



Fabrication, characterisation and durability performance of kenaf fibre reinforced epoxy, vinyl and polyester-based polymer composites

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Abstract

In this study, Kenaf fibre–reinforced polymer (KFRP) composites containing 10%, 30% and 40% of fibre volume fractions were produced to examine the effects of ageing on the polymer composites. The samples were exposed to a laboratory environment (the control sample), outdoor environment, along with immersion in water and acid (5 wt.%, H₂SO₄) for 12- and 24-month exposure periods. The control samples were stored under normal and darkroom conditions followed by the comprehensive characterisation of the physical properties and mechanical performance attributes of the composites. The results revealed significant surface degradation, while fungal growth, surface roughness and discolouration were observed on sample surfaces exposed to outdoor conditions after 12 and 24 months. The unexposed samples displayed higher tensile and compressive properties compared to the exposed samples. The higher fibre volume fractions resulted in higher mechanical properties and weathering degradation. The tensile strength of the Kenaf/epoxy composite with a fibre volume content of 40% was 31%, which is 133% higher than the 10% and 30% fractions. Kenaf/vinyl ester composites displayed the highest mechanical properties followed by the Kenaf/polyester and Kenaf/epoxy composites after 12- and 24-month ageing. Therefore, the KFRP composites are suited for lumber-based floor finishing, wall panels, ceiling finishing, doors and windows panels.

Keywords Polymer composites · Kenaf · Natural fibres · Resin · Ageing · Reinforced polymers

1 Introduction

The uncertainties and non-availability of petroleum-based materials and the demand for abundant and cheaper manufactured products have prompted research towards producing

natural fibre-based composites. These efforts are meant to save production costs and provide polymeric materials with superior mechanical and durability properties. Today, a universal movement towards the realisation of a “Green World” is being canvassed to preserve our environment and create a safer world [1, 2]. Biocomposites are needed for various reasons such as the growing demand for greener and affordable composites due to the rising costs of wood resources. Secondly, the global concerns about the environment and diminishing petrochemical resources have also driven the search for new materials such as fibre-based products and biopolymers [3, 4]. Likewise, the growing advances in technology and market competition in developed countries has catalysed the research and development of marketable biocomposite materials [5, 6]. Hence, the use of composite materials as alternative construction materials is now widely accepted due to its ability to sustain structural loads similar to the current conventional materials such as concrete, steel and timber [7, 8].

Biocomposites are produced from the combination of natural fibres and polymer matrix derived from renewable

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resources like vegetable oils, starches and non-renewable resources [9–11]. Natural fibres are agro-based resources categorised into different groups: leaf (pineapple fibre, sisal and henequen), bast (Kenaf, jute, flax, hemp and ramie) and fruit (oil palm empty fruit bunch) [12–15]. Natural fibres are low-cost, low-density, low energy content and recyclable materials that possess excellent strength-to-weight ratio, strong resistance to breakage during processing [16, 17]. Hence, natural fibres are widely considered an alternative to glass fibre, which is a popular composite reinforcement [18–20].

The production and handling of biocomposites require a comprehensive understanding of fibre combinations, processing methods, water absorption, aspect ratio and fibre volume fractions [21–23]. The outlined factors influence the properties and ability to modify natural fibre-based composites. The final properties are also considerably influenced by process parameters, which can change depending on the nature of the fibre matrix combination [24–26]. Lastly, the fabrication or processing methods such as compression moulding, injection moulding, extrusion moulding, and hand lay-up are also critical to the final properties of natural fibre composites [21, 27].

Kenaf (*Hibiscus cannabinus* L.) is a fast-growing herbaceous woody plant of the *Malvaceae* family, which has origins in Sub-Saharan Africa and Southeast Asia [28]. It is a high-yield perennial plant cultivated annually for its commercially viable applications in agriculture, energy, and materials [29]. The Kenaf plant is a rich source of natural cellulosic fibrous materials called the Kenaf fibre that is extracted from the plant stem or bast [30, 31]. The Kenaf fibre has attracted significant attention owing to its mechanical and physical properties that have extensive applications as substitute materials for composite reinforcement [32]. In Malaysia, the commercial viability of Kenaf as an industrial crop spurred the establishment of the natural Kenaf Research and Development Programme with an estimated RM 12 million (~USD\$ 3 million) budget under the 9th Malaysia Plan (2006–2010) [1, 33, 34]. The management of the Kenaf cultivation in Malaysia is handled by the National Kenaf and Tobacco Board (NKTB) [35].

Currently, Kenaf is commercially utilised in automotive panels, composite planks and insulation mats in the industry. Major global companies such as Panasonic and Toyota Motor are major stakeholders in the global Kenaf industry [36, 37]. Likewise, the construction industry has widely adopted the use of Kenaf fibres in the production of construction materials such as the Kenaf board, which is stronger and lighter than plywood and structural wallboard [38, 39]. Hence, it is a renewable and sustainable alternative to timber-based plywood [40, 41]. Furthermore, the use of natural fibres as reinforcements in polymer matrices for the manufacture of dough-moulding compounds and building

products has been extensively explored in the literature [42, 43]. The results demonstrated that natural fibre-based composite materials are susceptible to moisture, ultraviolet (UV) solar or thermal heat rays and microbial, acidic and corrosive substances. The severity of these factors adversely affects the performance, life span and environmental friendliness of natural fibre-based composites. Various researchers [44, 45] have shown that the addition of various volume fractions of synthetic fibres to concrete/cement enhanced the workability, durability, and performance of the resulting composites. Therefore, the appropriate selection of the matrix as well as the nature and volume fractions of the selected reinforcement could address the outlined challenges of natural fibre-based composites. However, studies on the impact of various volume fractions of low-cost, abundant, and environmentally friendly natural fibres such as Kenaf on various polymer matrices are limited in the scientific literature.

Therefore, this study seeks to examine the performance of Kenaf fibre-reinforced polymers (KFRP) comprising epoxy, polyester and vinyl ester as matrixes and Kenaf fibres as reinforcement under various exposure conditions for 2 years. The KFRP composites examined in this study contained 10%, 30% and 40% fibre volume fractions of Kenaf, which are higher than the 0.06 to 1.2% fractions of synthetic fibres reported in the literature [44, 45]. According to Mahjoub et al. [46], an increase in volume fraction enhances the tensile properties of fibre-based composites. It is envisaged that the findings will enhance the workability, durability, performance and sustainable use of KFRP and other natural fibre-based composites in the building/construction industry, which accounts of 8% of all anthropogenic carbon dioxide (CO₂) emissions worldwide [47, 48].

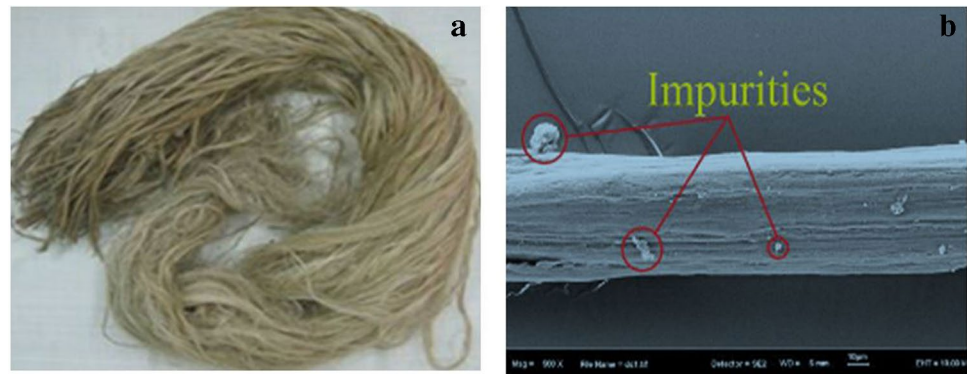
2 Experimental

2.1 Materials

2.1.1 Kenaf fibres

The Kenaf fibres used as reinforcement materials in this study were sourced from NKTB, Malaysia, as shown in Fig. 1a. The fibres were extracted manually from the base of the Kenaf plant stem through the water retting process. The physical properties of the fibres were examined by visual inspections (length, thickness, width and weight). The maximum length of the Kenaf fibres is 1.5 m. The preparation of Kenaf fibres for composites production was based on the size of the mould referring to the volume fractions for the fabrication of natural fibre composites. The fibre was alkali-treated using sodium hydroxide (5% NaOH) i.e. the mercerisation method after soaking for 3 h. According to

Fig. 1 **a** Kenaf fibre from water retting process. **b** SEM image of Kenaf fibre rough surface



Mahjoub et al. [46], alkali (mercerisation) treatment ensures fibre surface modification, which enhances hydrophobicity and the interface bonding of the fibre matrix through surface roughening.

Figure 1b shows the scanning electron microscopic (SEM) image of the rough fibre morphology and its inherent impurities. The treated Kenaf fibre has a density of 1.202 g/cm³ and 65.4 μm in diameter. The fibres were weighed and cut into the necessary weight of 2.31 g (10% of fibre volume fraction) and length of 200 mm, respectively. In theory, the increase in volume fraction enhances the tensile properties of fibre-based composites [46]. However, only 10%, 30% and 40% of fibre volume fractions were examined in the study. The percentage volume fraction was computed based on Eq. 1:

$$V_f = \frac{w_f}{\rho_f} \Rightarrow w_f = V_f \rho_f \quad (1)$$

The terms are as follows: w_f is the fibre weight (g); ρ_f the fibre density (g/cm³); and V_f the fibre volume (cm³).

2.1.2 Resin

The three types of resins used in this study were epoxy (EPI-COT 1006A System), polyester (Polyester 2597 PT/APT), and vinyl ester (Vinyl ester SR-825). The selected resins were purchased from a local supplier and the product specifications are detailed in Table 1. The selection of the resins was based on their suitability for the hand lay-up process widely used in the fabrication of composites [49].

Table 1 Properties of thermosetting polymer resins [50]

Type of resin	Blending ratio	Tensile strength (MPa)	Elongation (%)	Density (g/cm ³)
Epoxy (EPICOT 1006A System)	10 resin:6 hardener	51–100	1–4	1.11
Polyester (Polyester 2597 PT/APT)	1% catalyst	40–70		1.09
Vinyl ester (Vinyl ester SR-825)	1% catalyst	40–85		1.10

2.2 Composite fabrication

The sample fabrication process involved specimen preparation and the Kenaf fibre surface modification and treatment. Next, the constituents were subjected to mixing, curing, cutting and polishing of the samples to the standard size. The Kenaf fibre composites are labelled: KFREP (Kenaf fibre–reinforced epoxy polymer); KFRPP (Kenaf fibre–reinforced polyester polymer); and KRRVP (Kenaf fibre–reinforced vinyl polymer). Each sample was measured for dimensions and then weighed to calculate its density. The hand lay-up process was adopted for sample fabrication. The stages highlighted below are the details of the methods and procedures for the experiments.

2.2.1 Hand lay-up process

The Kenaf fibres were examined using 10%, 30% and 40% volume fractions. The three types of resins and the related hardener used are summarised in Table 1. The fabrication of the Kenaf fibre composites was performed at room temperature in the laboratory. The essential constituents of the resin and hardener were thoroughly mixed together in a beaker. Next, the fibres were submerged in the resin for a few seconds to expunge air bubbles in the Kenaf fibres. The Kenaf fibres were finally laid in the mould, and the resin was subsequently poured to fill the mould. The sample preparations and sample procedure were based on ASTM D-3039 Standard [51] for unidirectional fibre with a dimension of (25 × 6 × 200) mm³. For the determination of the tensile and compressive properties, moulds with (275 × 25 × 6) mm³ and



Fig. 2 Open mould system

($175 \times 25 \times 6$) mm³ were used respectively. The moulds were made of steel plates and were free of dust and dirt (Fig. 2). A layer of wax was applied to the mould before the fabricating process to ensure easy removal of the composite after solidification. All the procedures employed were for hand lay-up systems, and preventative action was taken into account during the specimen fabricating process. After composite preparation, the samples were attached with a strain gauge in the middle of the gauge region, where the strain gauge was attached in the longitudinal direction of the specimen axis. The composite strain gauge series of BFLA-5-8-1L with 1 m prewire was used to acquire the measured strain measurement.

2.2.2 Composite testing

The tensile strength and tensile modulus of the KFRP composites were examined under tropical climate conditions (i.e. ultraviolet (UV) exposure) and immersions in water

and acid. The fabricated composites were exposed to the high UV index characteristic of tropical climates as well as water and acid conditions to examine their performance during practical applications. The tensile test was conducted on the exposed and control KFRP samples (Fig. 3) after the specified period of different exposure conditions. During testing, the tensile stress–strain behaviour of KFRP samples exhibited approximately linear trends up to the point of failure similar to the initial tensile test of the materials. The tensile test was conducted using the Universal Testing Machine (INSTRON 5567, Capacity: 100 KN in Fig. 4) according to the ASTM D3039 standard [51]. The machine and the linear voltage displacement transducer (LVDT) were attached to the data logger (TDS-303) shown in Fig. 4. The test results were obtained from the high-precision and computerised control systems of the experimental set-up. The stress–strain curves were then plotted from the results using Microsoft Excel© (version 2013). Lastly, the ultimate tensile strength and Young's modulus of the KFRP composites were analysed.

3 Results and discussion

The Kenaf fibre physical properties and the tensile properties of KFRP composites formed using epoxy (KFREP), polyester (KFRPP) and vinyl ester (KFRVP) in different fibre volume contents are presented in this section. The results

Fig. 3 Sample of the tensile test



Fig. 4 Tests set-up and failure sample for the tensile test



describe the performance of the KFRP composites under the controlled and exposed conditions described in the experimental section.

3.1 Changes in thickness and width

The KFRP composites were first visually investigated in the laboratory. The visual investigations in this study were categorised into two parts: specimen thickness measurement and weight variation measurement. Table 2 illustrates the measurement of the controlled sample kept in the laboratory, devoid of any impactful exposure. According to the negative and positive deviation in Table 2, the positive deviation indicates tolerance expansion of the thickness and width, whereas the negative deviation denotes contraction. The results show that the width and thickness of the KFRP samples with different polymer matrix are not significant. The small percentage difference observed between the standard thickness and average thickness of the sample occurred due to the shrinkage the specimen experienced during the fabrication and curing process of composites. For the exposed

KFRP samples, the thickness variation was monitored after 12 and 24 months of exposure. The thickness measurement was based on an apparent thickness (shown in Fig. 5), which is considered the loose degradative depth. However, it was challenging to measure the effective thickness due to the unevenness and irregularities of the surface of the samples at either pre- or post-exposure conditions. Figure 6 presents the representative end to end thickness microscopic view of the control and exposed samples after 24 months of exposure, which is presented as a degradation layer on the sample surface.

Alternatively, the control sample remained in its original condition. The thickness measurements of the exposed samples are presented in Tables 3, 4 and 5. The positive value in differential thickness represents increment, whereas the negative value shows a reduction. The KFRP samples decreased in thickness after 12 and 24 months due to degradation process during exposure. The KFREP exhibited a greater reduction in thickness compared to KFRPP and KRRVP samples, respectively. The results indicate that the epoxy resin showed lower resistance

Table 2 Thickness of KFRP samples

Sample	Volume fraction (%)	Minimum thickness (mm)	Maximum thickness (mm)	Average (mm)	Nominal (mm)	Deviation (mm)	Allowable deviation (mm)
KFREP	10%	6.02	6.05	6.03	6.00	+0.03	±0.68
	30%	5.98	6.03	6.00	6.00	+0.00	±0.68
	40%	5.95	6.09	6.02	6.00	+0.02	±0.68
KFRVP	10%	5.93	5.97	5.95	6.00	0.05	±0.68
	30%	6.03	6.03	6.04	6.00	+0.04	±0.68
	40%	5.96	6.05	6.00	6.00	+0.00	±0.68
KFRPP	10%	5.92	6.08	6.00	6.00	+0.00	±0.68
	30%	5.99	6.01	6.00	6.00	+0.00	±0.68
	40%	5.90	5.94	5.92	6.00	-0.08	±0.68

Fig. 5 Description of initial, apparent and effective thickness of KFRP samples after exposure

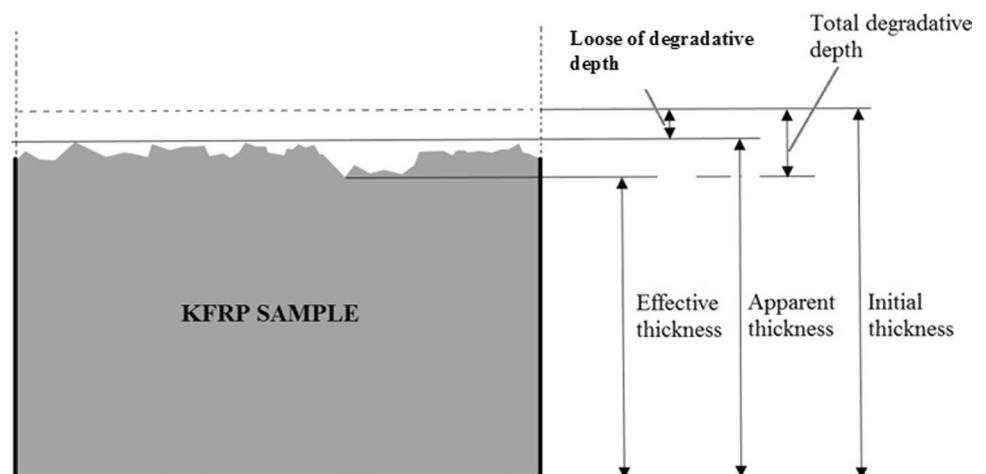


Fig. 6 Through thickness microscopic view of exposed and control samples after 24 months

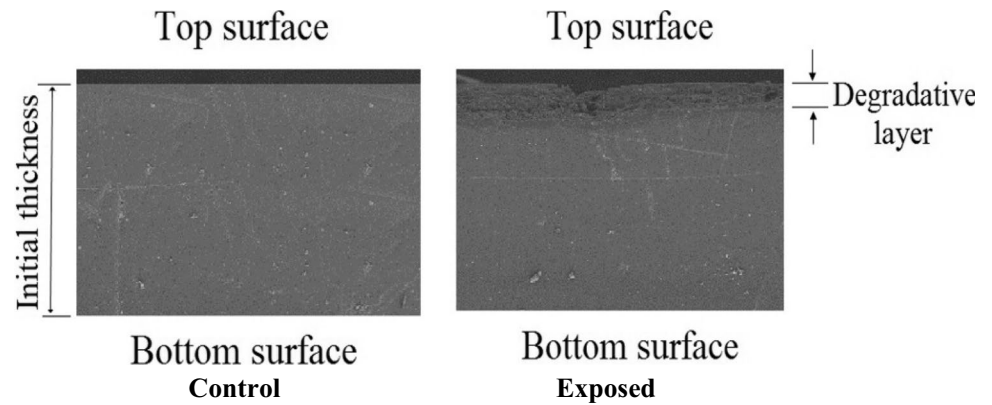


Table 3 Observed thickness of KFRP samples in tropical climate after 12 and 24 months

Sample	Volume fraction	Initial thickness (mm)	Thickness and different thickness (mm)			
			12 months		24 months	
KFREP	10%	6.02	5.87	-0.15	5.86	-0.16
	30%	5.98	5.82	-0.16	5.80	-0.18
	40%	5.95	5.77	-0.18	5.76	-0.19
KFRVP	10%	5.97	5.88	-0.09	5.88	-0.09
	30%	6.03	5.94	-0.09	5.92	-0.11
	40%	6.05	5.93	-0.12	5.91	-0.14
KFRPP	10%	6.07	5.96	-0.11	5.95	-0.12
	30%	5.99	5.86	-0.13	5.85	-0.14
	40%	5.94	5.80	-0.14	5.78	-0.16

Table 4 Observed thickness of KFRP samples immersed in 5% H₂SO₄ after 12 and 24 months

Sample	Volume fraction	Initial thickness (mm)	Thickness and different thickness (mm)			
			12 months		24 months	
KFREP	10%	6.07	6.00	-0.07	5.99	-0.08
	30%	6.03	5.96	-0.07	5.94	-0.09
	40%	5.98	5.88	-0.10	5.87	-0.11
KFRVP	10%	5.97	5.93	-0.04	5.92	-0.05
	30%	6.05	5.99	-0.06	5.99	-0.06
	40%	6.00	5.93	-0.07	5.92	-0.08
KFRPP	10%	6.08	6.02	-0.06	6.02	-0.06
	30%	5.99	5.92	-0.07	5.91	-0.08
	40%	5.94	5.86	-0.08	5.85	-0.09

under acid and water immersion along with the tropical climate conditions when compared to the polyester and vinyl ester. The results also showed that the thickness variation increased with the increasing volume fraction of Kenaf fibre. Lastly, the thickness variation of KFREP-40% in a tropical climate is more than other series of KFRP samples. The tropical climate is often hot, humid and dry. Due to heavy rains and high temperatures in a tropical climate, the apparent surface of composites as well as the depth is weakened and damaged.

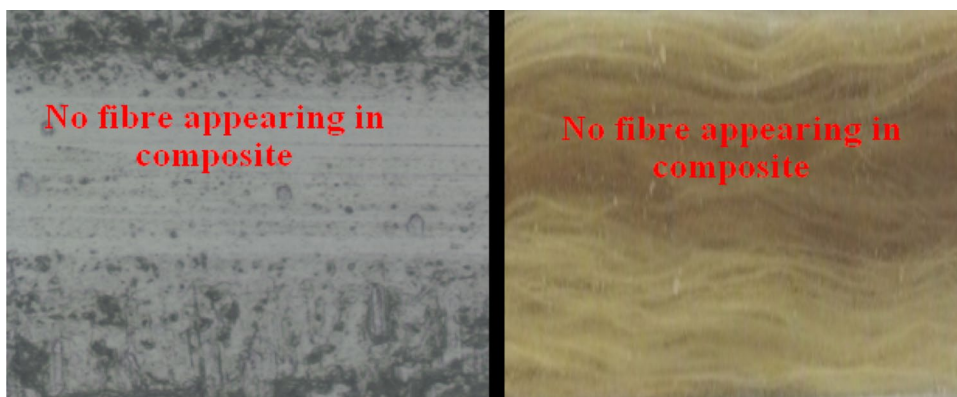
3.2 Weight variation and microscopic observation

The results from observations on the microstructure surface appearance, direct sample surface appearance and weight of KFRP control samples are shown in Figs. 7, 8 and 9 and Table 6, respectively. The microstructure surface appearance and the direct surface of the samples were examined using an optical microscope and digital camera. The comparison was made between the KFRP samples to identify the relative surface characteristics. The findings revealed that KFRP

Table 5 Observed thickness of KFRP samples immersed in water after 12 and 24 months

Sample	Volume fraction	Initial thickness (mm)	Thickness and different thickness (mm)			
			12 months		24 months	
KFREP	10%	6.05	6.00	-0.05	6.00	-0.05
	30%	6.01	5.95	-0.06	5.94	-0.07
	40%	6.09	6.01	-0.08	6.01	-0.08
KFRVP	10%	5.93	5.91	-0.02	5.91	-0.02
	30%	6.06	6.03	-0.03	6.02	-0.04
	40%	5.96	5.93	-0.03	5.91	-0.05
KFRPP	10%	5.92	5.89	-0.03	5.88	-0.04
	30%	6.01	5.97	-0.04	5.96	-0.05
	40%	5.90	5.84	-0.06	5.83	-0.07

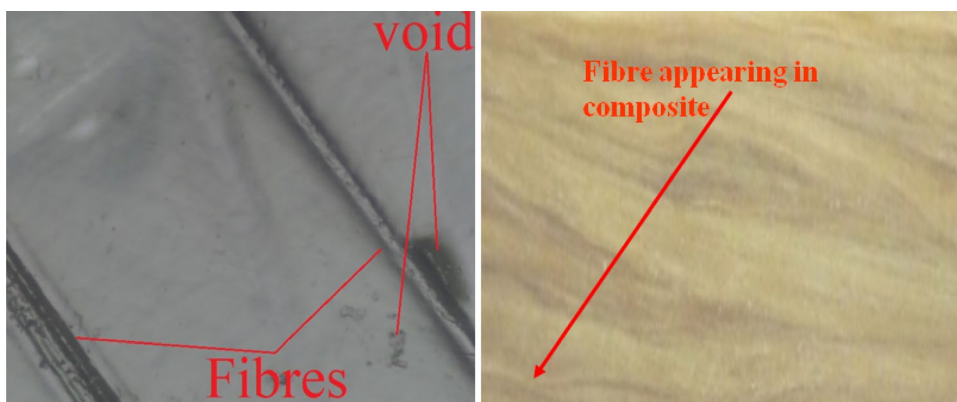
Fig. 7 Surface appearance of KFRP-10% (No voids or fibre exists in the resin-coated sample). **a** Microstructure surface appearance using an optical microscope. **b** Direct surface appearance using a digital camera



(a) Microstructure surface appearance using an optical microscope

(b) Direct surface appearance using a digital camera

Fig. 8 Surface appearance of KFRP-30% sample (no voids in the sample). **a** Microstructure surface appearance. **b** Direct surface appearance



(a) Microstructure surface appearance

(b) Direct surface appearance

samples exhibited smooth surfaces with no significant differences observed between the samples. However, the comparison of the KFRP (40%, 30% and 10%) samples indicated that the KFRP-40% exhibited a rougher surface compared to the other series. This observation is due to the high-fibre volume, which created bubbles and voids near the surface of the specimen. Likewise, the samples with 30% and 40% fractions exhibited shallow fibres underneath the surface.

Tables 7, 8 and 9 show the weight variation of exposed KFRP samples over 12 and 24 months in different conditions. The samples experienced an increase in weight due to moisture absorption. Conversely, the samples experienced weight decline due to contact with corrosive materials and particle separations under the different exposure conditions examined in the study. The weight variation of the laboratory and control samples was considerably unchanged with the

Fig. 9 Surface appearance of KFRP-30% sample (there are voids and fibre appearance underneath the resin-coated sample). **a** Microstructure surface appearance. **b** Direct surface appearance

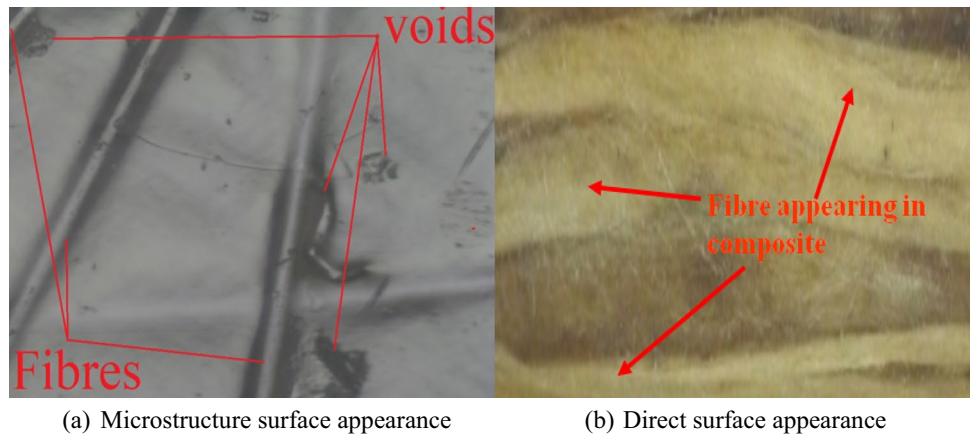


Table 6 Average of KFRP sample weights

Sample	Volume fraction	Average sample weight (g)	Standard deviation (S.D)	C.O.V (%)
KFRFP	10%	45.65	0.50	1.10
	30%	48.62	0.15	0.31
	40%	49.78	0.52	1.04
KFRVP	10%	45.89	0.21	0.46
	30%	48.74	0.43	0.88
	40%	49.65	0.11	0.22
KFRPP	10%	46.37	0.41	0.89
	30%	49.02	0.10	0.20
	40%	49.76	0.43	0.86

weight variation always below 0.25% of initial weight during the exposure period. The weight variation of KFRP-40% in UV, acid and water was observed to be very significant compared to KFRP-30% and KFRP-10% due to higher fibre volume fraction and increased water absorption. Furthermore, the weight variation of samples immersed in the acid liquid is more than water and tropical climate condition, respectively. In tropical climate conditions (UV), during

wet or rainy days, the relative humidity in the atmosphere is above 95%. Hence, it was observed that the samples absorbed a slight amount of moisture in the opened voids on the sample surface. However, the existing moisture in the openings or sample voids will be desorbed by evaporation on hot sunny days. For this reason, the samples experienced swelling leaching, dissolving and hydrolysis, which results in discolouration, chemical bond cleavage and debonding of the fibre-resin interface.

For the samples immersed in acid liquid, it was observed that acids could attack the polymer matrix, which makes the surface brittle. During the exposure times, the acid acts as a corrosive material and penetrates the middle part of composites, which results in swelling and disintegration of the fibre and matrix, along with the hydrolysis, discolouration and debonding of the fibre matrix. For the samples immersed in water, the degradation trend is similar to the other conditions, except that the fungi and algae grew randomly over the top surface of samples that could restrain the internal moisture from evaporating, which increased the depolymerisation process due to the availability of oxygen. To a large extent, it was observed that the continuous degradation process in UV, acid liquid and water conditions also caused the loss of thickness of the samples. Equation 2 shows a typical

Table 7 Effect of tropical climate on the weight variation of KFRP samples

Sample	Volume fraction	Initial weight (gramme)	Weight (gramme) and different weight (%)			
			12 months		24 months	
KFRFP	10%	45.52	46.50	+2.16	46.69	+2.58
	30%	48.59	49.89	+2.69	50.31	+3.54
	40%	49.18	51.05	+3.81	51.25	+4.22
KFRVP	10%	46.01	46.04	+0.07	46.05	+0.09
	30%	48.98	49.55	+1.17	49.74	+1.55
	40%	49.56	50.29	+1.49	50.46	+1.82
KFRPP	10%	45.97	46.44	+1.04	46.53	+1.21
	30%	49.10	49.84	+1.52	50.00	+1.84
	40%	49.88	50.84	+1.93	51.06	+2.36

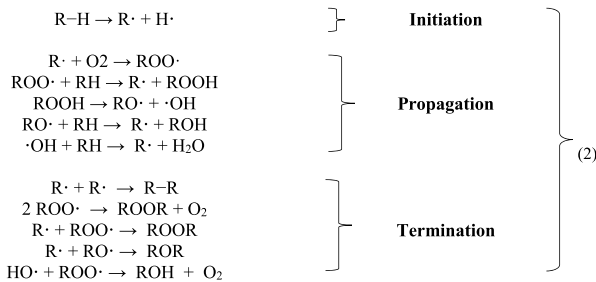
Table 8 Effect of acid liquid on the weight variation of KFRP samples

Sample	Volume fraction	Initial Weight (gramme)	Weight (gramme) and different weight (%)			
			12 months		24 months	
KFREP	10%	46.20	48.45	+4.87	48.52	+5.02
	30%	48.49	51.46	+6.12	51.85	+6.93
	40%	50.01	53.21	+6.41	53.68	+7.34
KFRVP	10%	45.65	46.59	+2.06	46.80	+2.53
	30%	48.25	49.54	+2.67	49.77	+3.16
	40%	49.77	51.29	+3.05	51.49	+3.46
KFRPP	10%	46.78	48.10	+2.82	48.24	+3.13
	30%	49.06	50.90	+3.75	51.11	+4.17
	40%	50.12	52.07	+3.90	52.38	+4.51

Table 9 Effect of water condition on the weight variation of KFRP samples

Sample	Volume fraction	Initial weight (gramme)	Weight (gramme) and different weight (%)			
			12 months		24 months	
KFREP	10%	45.23	47.01	+3.94	47.39	+4.79
	30%	48.78	50.85	+4.24	51.66	+5.92
	40%	50.16	53.03	+5.73	53.45	+6.56
KFRVP	10%	46.03	46.59	+1.23	46.75	+1.58
	30%	49.01	49.94	+1.90	50.35	+2.75
	40%	49.62	50.84	+2.46	51.13	+3.04
KFRPP	10%	46.38	47.19	+1.75	47.31	+2.01
	30%	48.91	50.15	+2.54	50.54	+3.33
	40%	49.28	50.81	+3.11	51.12	+3.74

representation of a chemical equation of the degradation process of polymer.



where *R* is the polymer; *R* the free radical; *O*₂ the oxygen molecule; *ROO*· the peroxy radical; *ROOH* the hydro-peroxide (formed by abstracting a hydrogen atom from another polymer chain) and (*RO*·) + (*OH*·) the two new free radicals which hydro-peroxide splits into.

3.3 Tensile strength and elastic modulus of KFRP

3.3.1 KFREP

The overall tensile properties of KFREP determined from the tensile test are presented in Fig. 10a, b, and c, and

Table 10. The tensile strength and elastic modulus for most of the KFRP samples reduced significantly after 12 and 24 months. The tensile properties under the tropical climate conditions are reduced due to environmental agents in the atmosphere such as ultraviolet radiation, moisture (water), oxygen, elevated temperature and impurities [52, 53]. Mohammed et al. [52] showed that the tensile strength of the fibre-reinforced polymers decreased by 15% when exposed to tropical atmospheric conditions. Likewise, Liew and Tan [53] reported that the tensile strength, bond strength and failure modes of fibre-reinforced polymers were adversely affected by extended exposure to atmospheric conditions. The decreased mechanical properties are ascribed to the decrease in the ultimate strain and modulus. The effects of the environmental agents are the leading causes of swelling, interfacial debonding (between fibre and resin) and decreased composite strength of fibre composites [54, 55]. The tensile properties of samples immersed in the acid liquid were reduced because of water and acidic liquid penetration through the fibre and resin. This observation could be ascribed to the swelling of Kenaf fibre and interfacial debonding of the fibre matrix, as similarly reported in the literature [56, 57]. Likewise, Bera et al. [58] and Mazuki et al. [59] reported that the absorption of moisture by *Luffa cylindrica* and Kenaf fibres, respectively, decreased the

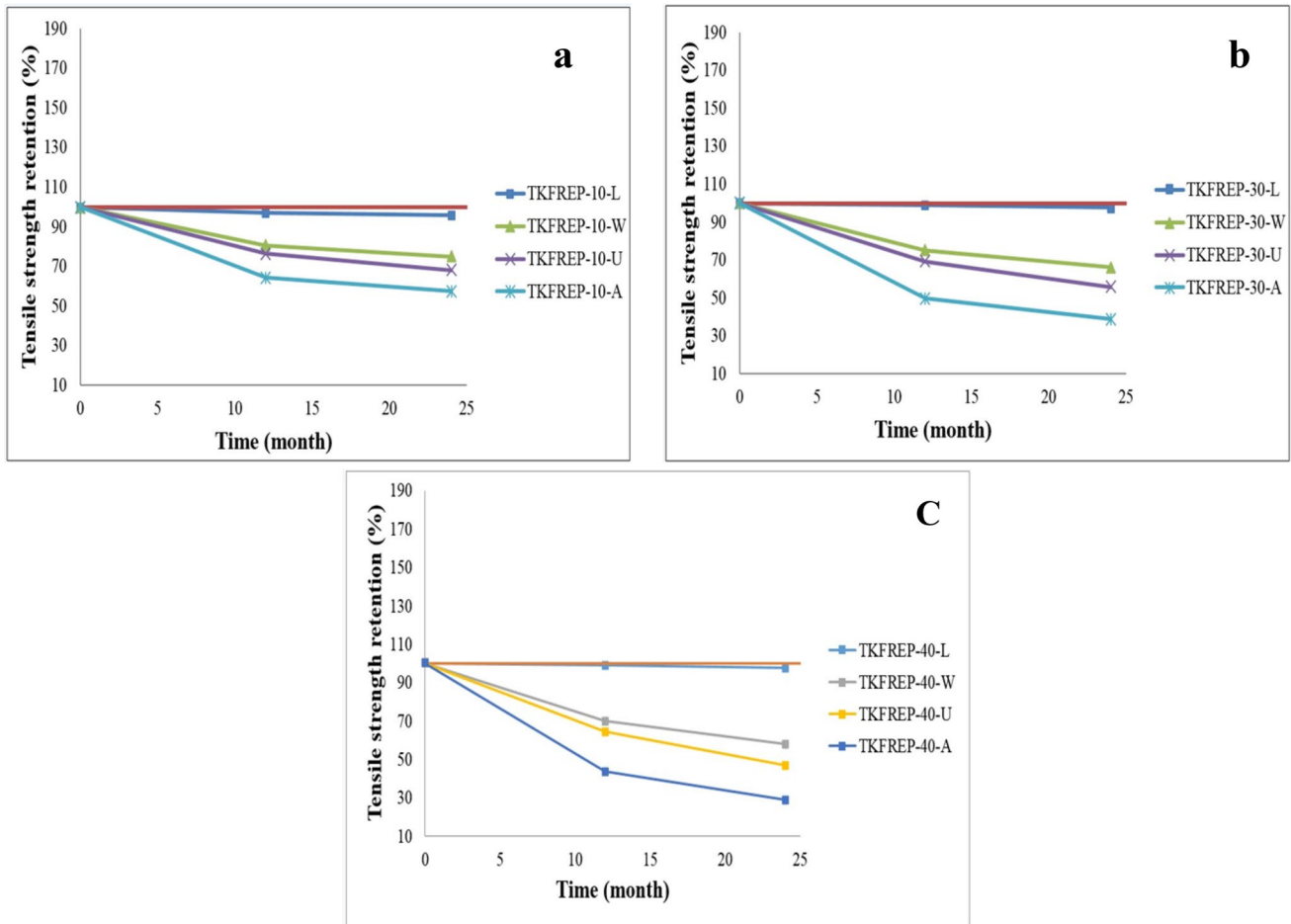


Fig. 10 The tensile strength of (a) KFREP-10%, (b) KFREP-30% and (c) KFREP-40% retention with respect to period of different conditions. *TKFREP, tensile strength retention of Kenaf fibre reinforced epoxy polymer composite; L, exposure condition in the laboratory; W, exposure condition in water; U, exposure condition to ultraviolet light ray; Air, exposure condition in air

Table 10 Tensile modulus of KFREP samples after exposure at different conditions

Fibre volume fractions (%)	Conditions	Initial value	Tensile modulus (N/mm^2) and (change in percent)			
			12 months	24 months	Standard deviation	C.O.V (%)
10%	LAB	8010	7820 (97.62)	7729 (96.5)	243–531	4.3–11.4
	WATER		5908 (79.2)	5413 (72.6)		
	UV		5524 (74.1)	4761 (63.8)		
	ACID		4704 (63.1)	4212 (56.5)		
30%	LAB	14,200	14,050 (98.9)	13,950 (98.23)	402–910	5.5–11.6
	WATER		10,366 (73.0)	8875 (62.5)		
	UV		9954 (70.1)	7228 (50.9)		
	ACID		6646 (46.8)	5211 (36.7)		
40%	LAB	17,900	17,684 (98.79)	17,579 (98.2)	264–1060	3.8–10.2
	WATER		12,154 (67.9)	9576 (53.5)		
	UV		11,277 (63.0)	7715 (43.1)		
	ACID		7142 (39.9)	4994 (27.9)		

mechanical properties of the fibre-reinforced composites due to changes in the cellulosic content. However, the destructive effect of acid liquid is greater than the UV and water conditions, as observed in this study. Hence, the tensile strength of the laboratory and control samples remained the same throughout the exposure period.

As observed, the samples under the laboratory conditions showed no significant reduction in tensile strength and modulus by less than 3% over 24 months compared to water immersion, ultraviolet exposure and acid liquid immersion conditions. The tensile strength and modulus of KFREP-W, KFREP-U and KFREP-A samples reduced less than 32%, 37% and 60% respectively, up to 12 months exposure and further reduced by up to 47%, 57% and 72% respectively, after 24 months of exposure. Similar findings were reported in the literature [52, 53]. The high degradation variations are because of the volumetric and lignocellulosic content of the fibres [58]. By increasing the volume content of composite, the degradation of the composite increased due to increased fibre swelling and the visible cracks all over KFRP composites.

Figure 11a shows the rupture section of the typical KFRP composite sample. It was noted that all KFRP composite series was subjected to rupture (failure) close to the middle of the gauge length, but there was no evidence of the fibres being pulled out from the matrix. This points to the strength of the interfacial bonding between the Kenaf fibre and polymer matrix, as indicated in the SEM images of fracture surface in Fig. 11b.

3.3.2 KFRPP

The trend of tensile properties of KFRPP is similar to the KFREP. The tensile strength and modulus for KFRPP samples showed significant reduction after 12 and 24 months, as shown in Fig. 12a, b, and c and Table 11, respectively. However, the variation of tensile strength and modulus of KFRPP samples is less than KFREP. The tensile strength

and modulus of KFRPP-W, KFRPP-U and KFRPP-A samples reduced below 22%, 30% and 51% respectively, up to 12 months of exposure, and further reduced by up to 30%, 45% and 71% respectively, after 24 months exposure. According to the results, the composite with polyester resin showed better resistance when exposed to various conditions when compared to the composite manufactured with epoxy resin.

3.3.3 KFRVP

The trend of tensile properties of KFRVP is similar to KFREP and KFRPP. The tensile strength and modulus for most of the KFRVP samples reduced significantly after 12 and 24 months, as shown in Fig. 13a–c and Table 12.

The tensile strength and modulus of KFRVP-W, KFRVP-U and KFRVP-A samples reduced by less than 16%, 21% and 40% respectively, after 12 months of exposure, and further reduced by up to 22%, 30% and 55% respectively, after 24 months exposure. According to the results, the vinyl ester resin showed high tensile properties compared to other series under different exposure conditions.

4 Conclusions

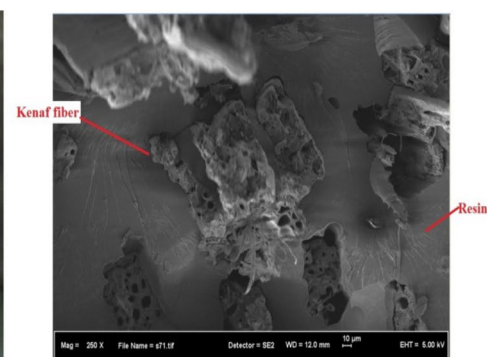
The fabrication, characterisation and durability performance of Kenaf fibre reinforced epoxy, vinyl and polyester-based polymer composites were examined in this study. The following conclusions have been deduced from the experimental findings of the study:

1. In the tropical climate condition, the top surface of the KFRP composites revealed greater degradation when compared to the bottom surfaces throughout the 24 months of exposure.
2. The thickness of exposed KFRP composites mostly reduced exponentially with time up to 24 months. The

Fig. 11 SEM image of the rupture area of KFRP. **a** Rupture section of KFRP composite sample. **b** SEM image of the rupture area of KFRP



(a) Rupture section of KFRP composite sample.



(b) SEM image of the rupture area of KFRP.

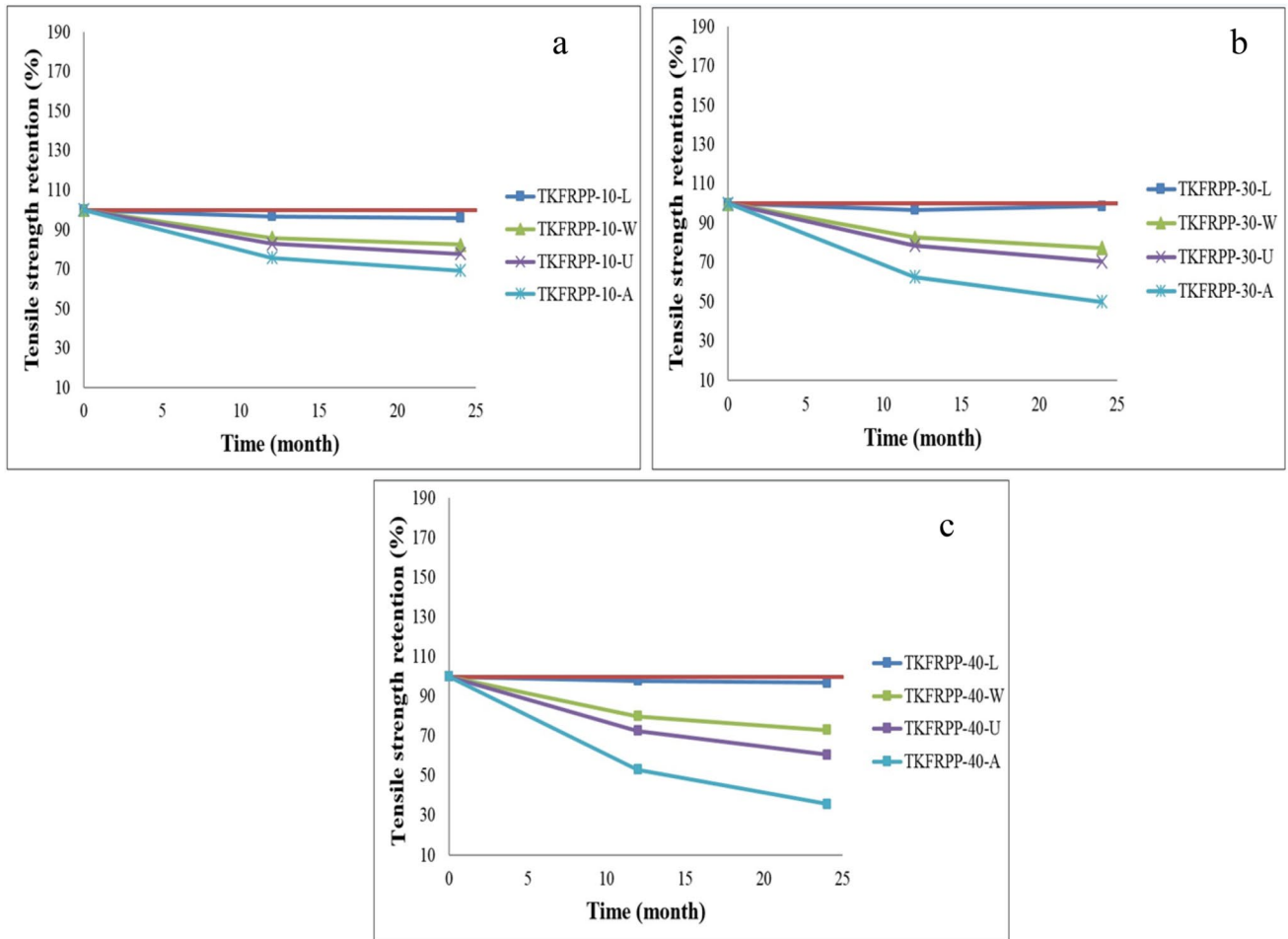


Fig. 12 Tensile strength of (a) KFRPP-10%, (b) KFRPP-30% and (c) KFRPP-40% retention with respect to period of different conditions

Table 11 Tensile modulus of KFRPP after the specified period of exposure in different conditions

Fibre volume fractions (%)	Conditions	Initial value	Tensile modulus (N/mm^2) and (change in per cent)			
			12 months	24 months	Standard deviation	C.O.V (%)
10%	LAB	7100	6880 (96.9)	6816 (96.0)	322–566	6.8–10.7
	WATER		6064 (85.4)	5765 (81.2)		
	UV		5794 (81.6)	5346 (75.3)		
	ACID		5311 (74.8)	4750 (66.9)		
30%	LAB	13,340	13,047 (97.8)	12,967 (97.2)	382–1070	3.5–11.3
	WATER		10,925 (81.9)	10,112 (75.8)		
	UV		10,178 (76.3)	8818 (66.1)		
	ACID		7977 (59.8)	5990 (44.9)		
40%	LAB	17,060	17,504 (102.6)	17,214 (100.9)	194–1054	2.3–9.6
	WATER		13,426 (78.7)	11,993 (70.3)		
	UV		11,908 (69.8)	9417 (55.2)		
	ACID		8411 (49.3)	4999 (29.3)		

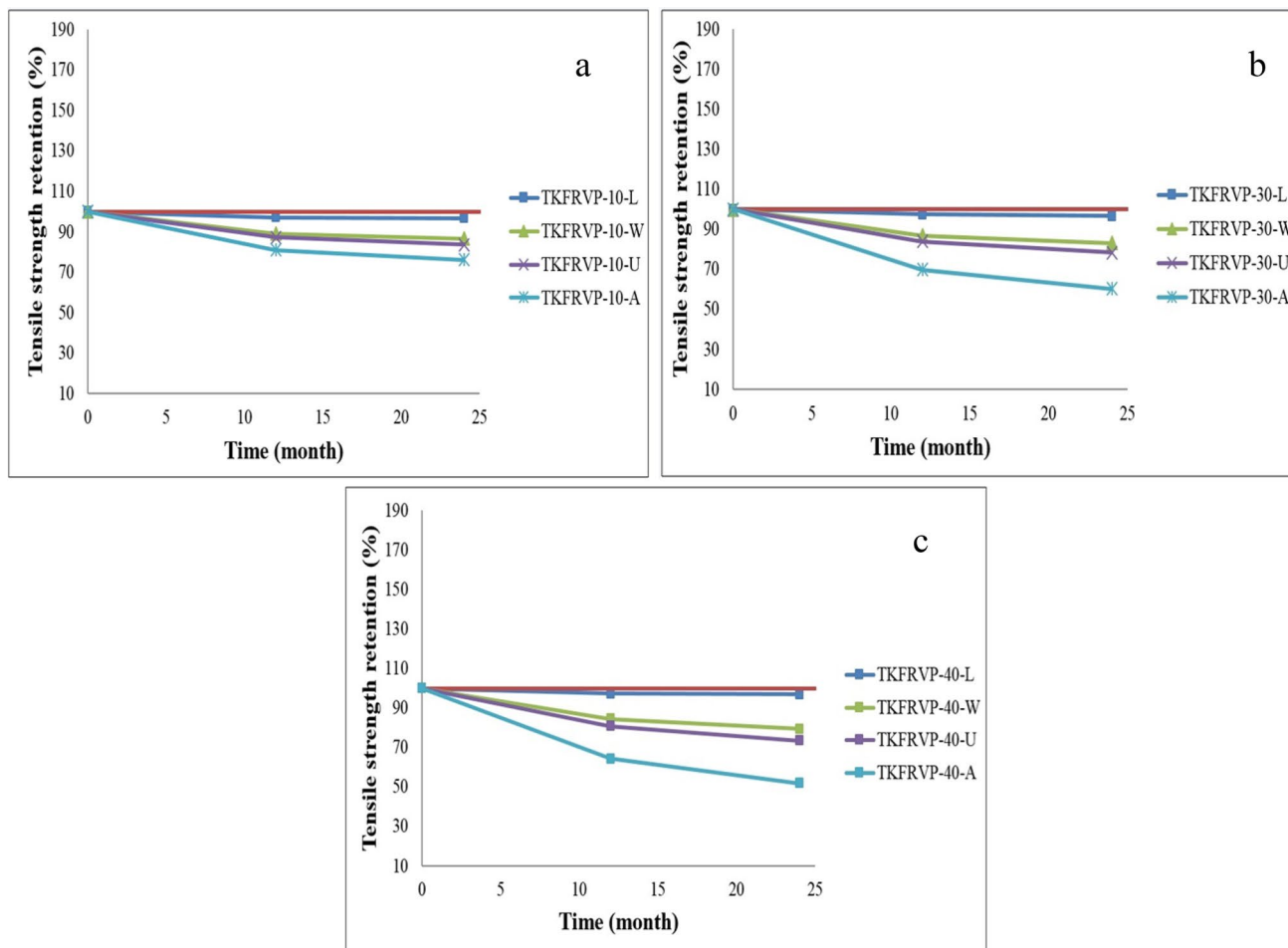


Fig. 13 Tensile strength of (a) KFRVP-10%, (b) KFRVP-30% and (c) KFRVP-40% retention with respect to period of different conditions

Table 12 Tensile modulus of KFRVP samples after exposure in different conditions

Fibre value fractions (%)	Conditions	Initial value	Tensile modulus (N/mm^2) and (change in percent)			
			12 months	24 months	Standard deviation	C.O.V (%)
10%	LAB	7500	7260 (96.8)	7230 (96.4)	213–645	3.3–11.7
	WATER		6668 (88.9)	6450 (86.0)		
	UV		6488 (86.5)	6165 (82.2)		
	ACID		5970 (79.6)	5505 (73.4)		
30%	LAB	13,850	13,504 (97.5)	13,435 (97.0)	359–1179	4.8–11.5
	WATER		11,842 (85.5)	11,191 (80.8)		
	UV		11,371 (82.1)	10,415 (75.2)		
	ACID		9390 (67.8)	7811 (56.4)		
40%	LAB	17,480	17,078 (97.7)	17,270 (98.8)	334–1204	2.8–10.5
	WATER		14,683 (84.0)	13,722 (78.5)		
	UV		13,809 (79.0)	12,253 (70.1)		
	ACID		10,505 (60.1)	7918 (45.3)		

maximum thickness reduction occurred up to 0.19 mm after 24 months.

3. The samples experienced weight variation because of moisture absorption. In contrast, the samples in the acidic medium experienced a decrease in weight due to contact with corrosive materials. Generally, the weight gain of composites increased after 12 and 24 months of exposure. The weight variation of laboratory and control samples was below 0.25% of the initial weight within the exposure period.
4. The variation of degradation of the composite during the first 12 months is more than 24 months, whereas immersion in the acid liquid significantly affected composite degradation compared to other conditions.
5. The KFRP composites experienced a reduction in mechanical properties under different conditions but this was highly dependent on the type of resin in the composite and age of exposure. The changes in the properties were quite significant after 12 months due to the degradation process. The control and laboratory KFRP composites were considerably unchanged in mechanical properties even after 24 months.
6. The tensile strength properties are reduced by increasing the fibre volume content during 12 and 24 months exposure; for this reason, the composite with 40% Kenaf fibre has the maximum variation of degradation compared to the 30% and 10%.
7. Due to exposure conditions (weathering by tropical climate conditions, acid attack by acid liquid immersion and moisture effects by water conditions), the changes in KFRP material properties did affect the overall performance of composites.

In summary, Kenaf fibre has suitable properties for utilisation as reinforcement in fibre-based reinforced polymers or composites. Based on the findings of this study, the fabricated KFRP composites could be potentially utilised as lumber for floor finishing, skating, partition wall panels, ceiling finishing, doors and windows panels in the future.

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