also be seen that using a scanning electron microscope (SEM), the amount of debris increased with higher of wt% of the natural fibre fillers in the composites. Hence it was demonstrated that the napier fibre-filled epoxy composites have higher scratch resistance compared to the PALF and hemp fibre-filled epoxy composites.

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1.   Introduction

Natural fibres can be utilised as alternatives for reinforcement in polymeric composites that are primarily used as structural components in lightweight applications compared to conventional synthetic fibres [1]. At the present state of the industry, transitioning from synthetic fibres to natural fibres can be beneficial from economical, environmental and societal standpoints [2,3]. This field of research remains the subject of interest to engineers and professionals alike. Use of natural fibre composites provides an alternative to the ever-depleting non-renewable sources that are currently in use. It has been established that the natural fibre composites have excellent mechanical properties, better electrical resistance, excellent thermal characteristics, superior tribological attributes, desirable acoustic insulating features, and higher strength to fracture [4–6]. In particular, recent works on natural fibre composites reveal that the mechanical properties of the natural fibre reinforced composites are as good as to those of the glass fibre composites [7–10]. Natural fibre reinforced composites for structural applications in the form of panels, tubing and structural sandwich plates have been previously employed to replace wooden fixtures and fittings for furniture and noise-insulating panels [11].

Scratch test is a technique engaged in assessing the scratch behaviour of materials [12]. To perform this test, a scratch-tip is drawn across the top surface while increasing the normal load up until a well-defined failure happens at the critical load [13]. This is an essential test to analyse the scratch properties and to understand the friction mechanism, such as the change in the coefficient of friction (COF). Friction is affected by numbers of parameters; surface roughness, plastic deformation, failure modes, physico-chemical interfaces, material properties and ambient environment [14]. The use of a scratch test on polymer composites has been increasing in recent years to investigate the scratching behaviour of various test materials [15–18]. Several scholars have used the scratch test to compare the scratch resistance of various polymer composites, and the scratch properties, such as scratch force, fracture toughness, penetration depth, hardness and brittleness.

The performance characteristics of polymer composites depend on their mechanical properties, such as tensile strength, flexural strength, and modulus as well as on their microstructure and molecular weight [19–21]. These properties may vary for the same material in bulk form, and the individual constituents due to different microstructural and defect conditions as a result of the deposition processes. Fibres, fillers and reinforcements, such as glass fibre [22], talc [23], kevlar [24], rubber [25], flax [26], napier [27,28], and minerals in the form of microparticles [29] can be added to the polymer composites to enhance the mechanical properties. Thus, the properties of the polymer composites are intrinsically complicated, and their response to scratch is substantially different from one another. As a result, the scratch properties are difficult to predict. Other than that, the geometry of the scratch indenter also considerably affects the scratch resistance properties of the composites. The indenters produce deeper scratches and cause brittle-like failure. Practically, however, the geometry of the indenters is highly

challenging to characterise. Therefore, surface texturing has been used extensively in polymer composites for their functionality, aesthetics, and material improvement over the last decades.

Fracture toughness (K_c) is a degree of a material's resistance to the onset of crack. It also depends on the temperature as well as the rate of loading [30]. Akono and Ulm [31] established an efficient way to evaluate the fracture toughness using scratch tests. Fracture mechanics is essential in deriving analytical expressions of the fracture toughness as a function of the penetration depth, indenter geometry and scratch forces. Akono et al. also suggested that scratching is fracture-dominated evolution [32]. The hardness of materials is defined as the resistance rendered by the test surface to the indenter. Scratch tests also used to measure the hardness and surface deformation appearances [33]. Scratch hardness is defined as the resistance of a material to the dynamic surface deformation for hard scratching element to grooves generated on the specimen surfaces, and the involvement of frictions between the surfaces of the indenter with the specimens [34].

In this research, an experimental study was carried out to characterise the scratch resistance properties of pineapple leaf (PALF), napier and hemp fibres as filler in epoxy composites. The aim of this work was to study the effect of filler content and weight percentage (wt%) of natural filler materials on the horizontal load, coefficient of friction (COF), penetration depth, fracture toughness, scratch hardness, brittleness index and scratch observations. By comprehensively evaluating the scratch resistance characteristics of cost-effective and eco-friendly natural fibre-filled epoxy composites, this study is expected to provide evidence to support their development and application.

2.   Materials and experimental methods

2.1.   Materials

Three types of natural fibres are investigated in this work. These three samples, namely, PALF, napier, and hemp fibres, were bought from local distributors. EpoxAmite™ 100 series resin and 103 slow hardener were supplied by Castmech Technologies Sdn Bhd, Malaysia. The resin has been mixed with hardener at a ratio of 3.5:1 as specified by the manufacturer, which was used in preparing the test specimens. The properties of the constituent materials are listed in Table 1.

2.2.   Specimen preparation procedure

Each of the natural fibres was prepared into the particulate form using a grinding machine, as shown in Fig. 1(a). The fibres were processed into smaller cuts before proceeding with grinding and sieving to produce fibres into filler form. The grinding and sieving were repeated several cycles to yield the fine filler. The size of the filler obtained from the sieving process ranged from 17 to 45 μm when observed under a scanning electron microscope (SEM). Each of the natural fibres was then mixed with the resin before the mixture was agitated using a magnetic stirrer for 30 min at a constant temperature of 70 °C to achieve a homogenous solution. The mixture was later

Table 1 – Properties of fibres and epoxy resin.

Properties	Materials			
	Pineapple leaf (PALF) fibre	Napier fibre	Hemp fibre	Epoxy
Density (g/cm³)	1.52	0.36	1.48	1.1
Strength (MPa)	413-1627	73	690	55
Modulus (GPa)	34.5-82.81	5.68	30–70	1.75
Elongation at break (%)	1.6	1.4	1.5–4.0	6
Cellulose (%)	74.33-85	45.66	57–77	–
Hemicellulose (%)	18.8	33.67	14–22.4	–
Lignin (%)	6.04	20.60	3.7–13	–
References	[35,36]	[37]	[36,38]	[39]

(a) Filler form

(b) Composites form

Fig. 1 – Samples of natural fibres filled epoxy composites.   **(a) Filler form.**   **(b) Composites form.**

degassed in a vacuum oven at 80 °C to remove existing air bubbles. Next, the advised amount of hardener was gently blended into the mixture for 3 min. The mixture was poured slowly into rectangular moulds until they were filled and levelled. Before curing, the mixture was again degassed in a vacuum oven to remove air bubbles from the mixture. Lastly, the mixture was then cured at 80 °C for 2 h and left cooled to room temperature (RT; 25 °C). The specimens were cut in dimensions of $30 \times 50 \times 10$ mm, as shown in Fig. 1(b) by using the Dremel 4000 cutting tool. The natural fibre-filled epoxy composites consisted of PALF, napier or hemp were fabricated with three different filler weight percentage of 5, 7.5 and 10 wt%.

2.3. Scratch tests and measurements

The scratch test consisted of forcing a sphere-conical diamond indenter across the surface of the composites while increasing the force to study the surface properties of the composites. The test was performed using the CSM Revetest Xpress machine, as shown in the schematic diagram of Fig. 2. The indenter type used was Rockwell – D247, which consist of a cone of half-apex angle of 60° ending in a sphere having a tip radius of 200 μm. The indenter scratch distance and speed were 7 mm and 1.5 mm/min, respectively. The scratch speed and force measurements were calibrated before starting new data collection. Throughout the tests, the vertical force was prescribed using piezo-actuation, while the force and distances were measured using a high accuracy transducer. The vertical force was set as a piezo-actuated active force feedback loop such that any tilt of the specimen top sur-

face had a minimum influence on the vertical force history. An acoustic emission sensor was also used to keep track of the stress-induced damage events.

2.4. Scanning electron microscope (SEM)

A scanning electron microscope (SEM) was utilised to observe the scratch deformation mechanisms. The scratch areas on top surfaces of the test samples were cut using a Diamond Dremel 4000 tool. A layer of platinum was evenly coated over the surface before scanning. The scanning images were obtained with accelerating voltages of 10 kV, under magnifications between $100\times$ and $130\times$.

2.5. Density and porosity measurement

Theoretical density (ρ_{theory}) of natural fibre-filled epoxy composites in terms of the weight fraction can be determined, as shown in Eq. (1). The experimental density (ρ_{exp}) of the natural fibre-filled epoxy composites were measured according to ASTM D792. The porosity of the natural fibre-filled epoxy composites was determined using Eq. (2); where w, ρ, f and e represent the weight fraction, density, natural fibre and epoxy, respectively.

$$\rho_{theory} = \rho_f w_f + \rho_e w_e \tag{1}$$

$$\text{Porosity (\%)} = \left[1 - \left(\frac{\rho_{exp}}{\rho_{theory}} \right) \right] 100 \tag{2}$$
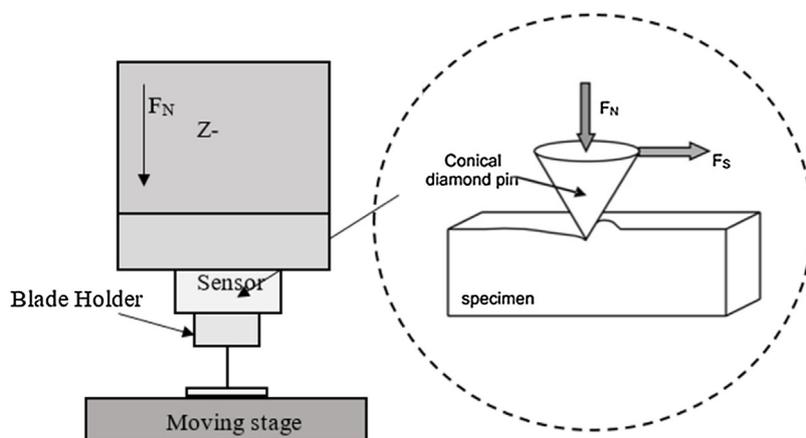
Fig. 2 – Schematic diagram of the scratch tester.

3. Results and discussion

3.1. Scratch resistance

3.1.1. Horizontal load

Scratch tests were performed on various natural fibre-filled epoxy composites with different filler weight percentage (wt%) of 5, 7.5 and 10 wt%. Fig. 3 demonstrates the horizontal load curves for the PALF, napier and hemp fibres filled epoxy composites. It was observed that the load increased to the peak load at certain scratch distances. The peak load was a critical point for the composites' failure. This figure also clearly indicates that the higher wt% of filler in the composites yields greater peak load for the PALF, napier and hemp fibre-filled epoxy composites. From the observations of Fig. 3(a), the peak load of the PALF fibre-filled epoxy composites were 10.5, 12.9 and 14.3 N for 5, 7.5 and 10 wt% for PALF fibres, respectively. It was followed by the improvement of the peak loads for hemp fibre-filled epoxy composites: 49, 44 and 44% for 5, 7.5 and 10 wt%, respectively, as illustrated in Fig. 3(c). The napier fibre-filled epoxy composite was observed to have the highest peak loads compared to the PALF and hemp fibre-filled epoxy composites. This was measured at 28.6, 30.2, and 36.4 N for 5, 7.5 and 10 wt% for napier fibres, respectively, as shown in Fig. 3(b). The higher content of the filler could improve the strength of the composites because it would create a robust molecular movement for each molecule between the natural fibre and the epoxy [40]. Therefore, it can be concluded that the higher filler content imparts the ability to resist the horizontal load before experiencing brittle failure. Other than that, the napier fibre-filled epoxy composites were found to yield greater scratch distance at the peak load compared to the PALF and hemp fibre-filled epoxy composites. In addition, the horizontal load of the napier at 7 mm of scratch distance is greater than that of the PALF and hemp fibre-filled epoxy composites. These indicate that the resistance of napier fibre-filled epoxy composites is higher than that the PALF and hemp fibre-filled epoxy composites. It was suspected influenced by the lignin content in the napier fibre, which is higher than the PALF and hemp, as shown in Table 1.
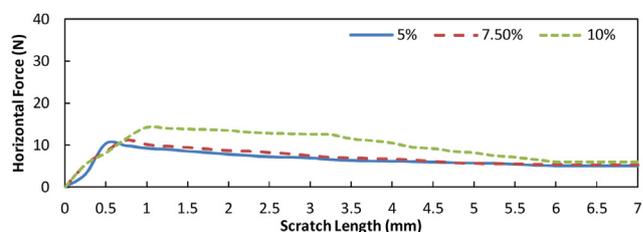
(a) PALF fibre-filled epoxy composites
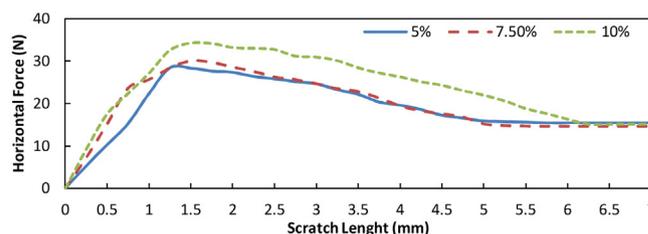
(b) Napier fibre-filled epoxy composites
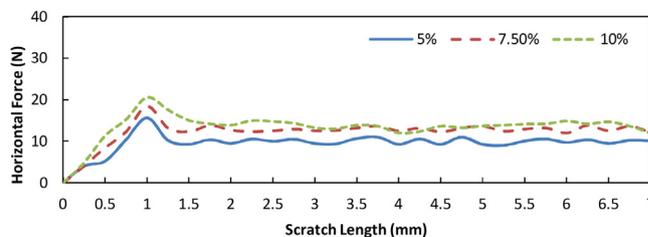
(c) Hemp fibre-filled epoxy composites

Fig. 3 – Horizontal force of natural fibre-filled epoxy composites.
(a) PALF fibre-filled epoxy composites.
(b) Napier fibre-filled epoxy composites.
(c) Hemp fibre-filled epoxy composites.

3.1.2. Coefficient of friction

Fig. 4 shows the coefficient of friction (COF) of the natural fibre-filled epoxy composites. As seen from the figure, the process can be separated into three phases. The first phase is a linear correlation between the COF and the scratch distance. The COF increases due to the manifestation of plastic deforma-

(a) PALF fibre-filled epoxy composites

(b) Napier fibre-filled epoxy composites

(c) Hemp fibre-filled epoxy composites
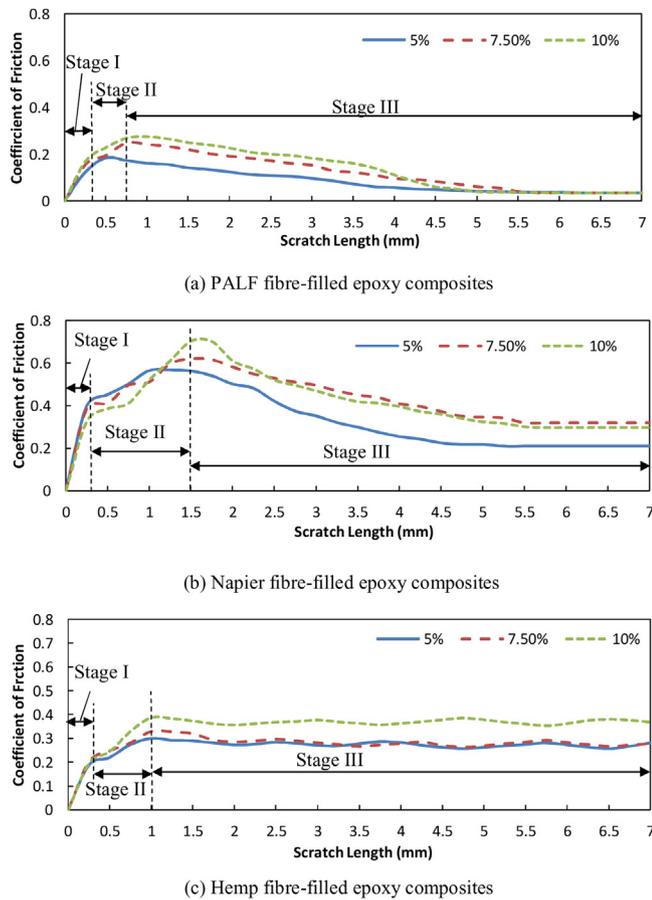
Fig. 4 – The coefficient of static friction (COF) of natural fibre-filled epoxy composites.
(a) PALF fibre-filled epoxy composites.
(b) Napier fibre-filled epoxy composites.
(c) Hemp fibre-filled epoxy composites.

tion where only spherical part of the scratch-tip is in contact with the specimen, and no significant fracture is observed. The second phase is the region where the COF is non-linear with the scratch distance, though it still shows an increasing pattern. At this stage, ductile fracture starts to appear though it is suspected that this failure mode does not affect the plastic deformation of the sample. Hence, the COF increases without any unexpected change. Lastly, the third phase shows the distance at the maximum value COF to the end of the scratch distance. The COF decreases continuously at this stage due to the decrease in asperity deformation, as the asperities of the surface are gradually detached, creating a mirror finish. The different damping behaviours of the sample may contribute to the variation in frictional behaviours, and the frictional behaviour has a significant influence on scratch damages to the samples [41].

The effects of wt% of filler on the COF for PALF, napier and hemp fibre-filled epoxy composites are shown in the figure. As the wt% of the filler in the composite increases, the maximum COF also increases. This results in better friction properties of the composites. The napier was higher than the PALF and hemp fibre-filled epoxy composite for each wt% of the filler. The maximum values of the COF for the napier fibre-filled

epoxy composites were 0.576, 0.625 and 0.710 for 5, 7.5 and 10 wt%, respectively, as shown in Fig. 4(a). The maximum COF experienced an increase of 18.9% when the wt% of the napier filler increases from 5 to 10 wt%. The COF of the hemp fibre-filled epoxy composites, on the other hand, are 0.394, 0.334, and 0.302 for 5, 7.5 and 10 wt%, respectively. The COF of the hemp fibre-filled epoxy composites also increases by 19.7% when the wt% of the hemp filler is increased in the composites. The lowest value of COF was recorded for the PALF fibre-filled epoxy composites, which have the value of 0.55, 0.72 and 0.87 for 5, 7.5 and 10 wt% of fillers, respectively. Similarly, the COF of the PALF fibre-filled epoxy composites also experienced an increase of 30.2% as wt% of filler was increased from 5 to 10 wt%.

3.2. Penetration depth

The evaluation of the penetration depth of the samples was performed at four locations of the scratch distance. The values of the penetration depth increased significantly at a higher scratch distance with the application of higher normal load. The observed trends for the penetration depths concerning the scratch distances are presented in Fig. 5. It can be seen that the penetration depth attains maximum value on the surface of the composites with lesser wt% of filler for the PALF, napier and hemp's fibre-filled epoxy composites. The value of the penetration depth relates to the resistance of that specific material to indentation/scratch, where a higher scratch resistance of material yields lower values of penetration depth. These penetration depths could be used to determine the fracture toughness of the composites. Fig. 5(a) shows the incremental percentage of the penetration depths along the scratch distance. This is about 25% for each wt% of filler in the PALF fibre-filled epoxy composites. However, the incremental percentage of the penetration depth along the scratch distance for each wt% of filler for napier and hemp is lower than that of the PALF fibre-filled epoxy composites. This variation (19 and 14%, respectively) is shown in Fig. 5(b–c). The napier fibre-filled epoxy composites have the lowest penetration depth for each wt% of filler. The results revealed that the napier filled epoxy composites has higher scratch resistance compared to the PALF and hemp fibre-filled epoxy composites. The increase in penetration depth and load-bearing area affect the value of the scratch hardness [42]. The penetration depth and load-bearing area are highly dependent on the matrix, their different phases and the interfaces between the matrix and the reinforcements.

3.3. Fracture toughness

The results from the scratch tests carried out on the natural fibre-filled epoxy composites were analysed to obtain the fracture toughness of the composites. The fracture toughness (K_c) of the composites were found via Eq. (1) and (2).

$$K_c = F_T / \sqrt{2pA} \tag{3}$$
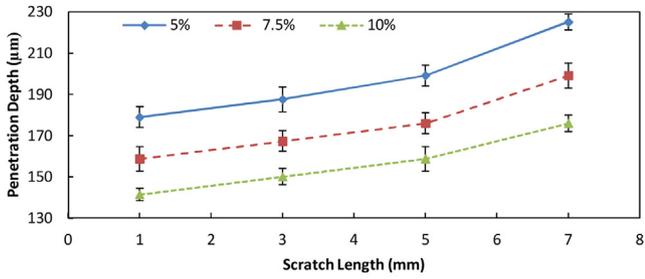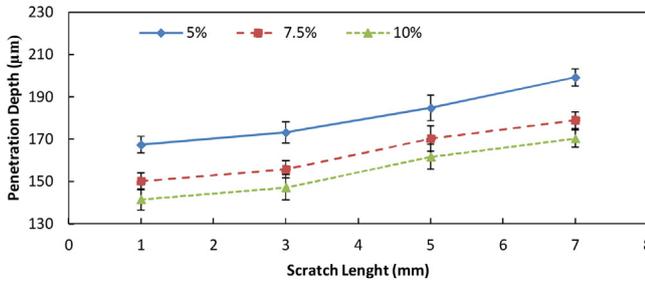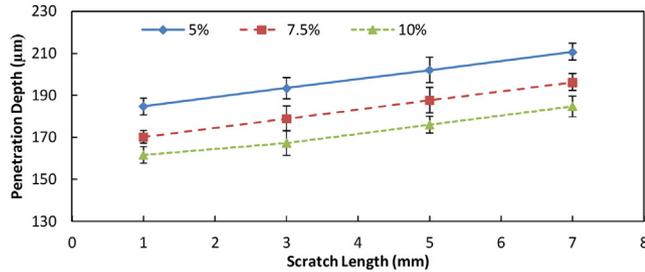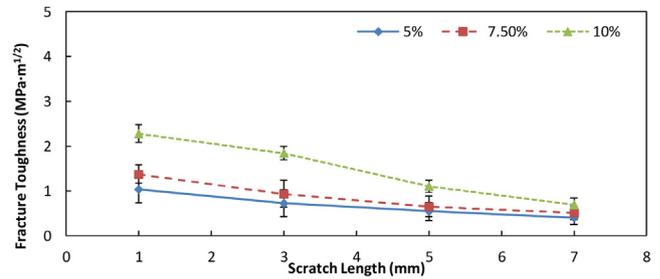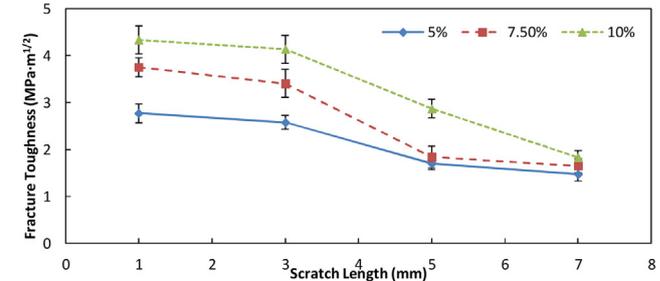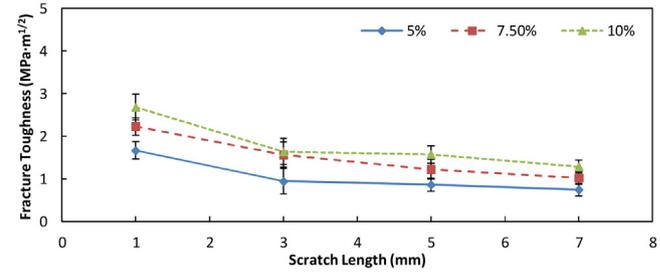
Fig. 5 – The penetration depth of natural fibre-filled epoxy composites.
(a) PALF fibre-filled epoxy composite.
(b) Napier fibre-filled epoxy composite.
(c) Hemp fibre-filled epoxy composite.

Fig. 6 – Fracture toughness of natural fibre-filled epoxy composites.
(a) PALF fibre-filled epoxy composite.
(b) Napier fibre-filled epoxy composite.
(c) Hemp fibre-filled epoxy composite.

Where,

$$\sqrt{2pA} = \sqrt{4d^3 \left(\frac{\tan \emptyset}{\cos \emptyset} \right)} \qquad (4)$$

K_c = Fracture toughness
F_T = Horizontal force
$2pA$ = Scratch probe shape function
d = Penetration depth
$\emptyset$ = Half-apex angle of conical indenter

This section emphases on the assessment of fracture toughness for PALF, napier and hemp fibre-filled composites at a different weight percentage (wt%) of fillers via Eq. (1) and (2). Fig. 6 shows that a higher wt% of filler indicates an improvement in fracture toughness for all three natural fibres. Therefore, the addition of filler content is expected to enhance the composite's surface properties. In a composite with higher wt% of filler, the structure tends to resist the propagation of cracks. Consequently, this leads to the improved fracture toughness as a result of the crack bridging

and crack deflection mechanism, which enhances the resistance to crack propagation inside the composite leading to improvement in toughness [30]. The fracture toughness was also found to reduce with a longer scratch distance. Based on Fig. 6, the fracture toughness for the napier fibre-filled epoxy composites was found to be the highest at all the scratch distances compared to the PALF and hemp fibre-filled epoxy composites. The fracture toughness was calculated at several scratch distances: 1, 3, 5 and 7 mm. The fracture toughness of the PALF fibre-filled epoxy composite was reduced to 51, 62 and 69% for 5, 7.5 and 10 wt% of fillers, respectively. The percentage of reduction in the fracture toughness for napier is lower than that of the PALF fibre-filled epoxy composite, which stands at 47, 56 and 58% for 5, 7.5 and 10 wt% of fillers, respectively. In addition, the fracture toughness for the hemp fibre-filled epoxy composites with 7.5, and 10 wt% of filler were reduced by, 54 and 52%, respectively. However, the percentage of reduction for 5 wt% of hemp filler is higher than that recorded for the napier fibre-filled epoxy composites measuring at 56%.
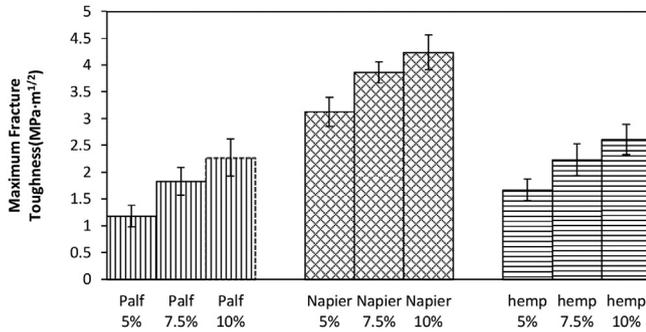
Fig. 7 – Maximum fracture toughness for natural fibre-filled epoxy composites.

The maximum fracture toughness for the natural fibre-filled epoxy composites was observed at a scratch distance where the horizontal force was maximum. Fig. 7 illustrates the maximum fracture toughness for the PALF, napier and hemp fibre-filled epoxy composites. The fracture toughness, K_c for the napier fibre-filled epoxy composite with 10 wt% of filler yielded the highest value of 4.33 MPa m$^{1/2}$. This is followed by 7.5 and 5 wt% of fillers, having a fracture toughness of 3.75 and 2.77 MPa m$^{1/2}$, respectively. The fracture toughness of the hemp fibre-filled epoxy composites was calculated at 1.671, 2.231 and 2.686 MPa m$^{1/2}$ for 5, 7.5 and 10 wt%, respectively. For the PALF fibre-filled epoxy composites, the recorded values are 1.038, 1.374, and 2.280 MPa m$^{1/2}$ for 5, 7.5 and 10 wt%, respectively. Therefore, it can be concluded that the napier filled composites yielded the highest resistance towards fracture, followed by the hemp and PALF fibre-filled epoxy composites. The results obtained through these tests are in good agreement with the models recommended by Akhono and Ulm [31] where the fracture toughness was shown to have a directly proportional relationship to the horizontal load produced by the indenter. In addition, this maintains an inversely proportional relationship to the depth of penetration.

3.4.   Scratch hardness

Scratch hardness is the ability of a material to resist scratch and abrasion. The scratch hardness of natural fibre-filled epoxy composites was found using Eq. (3) [30].

$$H_s = \frac{8F_N}{\pi D^2} \tag{5}$$

where,

H_s = Scratch hardness,
F_N = Normal load,
D = Scratch width

The experiments were conducted to evaluate the scratch hardness measured from the top surface of the samples. Fig. 8 shows that the scratch hardness reduces with an increase in the scratch distance. It has a trend similar to that of the fracture toughness of the composites. With a higher wt% of fillers, the scratch hardness attains maximum values for all three composites samples. Fig. 8(a) shows that the scratch hardness of the PALF fibre-filled epoxy composites are 0.725, 1.033 and 1.817 at 1 mm of scratch distance for 5, 7.5 and 10 wt%
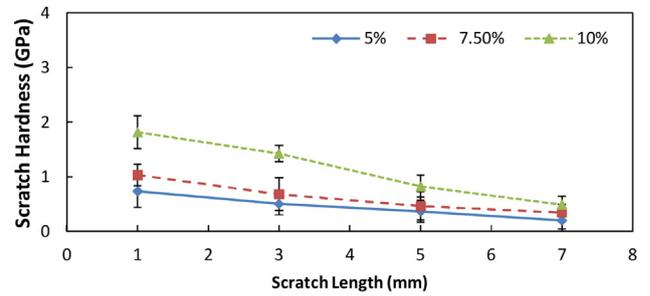
(a) PALF fibre-filled epoxy composites
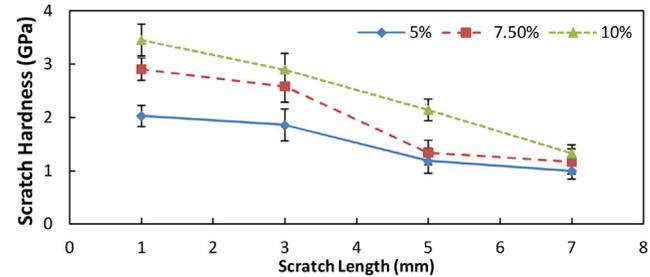
(b) Napier fibre-filled epoxy composite
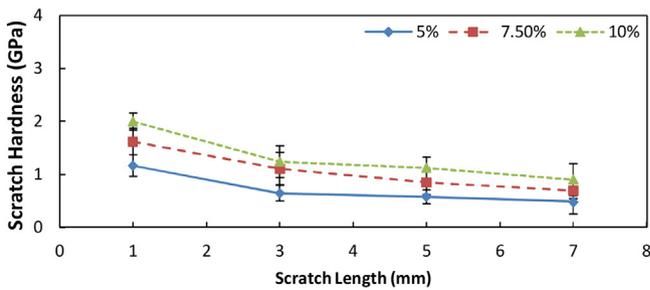
(c) Hemp fibre-filled epoxy composite

Fig. 8 – Scratch hardness of natural fibre-filled epoxy composites.
(a) PALF fibre-filled epoxy composites.
(b) Napier fibre-filled epoxy composite.
(c) Hemp fibre-filled epoxy composite.

of fillers, respectively. The percentage of reduction in scratch hardness is 2% for 5 and 7.5 wt%, and 72% for 10 wt% of fillers, respectively as the scratch distance varies from 1 to 7 mm. The scratch hardness of the napier fibre-filled epoxy composite increases to 2.029, 2.903, 3.454 GPa at 1 mm of scratch distance for 5, 7.5 and 10 wt% of fillers, respectively as shown in Fig. 8(b). The percentages of reduction in scratch hardness are 51, 59 and 62% for 5, 7.5 and 10 wt% of napier filler as the scratch distance varies from 1 to 7 mm. However, the percentage of reduction for the hemp fibre-filled epoxy composites was lower than that of the napier fibre-filled epoxy composite. It was measured at 1.165, 1.62 and 2.002 GPa at 1 mm of scratch distance for 5, 7.5 and 10 wt% of hemp fillers, respectively. The percentages of reduction in scratch hardness are 55, 57 and 58% for 5, 7.5 and 10 wt% of hemp filler, respectively (for variation in scratch distance from 1 to 7 mm) as shown in Fig. 8(c). According to Eq. (3), scratch hardness is proportional to the normal force on the indenter and is inversely proportional to the load-bearing area of the scratch [30]. The

load-bearing area of the scratch depends on the penetration depth.

3.5. Brittleness index

Brittleness index, also known as the ratio of hardness and fracture toughness, takes into account both the response of the material regarding the fracture toughness and the scratch hardness. This could be used to adequately judge the mechanical characteristics of the material without considering the hardness and fracture toughness independently [43]. The procedure for evaluating the brittleness index for these composites was based on the model proposed by Lawn and Marshall [44]. Fig. 9 illustrates that a higher wt% of filler in a composite increases the brittleness index, exhibiting a pattern similar to penetration depth, fracture toughness and scratch hardness. The highest brittleness index of the napier fibre-
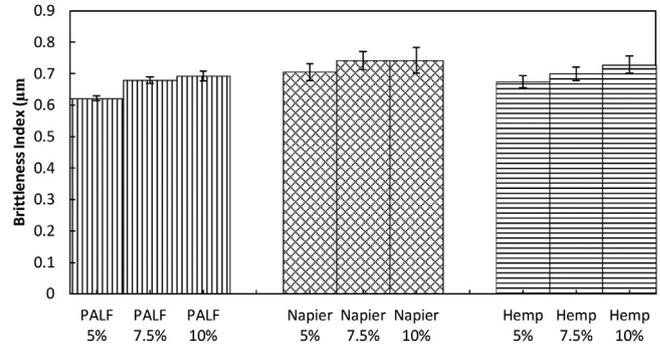
**Fig. 9 – Brittleness index of natural fibre-filled epoxy composites.**
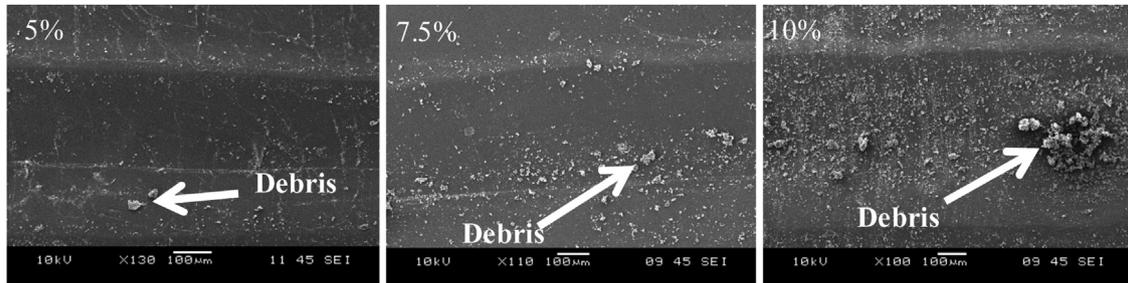
(a) PALF fibre-filled epoxy composites
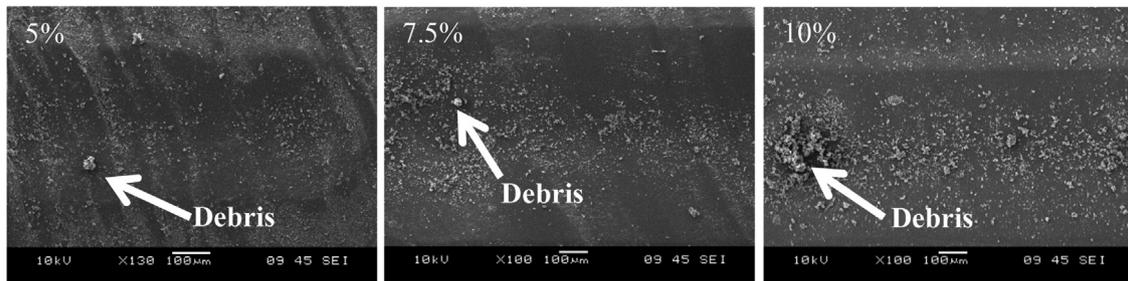
(b) Napier fibre-filled epoxy composite
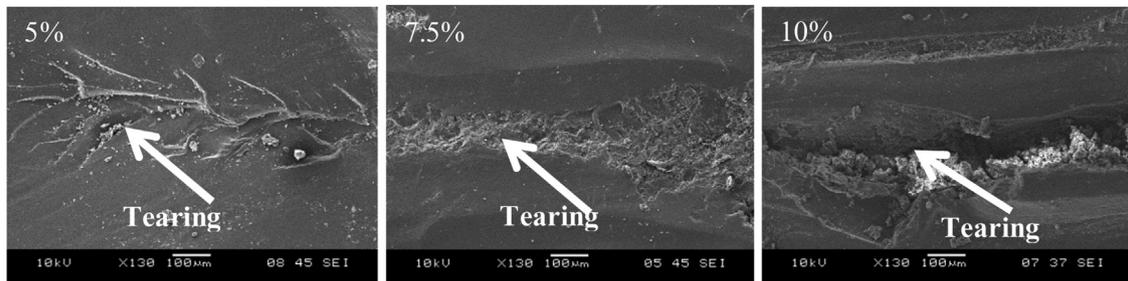
(c) Hemp fibre-filled epoxy composite

Fig. 10 – Scanning electron microscope images of natural fibre-filled epoxy composites.
(a) PALF fibre-filled epoxy composites.
(b) Napier fibre-filled epoxy composite.
(c) Hemp fibre-filled epoxy composite.

filled epoxy composites for 10 and 7.5 wt% was 0.74 $\mu m^{-\frac{1}{2}}$, followed by 5 wt% with brittleness index of 0.71 $\mu m^{-\frac{1}{2}}$. The hemp fibre-filled epoxy composite resulted in a brittleness index of 0.67, 0.70, and 0.73 $\mu m^{-\frac{1}{2}}$ for 5, 7.5 and 10 wt% of fillers, respectively. The PALF fibre-filled epoxy composite achieved the lowest brittleness index among these composites, which was found to be 0.62, 0.68 and 0.693 $\mu m^{-\frac{1}{2}}$ for 5, 7.5 and 10 wt%, respectively. Therefore, the napier fibre-filled epoxy composites were found to produce the peak brittleness index for each wt% of filler compared to the PALF and hemp fibre-filled epoxy composites.

3.6. Scratch observation

Fig. 10 shows the scanning electron microscopic (SEM) images of surface scratches for the natural fibre-filled epoxy composites under different wt% of filler. The study revealed that the composites' deformation is strongly dependent on the nature of the polymer composites. It can be seen through different wt% of the filler and different types of natural fillers. In order to assess the effects of wt% of filler and different types of fillers on the scratch behaviour of the composites, it is essential to understand and analyse the scratch deformation mechanisms on the surfaces of the composites using SEM images. In general, from the SEM images, it can be observed that a higher wt% of the natural filler increases the amount of debris on the composites' surfaces. The scratch test for the PALF and napier fibre-filled epoxy composites produced debris. It can also be seen that the amount of debris increased with higher of wt% of the natural fillers in the composites. However, the observations from the SEM images for the hemp filled epoxy composites indicate tearing on the surface of the composites. The tearing increased and enlarged with higher wt% of the Hemp fibres in the composites. Tearing was only observed with the hemp filled composites, which may relate to the penetration depth during the test. The penetration depth of hemp is higher than that of the PALF, and napier filled epoxy composites, as shown in Fig. 5. The higher depth at the beginning of the test caused an increase in the amount of material being pushed out as a result of the stick-slip motion of the tip, which becomes severe at higher loads. The high interfacial friction tends to bring the tip more in-depth into the material, resulting in an increase in the volume of the deformed material [45]. The COF of the hemp filled epoxy composites (from the initial part of the test to the end of the test) were quite consistently compared to that of the PALF, and napier filled epoxy composites as shown in Fig. 4.

3.7. Scratch resistance properties of polymer, ceramics and natural fibre composites

The scratch resistance properties of polymers, ceramics and natural fibre composites are tabulated in Table 2. The scratch resistance properties of polymers and ceramics were acquired from the literature, while the scratch resistance properties of natural fibre composites were obtained from the experimental data. In the previous study, the natural fibres as reinforcement materials show significant improvement in the mechanical properties of the epoxy composites [46]. In addition, they also reported the natural fibres composites has potentials in automobiles such as package trays, sun visors, seat backs, door panels, hat racks, and exterior/underfloor panelling [47], and also has been used in interior materials in aerospace industries [48]. Therefore the comparison of scratch performance between natural fibres composites with polymers and ceramics are very significant.

Overall, Table 2 shows that the scratch resistance properties of natural fibre composites are comparable with those of the polymers. The comparison of peak load indicates that the napier and hemp fibre-filled epoxy composites were performed higher compared to polymers. This is due to the reinforcement materials influence on the strength properties of the materials. The penetration depth of natural fibre composites also shows a lower value than the polymers, which indicates that they have high scratch resistance compared to polymers. The fracture toughness between natural fibres

Material	Peak load (N)	COF	Penetration depth	Fracture toughness	Scratch hardness	References
Table 2 – Scratch resistance properties of polymer, ceramics and natural fibre composites.						
Polymers						
Polyvinylchloride (PVC)	17	–	440.01	–	0.290	[13]
Polypropylene (PP)	15.5	–	486.09	–	0.350	[13]
Polycarbonate (PC)	18.2	–	375.51	–	0.490	[13]
Polyetheretherketone (PEEK)	17	–	330.59	–	0.510	[13]
Polymethylmethacrylate (PMMA)	14	–	368.6	–	0.420	[13]
Polyoxymethylene (POM)	15	–	334.04	–	0.610	[13]
Polyethylenetrephthalate (PET)	14	–	336.35	–	0.420	[13]
Ceramics						
Aluminium Oxide (Al2O3)	–	–	–	2.7	15	[30]
Silicone Carbide (SiC)	–	–	–	4.1	17	[30]
Titanium Diboride (TiB2)	–	–	–	1.67	–	[30]
Chromium(III) Oxide (Cr2O3)	–	–	–	3.9	–	[30]
Natural fibre composites						
PALF fibre-filled epoxy composites	14.28	0.276	141	2.27	1.82	–
Napier fibre-filled epoxy composites	34.27	0.703	147	4.24	3.45	–
Hemp fibre-filled epoxy composites	20.55	0.388	161	2.61	2.01	–

Table 3 – Density and porosity of natural fibre-filled epoxy composites.

Composites	w_f	w_e	ρ_{exp} (kg/m^3)	ρ_{theory} (kg/m^3)	Porosity (%)
PALF 5%	0.050	0.950	1100.0	1121.0	1.82
PALF 7.5%	0.075	0.925	1102.9	1131.5	2.53
PALF 10%	0.100	0.900	1109.5	1142.0	2.85
Napier 5%	0.050	0.950	1046.3	1063.0	1.57
Napier 7.5%	0.075	0.925	1022.4	1044.5	2.12
Napier 10%	0.100	0.900	1001.0	1026.0	2.35
Hemp 5%	0.050	0.950	1100.0	1119.0	1.67
Hemp 7.5%	0.075	0.925	1102.4	1128.5	2.31
Hemp 10%	0.100	0.900	1108.4	1138.0	2.60

composites and ceramics are also comparable; the significant difference can be seen with napier fibre-filled epoxy composites yielding the highest fracture toughness. The scratch hardness of natural fibre composites has been seen higher than polymers, but the scratch hardness of ceramics higher than natural fibres composites.

3.8. Density and porosity of the natural fibre-filled epoxy composites

Table 3 displays the theoretical and experimental density, and also the porosity of the natural fibre-filled epoxy composites. It can be seen that the theoretical density is slightly higher than the experimental value for each composites sample. The density values of PALF and hemp fibre-filled epoxy composites are found to increase as the percentage of fibre weight fraction increases. However, the density of napier fibre-filled epoxy composites decreases as the percentage of fibre weight fraction increases. The results reveal that the percentages of the porosities were 1.82–2.85, 1.57–2.35 and 1.67–2.31 % for PALF, napier and hemp fibre-filled epoxy composites respectively. The porosity of the napier fibre-filled epoxy composites was the lowest compared to PALF and hemp fibre-filled epoxy composites for each weight fraction (wt%) of filler. The lower porosities percentage were correlated to produce the highest fracture toughness, and scratch hardness of the natural fibre-filled epoxy composites. This would be expected to increase the scratch resistance of the composites materials.

4. Conclusion

In this work, the scratch resistance properties of pineapple leaf (PALF), napier and hemp fibres as filler in epoxy composites with varying amounts of wt% of fillers were investigated. A higher wt% of fillers enable resistance of the horizontal load before brittle failure for all composites samples. The napier fibre-filled epoxy composites yielded a greater scratch distance at the peak load compared to the PALF and hemp fibre-filled epoxy composites. This suggests that the napier fibre-filled epoxy composites can yield greater resistance than the PALF and hemp fibre-filled epoxy composites. A higher wt% of filler in natural fibre-filled epoxy composite increases the maximum value of the COF, which results in a better frictional behaviour of the composites. The COF of napier was higher than the PALF and hemp fibre-filled epoxy composite at each of wt% of filler. The napier fibre-filled epoxy com-

posites result in the lowest penetration depth for each wt% of the fillers. This reveals that napier has a higher scratch resistance compared to PALF and hemp fibre-filled epoxy composites. The increase in penetration depth and load-bearing area affects the fracture toughness and scratch hardness. The fracture toughness and scratch hardness for the napier fibre-filled epoxy composites were highest for all scratch distances compared to the PALF and hemp fibre-filled epoxy composites. In addition, the porosity of the napier fibre-filled epoxy composites was the lowest compared to PALF and hemp fibre-filled epoxy composites for each weight fraction (wt%) of filler. Therefore, it can be concluded that napier has the highest resistance towards fracture, followed by hemp and PALF fibre-filled epoxy composites. Finally, the comparison of scratch resistance properties of natural fibre-filled epoxy composites with the polymers and ceramics are comparable.

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