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Effect of oil palm nano filler on mechanical and morphological properties of kenaf reinforced epoxy composites

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HIGHLIGHTS

- Nano OPEFB kenaf hybrid epoxy nanocomposites were fabricated by hand lay-up.
- Effects of nano OPEFB incorporation on mechanical properties were investigated.
- Effects of nano OPEFB incorporation on morphological properties were determined.
- Comparative study were made with MMT and OMMT kenaf hybrid epoxy nanocomposites.

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ABSTRACT

Epoxy based hybrid nanocomposites was prepared by dispersing the nano filler (nano OPEFB filler, MMT, OMMT) at 3% loading through high speed mechanical stirrer followed by wet hand lay-up technique. Mechanical and morphology properties of hybrid nanocomposites were carried out. Obtained results indicated that the addition of 3% nano OPEFB filler into the kenaf epoxy composites considerably improves the mechanical and morphological properties. Nano OPEFB/kenaf hybrid epoxy nanocomposites displayed comparable properties to MMT/kenaf but less than OMMT/kenaf hybrid epoxy nanocomposites. We concluded that nano OPEFB hybrid composites will provide alternative constructional materials respect to steel, bricks and cement for Malaysia.

1. Introduction

Composite materials are the most attractive materials having properties that are not found in nature, consisting of two or more chemically different constituents namely the polymeric matrix and reinforcement. The reinforcement normally is more stiffer and stronger with relative to the matrix, while the matrix hold the reinforcement in its set place [1,2]. Considerable growing awareness and issues of greener and sustainable environment in the society generated profound interest in the usage of natural fiber as reinforcements in polymer composites [3,4]. Numerous recycling and renewable waste materials resources involving leaves, wood chips, waste newspaper, waste concrete, reservoir silt, etc., are being successively utilized in gypsum or polymer matrix due to growing environmental issues from past recent years in the constructional and building applications in ordered to replace traditional expensive building materials like bricks and concrete [5]. This thereby reduces the need for raw materials, waste management/production and a wide range of environmental impacts [6]. Natural fiber reinforced composites exhibit many advantages and disadvantages compared with conventional synthetic composites. The disadvantages such as poor wetting and weak interfacial bonding reduced the mechanical as well as thermal properties of the composites, however it can be overcome by modification of the fibers through physical/chemical treatment or by incorporating interfacial additives/compatibilizers [7–9]. The interfacial additives may be nano sized filler (nano silica, nanotubes, nanoclay) or synthetic fiber (glass fibers, aramid fibers) to produce hybrid composites through proper material design [10]. The properties of these hybrid

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composites solely governed by many factors including; matrix, fibers dimension, type of nano filler, fiber–matrix interface bonding, nano filler–matrix interface bonding [11,9].

Currently, hybrid composites are receiving considerable attention as the advanced constructional and structural materials with true balance between cost effectiveness and better performances. The hybrid materials are made by combining two or more different types of fibers in a common matrix or reinforcement in polymer blends [12–14], and offered interesting potential application for both structural, semi and non-structural industrial areas.

Nanocomposites is a multiphase dense complex material in which at least one of its phase has either one, two or three dimensions lower than 100 nm [11]. Nanocomposites represents the most promising, attractive, indispensable and encouraging approaches in the field of future advanced engineering applications tailored by adding nano scale fillers in the polymer matrix to meet the growing demands of the specific properties in the versatile industrial and practical applications [15,16]. Nanocomposites offered unique mechanical, thermal, optical, electrical, magnetic and barrier properties relative to pure polymer [17] and even to traditional/conventional composites such as glass fiber reinforced composites [11].

The hybrid nanocomposites bring the revolution in the field of material science displaying the most hi-tech advanced composite materials. The addition of nano particles shows remarkable improvement in the thermal, physical, mechanical and thermomechanical properties due to perfect dispersion, a high aspect ratio and effective polymer filler interaction [18,9].

Kenaf fiber is comparatively commercially available and economically cheaper among other natural fiber found in Malaysia and it is regarded as an industrial and most beneficial crop (Fig. 1), generating huge biomass content for both research and innovation. Kenaf fiber are extensively been used in fiber reinforced polymer composite sector as it displayed remarkable properties for reinforcement in composites consisting of different polymeric matrix under stress and varied flexural loading condition [19,15,20].

Epoxy is the most widely used thermosetting matrix materials, showing extensive applications. However cured epoxies represent low fracture toughness, inherently low impact resistance, reduced resistance to crack initiation and propagation [21,16]. It has been established that the addition of additives and nano fillers (<10 wt.%), such as reactive oligomeric compounds, low molecular weight polymers, plasticizers, nano-particles and nano-fillers certainly modify the epoxies, with enhanced mechanical, morphological, thermal and electrical properties [22,23].

The lignocellulosic and agriculture-plant based biomass materials are presently the most appropriate and inexpensive precursors for the production of nanomaterials or fillers. Saw dust, bagasse, rice husk, cellulosic nano fibers from rubber wood, coconut shells, nano fly ash and coir pith are being successively reported by several researchers [24–29].

Moreover, palm oil fuel ash to prepare cellulose acetate butyrate (CAB) composite, oil palm shell and oil palm ash as nano filler, carbon blacks (CB) and activated carbons (AC) derived from bamboo stem, coconut shell and oil palm empty fruit bunch fibers (OPEFB) fibers are also been explored and reported as filler in epoxy and polyester matrix to improve their properties [30–33].

Currently nanoparticle fillers and layered silicate minerals such as montmorillonite (MMT) and organically modified montmorillonite (OMMT) nanoclay received higher attention as they possess the potential tendency to modify significantly the mechanical, thermal and functional properties of both thermoset and thermoplastic polymers due to its high modulus, high strength and high aspect ratio [34,35]. Nanoclay are the general term for naturally occurring layered mineral silicates nanoparticles, having phyllosilicate or sheet structure with a thickness of about 1 nm and surfaces about 50–150 nm in one dimension [36,37]. MMT are the most commonly used layered silicate in polymer nanocomposites, among hectorite, pyrophyllite, nontronite and saponite nanoclay [37]. MMT belong to 2:1 phyllosilicates nanoclay family, having 2 tetrahedral sheets sandwiching a central octahedral sheet [38]. Naturally occurring MMT is highly hydrophilic, hence are typically modified by clay surface modification usually with ammonium salts or phosphonium salts through compatibilization or “intercalation” methods, in order to make them compatible with hydrophobic polymers [39]. The surface energy of MMT decreases and the interlayer spacing expands in the resulting organically modified nanoclays (OMMT) material, thus it can compatibilized with a wide variety of matrix polymers [40]. Currently, OMMT or ‘organoclays’ are one of the attractive and most promising hybrid organic inorganic nanomaterials generally used for improving the

Fig. 1. The dense kenaf plantation in Malaysia [20].

properties of polymers and polymer based composites modification [41,38]. Research study illustrates that the usual content of lamellar nanoclay and OMMT is in the range of 5–10 wt.% due to their high aspect ratio (more than 1000), high surface area (more than 750 m^2/g) and higher modulus values (176 GPa) [42].

Few research study based on nano filler/natural fiber hybrid polymer nanocomposites until now has been made reported, such as nanoclay/bagasse/polypropylene [43], graphene nano platelets/kenaf fibers/polypropylene [44], nanoclay/bagasse flour/recycled polyethylene [45], nanoclay/bagasse flour/high density polyethylene [46], oil palm shell nanoparticles/woven kenaf fiber mat/coconut fiber mat/polyester [47]. All the reported hybrid nanocomposites displayed better mechanical, thermal even electrical and barrier properties.

Present research study is the extension of my previous research work involving development of nano-filler from oil palm empty fruit bunch fibers through combined effects of cryogenizer and high energy ball milling (HEBM) techniques [35]. This paper evaluates the effect of developed nano OPEFB filler on the mechanical and morphological properties of kenaf fibers reinforced epoxy composites by combining the locally available Malaysian kenaf bast fibers. It is evident from literature review that no work has been yet reported on the addition of HEBM derived nano OPEFB filler to improve the mechanical properties of kenaf epoxy composites. The pure kenaf epoxy composites and kenaf hybrid nanocomposites having total 40% of kenaf fibers loading by weight together with 3% nano filler loading in kenaf epoxy hybrid nanocomposites are fabricated by hand lay-up technique. Effect of nano OPEFB filler loading on the tensile, elongation at break, impact and morphology of kenaf epoxy composites were investigated and compared with pure kenaf epoxy composites. The results are also compared with MMT nanoclay filled kenaf hybrid epoxy nanocomposites and OMMT nanoclay filled kenaf hybrid epoxy nanocomposites in order to provide a new step to utilize the green nano filler for renewable and sustainable structural products, while diverting the existing flow of using inorganic and expensive nano fillers.

2. Materials and methods

The OPEFB fiber was obtained from Malaysian oil palm board (MPOB), Bangi-Selangor, Malaysia. The kenaf non-woven mat was obtained from Innovative Pultrusion Sdn, Bhd, Malaysia. Physical and mechanical properties of OPEFB and kenaf fiber are shown in Table 1 [48,49,20,19,50,51].

Montmorillonite (MMT) and organically modified montmorillonite (OMMT) nanoclay were procured from Zarm scientific & Supplies Sdn., Bhd, Malaysia. The MMT powder has surface area of 250 m^2/g with the pH 3–4. OMMT were the nanoclay Nanomer® I.31PS, contains 0.5–5 wt.% aminopropyltriethoxysilane, 15–35 wt.% octadecylamine as montmorillonite clay base material. It is white to off white powder having density 200–500 kg/m^3. The epoxy resin D.E.R 331 used in this study is a clear liquid resin based on diglycidyl ether of bisphenol A (DGEBA), obtained from Dow Chemical Pacific Singapore, Singapore. The curing agent, epoxy hardener Jointmine 905-3S is a clear and transparent color liquid. It is a modified cycloaliphatic amine, supplied by Epochemie International Pte Ltd. Singapore. The typical properties of the used epoxy resin D.E.R 331 and epoxy hardener (Jointmine 905-3S) are summarized in Tables 2 and 3. Silicone spray used in this study is procured from

Table 1
Physical and mechanical properties of OPEFB and kenaf fiber [48,49,20,19,50,51].

Properties	OPEFB fiber	Kenaf fiber
Density (g/cm^3)	0.7–1.55	1.3
Tensile Strength (MPa)	50–400	500–600
Young's modulus (GPa)	1–9	40–53
Elongation at break (%)	8–18	1.5–3.5
Cellulose content (%)	43.7	62.59
Hemicellulose (%)	29.02	16.79
Lignin content (%)	13.33	7.83
Microfibril angle (deg)	42–46	9–15
Lumen width (μm)	6.90	15.44

Table 2
Typical properties of epoxy resin 331.

Characteristics	Description
Epoxide Equivalent Weight	182–192
Viscosity @ 25 °C	11,000–14,000
Color	Water-white to yellow
Hydrolyzable Cl	0–500
Epichlorohydrin	5.0 Max
Water Content	700 Max
Density (25 °C, g/cm^3)	1.16
Flash Point (Cooled Cup °C)	255
S.P.I. Skin rating	2

Table 3
Typical properties of epoxy hardener (Jointmine 905-3S).

Characteristics	Description
Type	Modified cycloaliphatic amine
Color (Gardner)	<2
Viscosity (poise@25 °C)	200–400
Amine Value (mg KOH/gm)	280–320
Pot life (100 g @25 °C)	75 min
Thin film set time (@25 °C)	5 h
Hardness (Shore D)	85
Equivalent weight per Active-H	95
Recommended Usage rate (phr)	50

Dow Chemical Pacific Singapore, Singapore. Teflon sheets are procured from NR Medicare Sdn. Bhd., Selangor, Malaysia. All purchased chemicals were used without any further purification.

2.1. Fabrication of epoxy composites

The non-woven kenaf mats are used in this research study for the fabrication of both, pure kenaf fibers reinforced epoxy composites and filler filled kenaf reinforced hybrid nanocomposites. In the fabrication of hybrid nanocomposites, the prior dried nano fillers (OPEFB, MMT, OMMT) are uniformly dispersed at 3% (by weight) loading in epoxy resin through high speed mechanical stirrer at room temperature for 60 min. After this a stoichiometric ratio of the aliphatic amine hardener was maintained, and the mixture again mechanically stirred once, for at least 20 min. The same procedure is carried out with all nano fillers used for this study. The dispersed nano filler are then poured in the stainless steel mold cavity previously cleaned and covered with teflon sheet coated with silicone spray. After pouring some fraction of nano filler-epoxy system, kenaf compressed mat are put over it, followed by same layering of kenaf mat and nano filler-epoxy system one more time. The mold is then covered and allows putting in the compress machine for 10 min, to achieve better reinforcements, followed by leaving the mold for 24 h, at room temperature. The composite was then detached carefully from the steel mold. The same procedure is carried out for the fabrication of rest of filler filled/kenaf hybrid epoxy nanocomposites.

Pure kenaf epoxy composites are fabricated by the same hand lay-up technique procedure to make comparative study, by using two compressed kenaf non-woven mats, with the only exception that no nano fillers has been incorporated. The kenaf non-woven mat roll, hot press machine and the produced compressed kenaf mat by keeping for 8 min in the hot press used in this research study are illustrated in Fig. 2 (a–c).

2.2. Characterization

2.2.1. Tensile test

The tensile strength, modulus and elongation at break of pure kenaf epoxy composites and kenaf/epoxy hybrid nanocomposites were measured through Universal Testing Machine (Instron 5567). All the samples preparation was carried out as per specifications of ASTM D 3039. A standard head displacement at a speed of 5 mm/min was applied. For each type of composites sample, six replicate specimens were tested and average results of tensile strength, modulus and elongation at break were calculated.

2.2.2. Impact test

The izod notched impact test was carried out for evaluating the impact load carrying capability of the kenaf epoxy composites and different filer filled kenaf/epoxy hybrid nanocomposite specimens, were measured through CEAST 9050 impact testing machine. The composite samples are cut in dimension of $70 \times 15 \times 3$ mm through band saw machine. Prior testing V-notch on seven replicate of each samples are made by using NOTCHVIS, then tested according to the ASTM D256 speci-

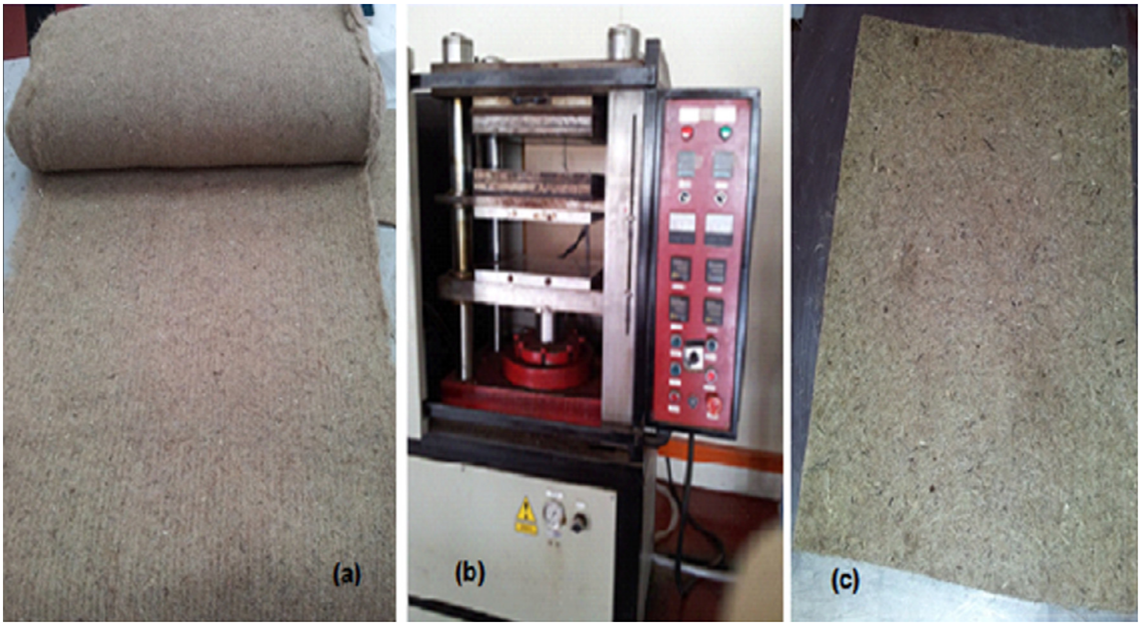

Fig. 2. (a) Kenaf non-woven mat roll (b) Hot press machine, and (c) Compressed kenaf non-woven mat.

fications. Appropriate pendulum hammers were mounted at the speed 10 kJ, and the test specimen was supported as a vertical cantilever beam and broken by a single swing of a pendulum at room temperature. The machine was calibrated for accurate impact energy (J/m) determination involved in the tests, followed by the average impact energy calculations. The V-notch making machine, the notched seven replicate specimens of nano OPEFB/kenaf/epoxy hybrid nanocomposites and the impact testing machine are presented in Fig. 3.

2.2.3. Transmission electron microscopy (TEM)

The morphology and the distribution of different 3% nano fillers (OPEFB, MMT AND OMMT) in the fabricated kenaf/epoxy hybrid nanocomposites were studied through transmission electron microscopy (TEM, Hitachi-7100 instrument). For the analysis, the dried sample of nanocomposites were dissolved in acetone and dispersed thoroughly by subjecting to sonication with an ultrasonicator (JP SELECTA 3000512) for 30 min. Further, a drop of the colloidal dispersion containing nanocomposites powder are transferred onto the carbon coated 300 mesh copper grid and allowed to dry completely at room temperature before examined under TEM.

2.2.4. Scanning electron microscopy (SEM)

The microstructure and morphology characteristics of the tensile fractured sample of pure kenaf/epoxy and nano filler filled/kenaf/epoxy hybrid nanocomposites were performed by using scanning electronic microscopy (SEM) followed by micrographs with NOVA NANO SEM 230 (USA) field emission instrument. The samples were mounted onto SEM holder using double sided electrically conducting carbon adhesive tapes to prevent surface charge on the specimens when exposed to the electron beam. But prior to their morphological observation, uniform thin layer gold coating on fractured end of tensile specimens with EMITECH, K575X (Korea) peltier cooled for 2 min were conducted in order to prevent from burning of the specimens on exposing to the electron beam.

3. Results and discussion

3.1. Tensile properties

Tensile strength of hybrid composites determined its ability to resist breaking under tensile stress. Fig. 4(a–b) shows the variation

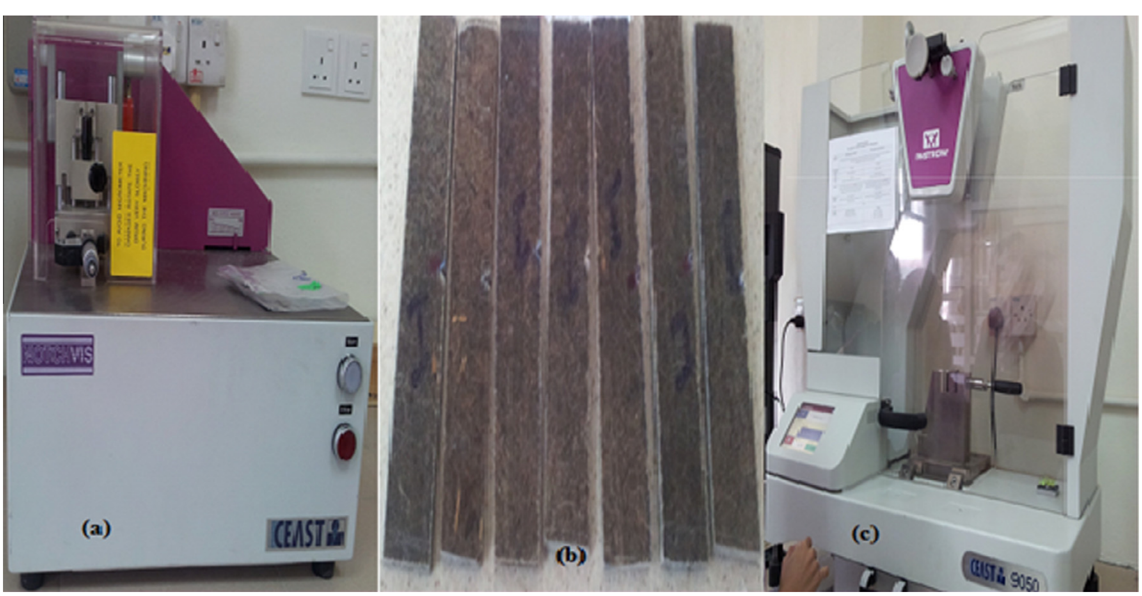

Fig. 3. (a) V-notched making machine (b) 7-V-notched specimens and (c) Impact testing instrument (INTROP).

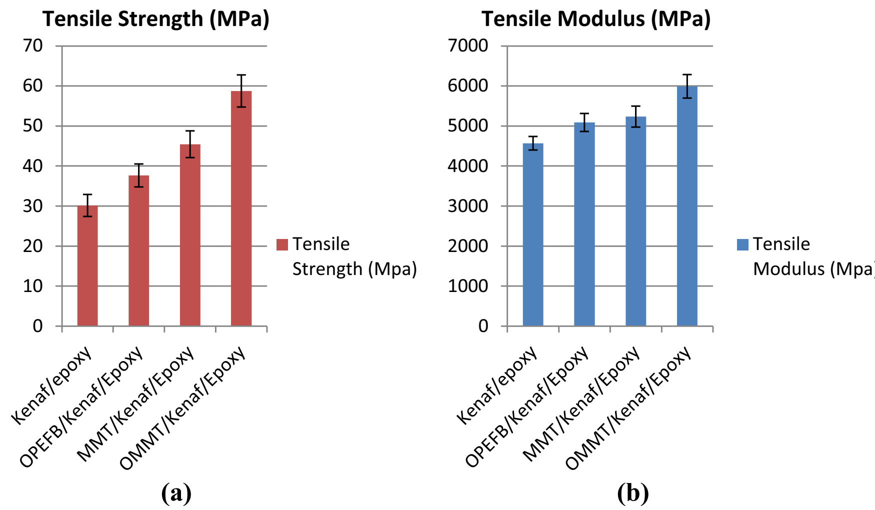

Fig. 4. Effect of nano filler loadings on (a) tensile strength and, (b) tensile modulus of filler filled kenaf epoxy hybrid nanocomposites.

of tensile strength and tensile modulus respectively with the incorporation of different nano fillers at 3% by wt. loadings (nano OPEFB, MMT, OMMT) for samples containing kenaf fiber non-woven mat reinforced in epoxy matrix. Fig. 4(a) evidently depicts that the addition of nano OPEFB filler in the kenaf epoxy composites increases the tensile strength as compared with the kenaf/epoxy composites by transmitting and distributing the applied stress. The addition nano OPEFB filler in the kenaf/epoxy composites minimizes the free spaces within the hybrid and increases the stiffness of the nano OPEFB filler/kenaf/epoxy composites thereby results improvement in tensile modulus and tensile toughness properties of hybrid nanocomposites as shown in Fig. 4(b).

The improved tensile strength and modulus can be explained by considering the larger surfaces are of nano fillers which act as a connection link between the reinforced fibers and matrix, resulting better bonding between the matrix and fiber. Thus when the stress or loads are applied, the stress concentration can easily get transferred from matrix to fiber resulting delayed in fracture or crack initiation mechanisms. Thus it can be concluded that the nano OPEFB filler incorporations in the kenaf epoxy composites enhances the physical adhesion at the interface and results effective stress transfer underload, leading ultimately the increase in tensile properties. Same conclusion were made by researchers where the addition of 3% oil palm shell nanoparticles in kenaf mat/coconut fiber mat reinforced polyester hybrid nanocomposites results improved tensile strength and tensile modulus properties [47].

The obtained results are also in agreement with other reported research study involving short nylon fiber/nanoclay/NR/SBR [52], red mud/banana fiber/polyester hybrid nanocomposites [53], MMT nanoclay/coir fiber/wood fiber/polypropylene [54] and graphene oxide/polyhedral oligomeric silsesquioxane/carbon fiber/epoxy nanocomposites [55]. The obtained improved tensile results are also in line with research study reported on the enhanced mechanical properties of hybrid jute/glass fiber/epoxy composites [56], oil palm fibers/coir fibers/polypropylene hybrid composites [57], kenaf fiber/aramid fiber/epoxy hybrid composites [58] and pennisetum purpureum/glass fiber/epoxy hybrid composites [10].

Moreover, the nano OPEFB filler/kenaf/epoxy hybrid nanocomposites displayed quite comparable tensile strength and tensile modulus properties with relative to MMT/kenaf/epoxy hybrid nanocomposites and OMMT/kenaf/epoxy hybrid nanocomposites. The tensile strength of nano OPEFB filler/kenaf/epoxy hybrid nanocomposites increased by 24.9% with kenaf/epoxy composites whereas increment of 20.7% with MMT/kenaf/epoxy hybrid nanocomposites was observed with respect to nano OPEFB/kenaf/epoxy hybrid nanocomposites. After adding 3% OMMT in kenaf/epoxy it increased by 29.3% in respected to MMT/kenaf/epoxy hybrid nanocomposites while 56% increment noticed as compared to nano OPEFB/kenaf/epoxy hybrid nanocomposites.

The relatively higher tensile strength of OMMT filled hybrid nanocomposites can be ascribed due to strong reinforcing effects, high aspect ratio, better interlayer spacing, and platelet structure of OMMT. Thus it can effectively reduce the stress concentration under the action of tensile load on the nanocomposites. Whereas, MMT is soft nanoclay materials and hydrophilic in nature which makes it incompatible with the hydrophobic epoxy polymer matrix, resulting relatively lesser tensile strength with OMMT filled kenaf hybrid nanocomposites. Consequently, a strong interphase interaction between the epoxy matrix and the dispersed phase not developed to reduce the applied tensile stress concentrations. The statement are also in agreement with other conveyed research studies [40,59,60].

The tensile modulus display similar trends as evident for tensile strength. Nano OPEFB filler/kenaf/epoxy hybrid nanocomposites also increased by 11.4% compared with kenaf/epoxy composites. Tensile modulus of MMT/kenaf/epoxy hybrid nanocomposites increased 2.9% while OMMT/kenaf/epoxy hybrid nanocomposites increased by 17.7% as compared to nano OPEFB filler/kenaf/epoxy hybrid nanocomposites. It also noticed that OMMT hybrid nanocomposites displayed highest tensile modulus and is increased by 14.5% with respect to MMT/kenaf/epoxy hybrid nanocomposites. The enhancement of tensile modulus of nanoclay (OMMT, MMT) based kenaf hybrid nanocomposites are better than OPEFB based kenaf hybrid nanocomposites and can be reasonably ascribed due to their better stiffening and clay layers rigidity properties. The similar conclusion are also been reported by other researchers [59,61].

Fig. 5 illustrates the elongation at break values for kenaf/epoxy composites and 3% filler filled (nano OPEFB, MMT, OMMT) hybrid epoxy nanocomposites. Elongation at break values where observed and calculated when longitudinal stress/load are applied to the composites material. Fig. 5 perfectly shows that the incorporation of nano filler improves the elongation at break (%) with relative to kenaf/epoxy composites. The obtained data are in agreement with the results obtained from tensile strength and tensile modulus of nano filler filled kenaf epoxy hybrid nanocomposites. Furthermore the elongation at break of nano OPEFB filler/kenaf/epoxy hybrid

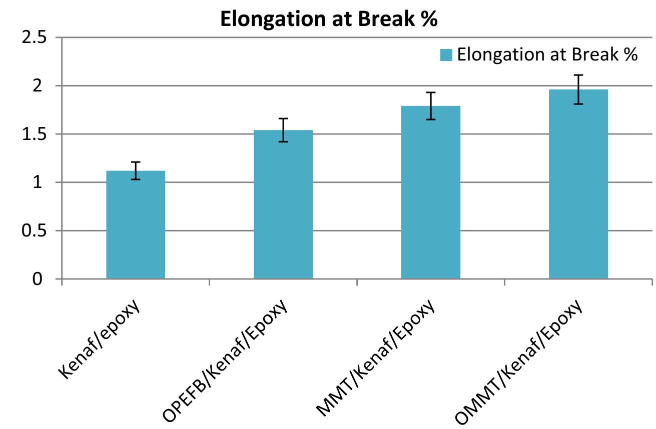

Fig. 5. Effect of nano filler loadings on elongation at break of kenaf epoxy hybrid nanocomposites.

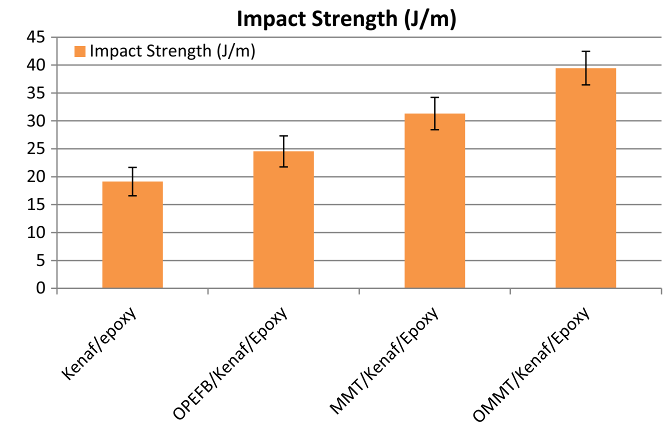

Fig. 6. Effect of nano filler loadings on impact strength of kenaf epoxy hybrid nanocomposites.

nanocomposites increased by 37.5% with respect of kenaf/epoxy composites whereas increment of 16.2% with MMT/kenaf/epoxy hybrid nanocomposites was observed with respect to nano OPEFB/kenaf/epoxy hybrid nanocomposites. After adding 3% OMMT in kenaf/epoxy it increased by 9.5% in respected to MMT/kenaf/epoxy hybrid nanocomposites while 27.3% increment observed as compared to nano OPEFB/kenaf/epoxy hybrid nanocomposites.

The addition of rigid nano OPEFB filler would restrict the chain mobility of matrix responsible for elongation consequently increases the toughness and stiffness properties of hybrid nanocomposites. The observed results are in agreement with other research work involving oil palm shell nanoparticles/kenaf mat/coconut mat/polyester hybrid nanocomposites [47] and nanoclay/short nylon fiber/NR/SBR [52].

The incorporation of OMMT improves the interfacial interaction between the epoxy and kenaf fibers in the kenaf fibers reinforced epoxy composites, resulting stiffer and tougher hybrid nanocomposites, on account of its comparatively better reinforcing effects compared with MMT and nano OPEFB fillers. All this leads to higher elongation at break% value for OMMT among the rest kenaf epoxy composites.

3.2. Impact strength

Impact strength is the tendency of polymer composites to endure high energy impact without its breaking or fracturing [53]. The impact properties of fiber reinforced composites or hybrid composites depend on the properties of the individual fibers used for hybridization, inter-laminar and interfacial adhesion between the fiber and the matrix [4]. Fig. 6 presents the impact strength of kenaf/epoxy composites and the effect of different nano fillers addition on the impact strength of kenaf/epoxy hybrid nanocomposites. From the graph it is clearly observed that the kenaf/epoxy composites shows the lowest impact strength and the OMMT/kenaf/epoxy hybrid nanocomposites shows the highest impact strength. The increase of 28.3% impact strength of nano OPEFB filler/kenaf/epoxy hybrid nanocomposites as compared with kenaf epoxy composites was perceived. The enhancement of 27.6% and 60.8% impact strength in MMT/kenaf/epoxy hybrid nanocomposites and OMMT/kenaf/epoxy hybrid nanocomposites as compared with nano OPEFB filler/kenaf/epoxy hybrid nanocomposites was observed. It also evident that impact strength of OMMT/kenaf/epoxy hybrid nanocomposites increased by 25.9% as compared to MMT/kenaf/epoxy hybrid nanocomposites.

The impact strength graph evidently shows that the incorporation of nano OPEFB filler improves the impact strength properties primarily due to absorption of applied energy more easily which then prevent the crack initiation, crack pinning mechanism and its propagation within the composite materials under stress load. This inference can also justified by the SEM micrograph shown in Fig. 8(a–b), which clearly shows fewer voids and more fractured fibers instead of more fiber pull-out. Similar results are observed for research study on OMMT nanoclay/PLA/LLDE [8] and nanoclay/bagasse fiber/polypropylene hybrid nanocomposites [43].

The results are also in line with the findings for banana fiber/kenaf fiber polyester reinforced hybrid composites [4], jute fiber/bamboo unidirectional fiber/epoxy composites [62], non-woven hemp fiber mat/woven basalt fabric/unsaturated polyester [63] and banana fiber/hemp fiber/glass fiber epoxy [64]. Thus it can be concluded from the mechanical testing results that, the combination of nano filler and micro-size reinforcements in the polymer can be perfectly exploited to fabricate stronger and light-weight hybrid composites with enhanced mechanical properties for various housing and bridging applications. The developed hybrid nanocomposites would be the potential materials for attending the growing attention towards greener and sustainable buildings materials in order to minimize or eliminate the buildings excessive energy consumption.

3.3. Scanning electron microscopy (SEM) analysis

The surface characteristics of the tensile fractured composite material used for the investigation were studied through SEM analysis, displayed in Figs. 7–11. The SEM micrograph of kenaf/epoxy composites displayed in Fig. 7(a–b), whereas the SEM micrographs of nano OPEFB/kenaf hybrid, nano OPEFB filler, MMMT/kenaf hybrid and OMMT/kenaf hybrid nanocomposites are presented in Figs. 8–11 respectively.

The micrograph evidently shows huge numbers of trace of fiber pulled out, air bubbles due to presence of air bubbles within the matrix and the presence large numbers of voids due to absence of epoxy matrix. In response to applied stress and pressure, fibers get detached from surface of the matrix due to the poor interfacial bonding between them, thus could not provide an efficient stress transfer from the matrix to the fiber ultimately leading to lower mechanical properties. Comparable SEM images are also analyzed for nanoclay/oil palm mesocarp fiber/poly lactic acid/polycaprolactone hybrid nanocomposites [65] and in exfoliated graphene nanoplatelets/kenaf fiber/polypropylene hybrid nanocomposites [44]. The appearance of more fiber-pull outs and voids in the epoxy

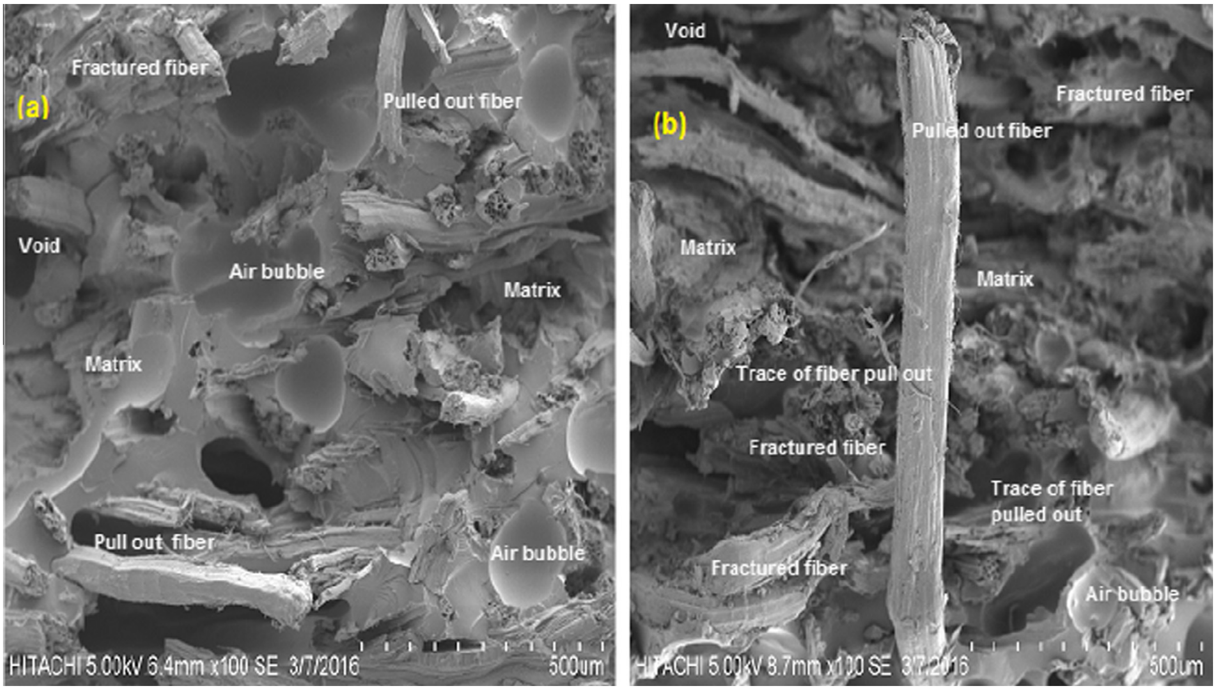

Fig. 7. (a–b) SEM micrograph of the fracture surfaces of kenaf epoxy composites.

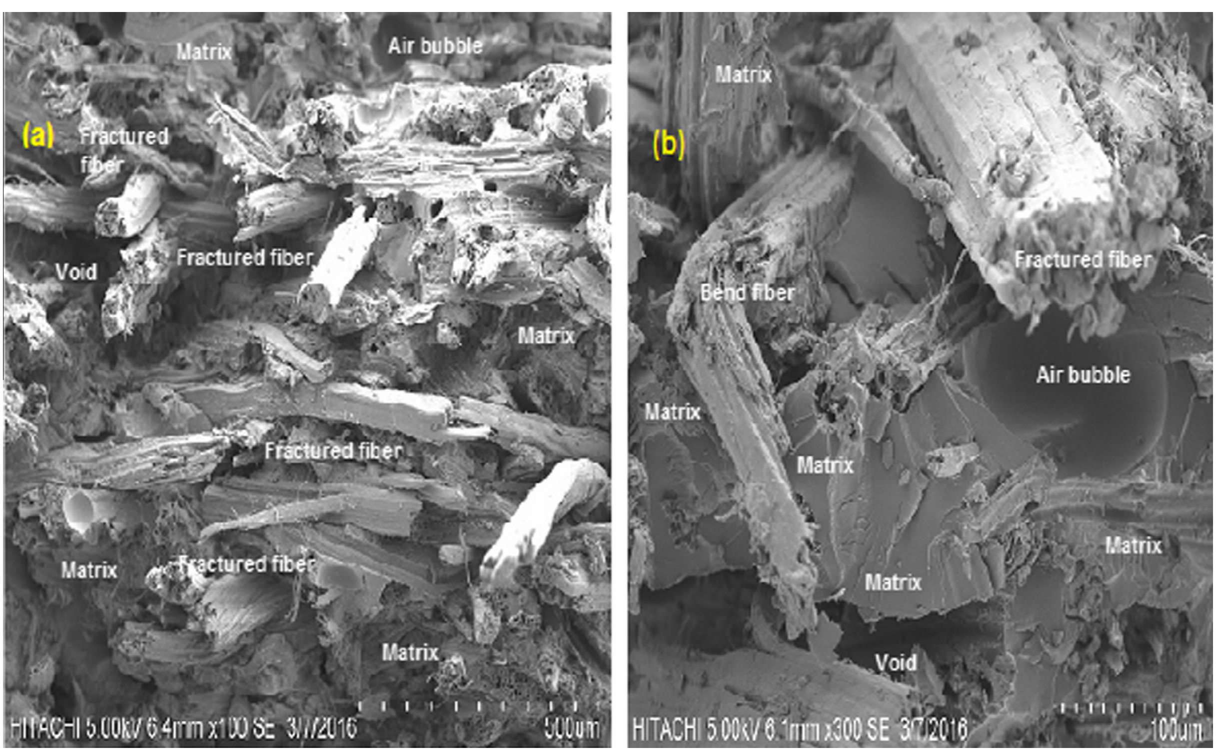

Fig. 8. (a–b) SEM micrograph of the fracture surfaces of nano OPEFB/kenaf/epoxy hybrid nanocomposites.

matrix of kenaf epoxy composite is thought to be responsible for the decline in tensile and impact properties.

However, the SEM of nano OPEFB filled kenaf hybrid epoxy nanocomposites in Fig. 8(a–b) shows comparatively lesser cavity, voids and air bubbles due to better fiber/matrix adhesion. Thus instead of fiber pulled out from the surface during applied stress, the fiber undergoes breakage or bending, illustrating better stress transfer from epoxy matrix. The SEM micrograph of rougher and spherical nano OPEFB filler developed by combined effects of cryogenizer and HEBM technique are displayed in Fig. 9 [35], to support the SEM morphology of fabricated OPEFB filled kenaf epoxy hybrid nanocomposites.

We can concluded that 3 wt.% loading of nano OPEFB filler bear a more appropriate connection between the epoxy matrix and the

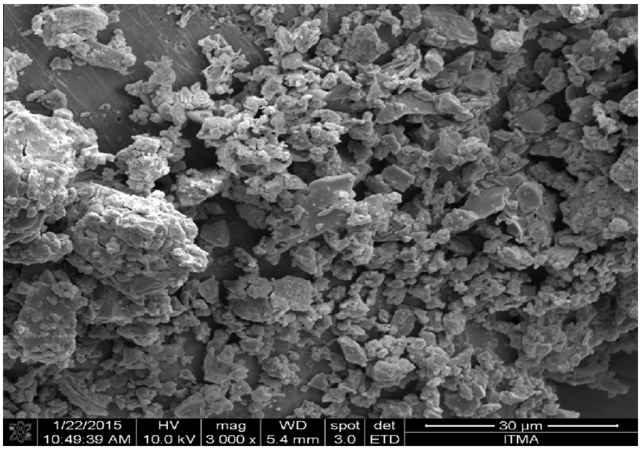

Fig. 9. SEM micrographs of developed nano OPEFB filler [35].

kenaf fibers in the hybrid nanocomposite material. The obtained SEM images clearly justified the improved mechanical strength by the incorporation of nano OPEFB filler with relative to kenaf/epoxy composites. Recently a similar conclusion also been observed for nanoclay/bagasse flour/reprocessed high density polyethylene [46].

Figs. 10(a–b) and 11(a–b) shows the SEM micrographs of tensile fractured samples of MMT/kenaf/epoxy hybrid and OMMT/kenaf/epoxy hybrid nanocomposites.

The SEM micrograph of nano OPEFB/kenaf hybrid epoxy nanocomposites are quite similar to MMT/kenaf and OMMT/kenaf hybrid epoxy nanocomposites with lower voids and traces of fiber pull out, indicating better tensile strength and impact properties as compared with kenaf/epoxy composites.

3.4. Transmission electron microscope (TEM)

TEM was used to investigate the morphology and level of distribution of nanoparticles in matrix governing the improved thermal, mechanical and physical properties of the nanocomposites [44]. Fig. 12(a–b) presents the TEM images for nano OPEFB/kenaf/epoxy hybrid nanocomposites and TEM images for developed nano OPEFB filler respectively. TEM images for nano OPEFB filler clearly shows spherical uniform and mono dispersed OPEFB particles in nano sized range [35]. Fig. 13(a–b) shows the MMT/kenaf/epoxy hybrid and OMMT/kenaf/epoxy hybrid nanocomposites respectively.

From Fig. 12(a) it is clearly evident that nano OPEFB filler dispersed uniformly within the matrix forming a continuous interconnected network in the presence of reinforced kenaf fibers, as shown by arrows, This present the evidence of exfoliation type of nanocomposites due to the perfect dispersion and homogenous distribution in the epoxy matrix providing a favorable medium for strong interfacial interaction with the polar epoxy matrix of nano OPEFB/kenaf/epoxy hybrid nanocomposites. TEM results are also in consistent with the obtained enhanced mechanical properties with relative to kenaf/epoxy composites.

Fig. 13(a–b) shows the TEM images of MMT/kenaf/epoxy hybrid and OMMT/kenaf/epoxy hybrid nanocomposites. The distribution of layered nanoparticles of MMT and OMMT in epoxy matrix having kenaf fibers are also indicated by arrows. TEM images of both hybrid nanocomposites displayed quite homogenous dispersion and distribution leading to the intercalation and some degree of exfoliation. Exfoliation or intercalation of clay platelets within the kenaf/epoxy composites systems results improved interfacial or physical bonding as the net aspect ratio (length/thickness) of clay nano layer increases, which finally contributes towards better toughness, tensile, impact strength, thermal and wear properties of the matrix. This statement is also in agreement with other researchers [44,66,67].

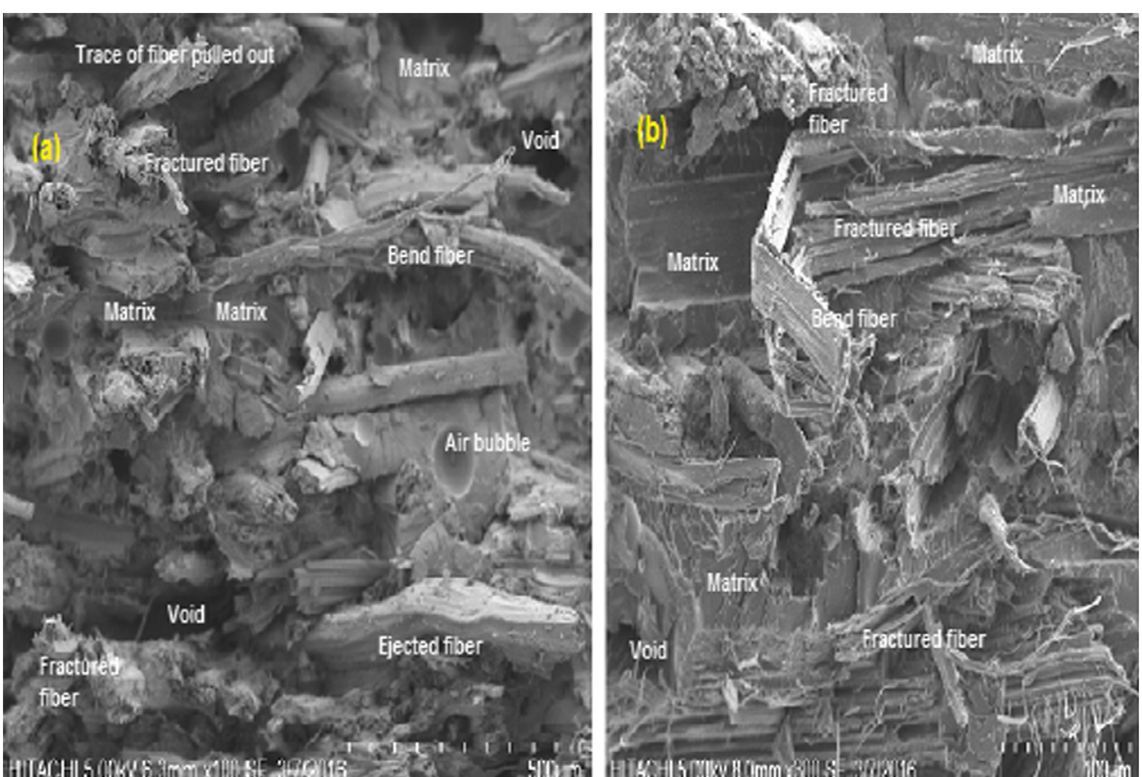

Fig. 10. (a–b) SEM micrograph of the fracture surfaces of MMT/kenaf/epoxy hybrid nanocomposites.

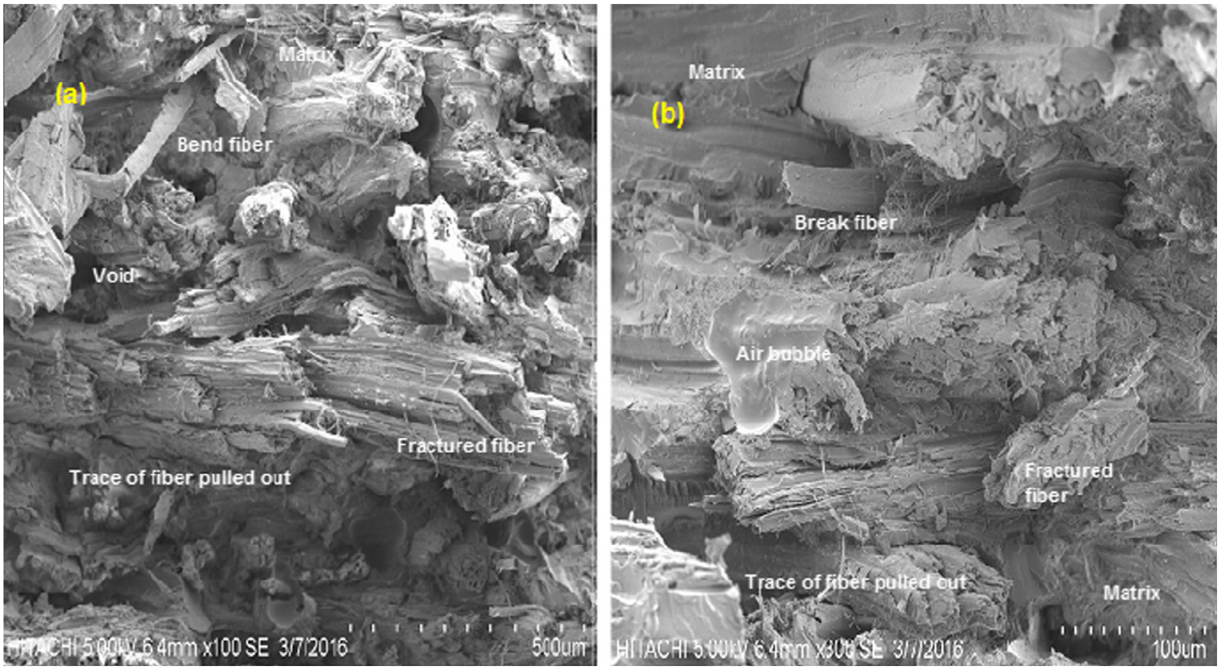

Fig. 11. (a–b) SEM micrograph of the fracture surfaces of OMMT/kenaf/epoxy hybrid nanocomposites.

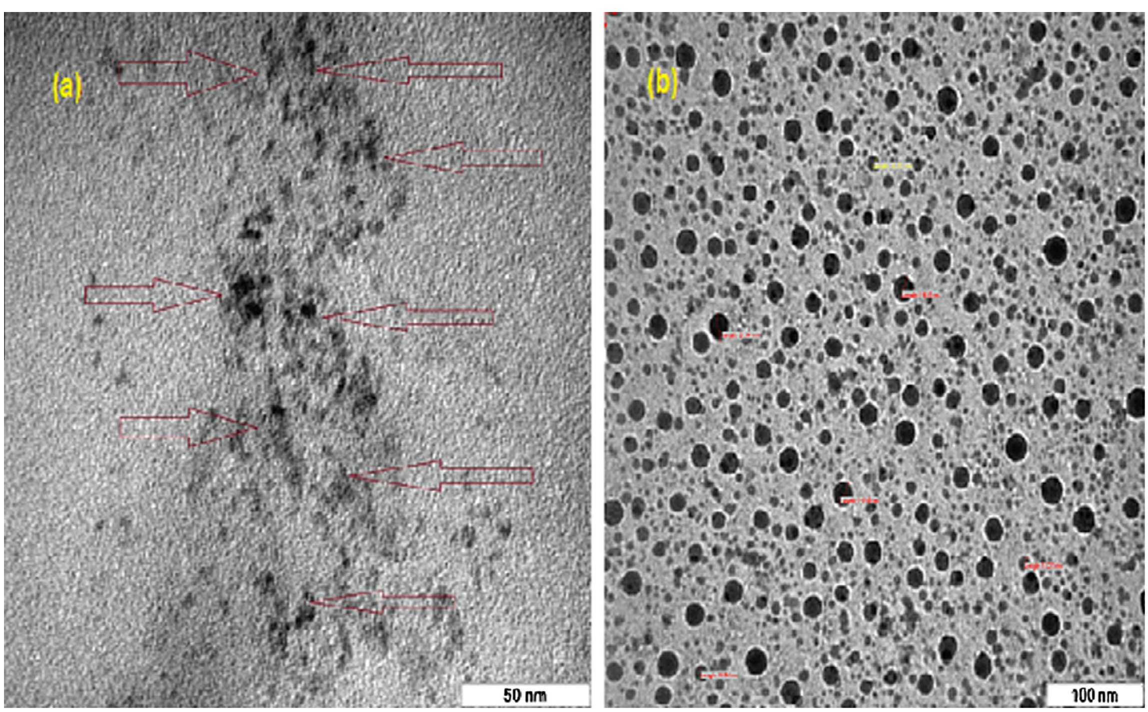

Fig. 12. (a–b) TEM images of nano OPEFB/kenaf/epoxy hybrid nanocomposites, and (b) TEM images of nano OPEFB filler [35].

4. Prospective applications

The potential application of nano OPEFB filler filled kenaf hybrid nanocomposites will acts as the ingredient for alternate sustainable construction materials to offers reduction in natural resource use as well as energy. The obtained kenaf epoxy hybrid nanocomposites will replace the traditional constructional materials such as ceramic bricks, cement, aggregates, steel, aluminium, wood, cladding and partitioning materials in order to developed green buildings. The developed lighter weight hybrid composites will shows a great potential to be used for walls, wooden board substitute, economically alternative to the concrete blocks, ceiling panels, sound barrier panels. The resulting materials will consumes comparatively lesser thermal and electrical energy and relatively lesser polluting the air, water and land during processing, due to their renewable and biological origin. The inclusion of this material in a construction project by replacing conventional and expensive materials considerably results cost effective structural building materials, due to their lower material cost, fabrication cost, constructional cost and minimal repairing costs.

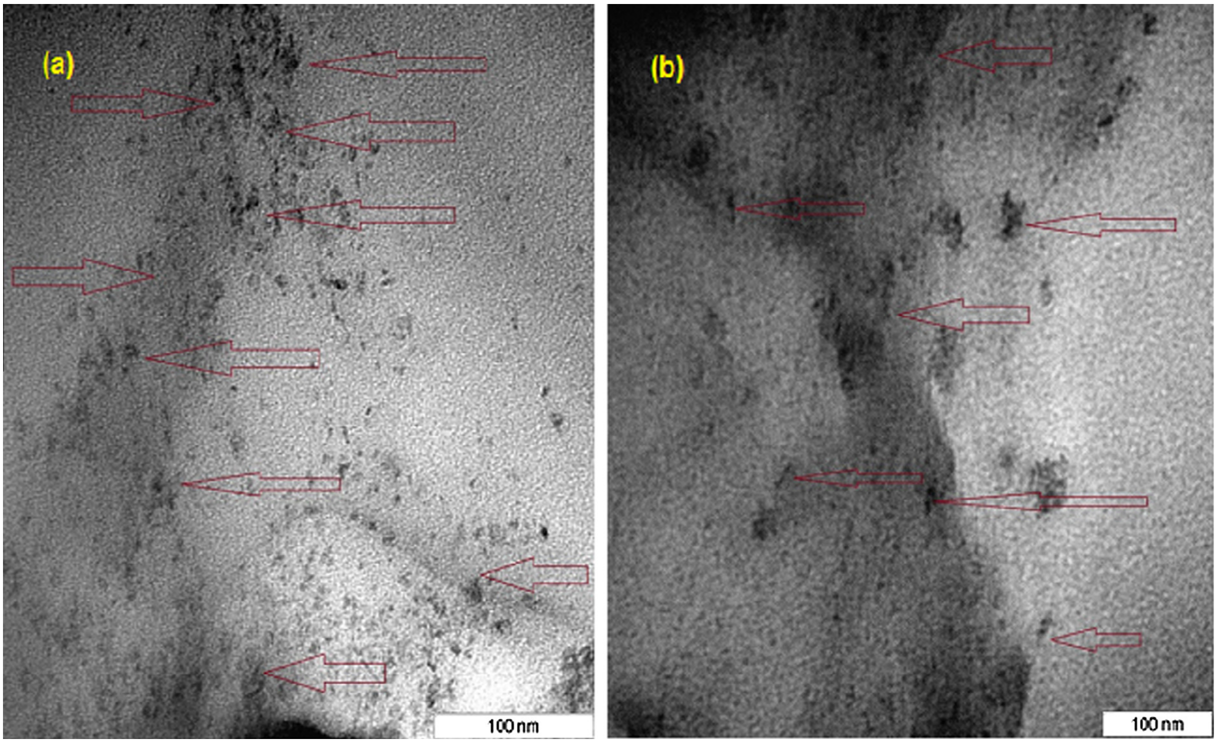

Fig. 13. (a–b) TEM images of (a) MMT/kenaf/epoxy hybrid and, (b) OMMT/kenaf/epoxy hybrid nanocomposites.

The combination of high specific strength, stiffness and elongation at break properties can also enable the civil infrastructural designers to develop the designs of road interchanges, modular components, connecting bridges, channel bridges, arched footbridge, bridges decks, stairs, railing and outdoor decking, doors, doors frames and plumbing components with better seismic and corrosion resistance on account of its lower weights, compared with steel and cemented bricks. Its applications can also be extended in many low stress applications areas such as housing sectors, windmill blades, industrial drive shafts, support beams of highway bridges and even paper making rollers, as an alternate and promising material to replace costly steel, aluminium, stones, concrete and timber wood.

5. Conclusions

In this present study a novel hybrid biocomposite was developed with the addition of nano OPEFB as reinforcing filler with kenaf fiber mat reinforced epoxy composites. The result obtained from this study is encouraging as the fabricated hybrid nanocomposites prepared by nano OPEFB filler and kenaf fibers shows improved mechanical properties without additional coupling agent and treatment of kenaf fibers. The addition of nano OPEFB filler in the kenaf/epoxy composites significantly improves the mechanical strength in terms of tensile, impact strength and elongation at break compared to the conventional kenaf fibers reinforced epoxy composites by hindering the crack initiation or propagation paths. TEM analysis exposed the better distribution of nano OPEFB filler within the epoxy matrix. Morphological analysis by SEM clearly revealed that loading of 3% nano OPEFB filler into kenaf/epoxy composites reduces the void contents, number of fiber pull out, fiber protruding and tearing on the fractured surface by only fracturing or breaking/bending of the fiber due to the better adhesion and interfacial bonding between fiber and matrix. The tensile fractured surface morphology of nano OPEFB/kenaf/epoxy also display quite comparable with MMT/kenaf/epoxy and OMMT/kenaf/epoxy hybrid nanocomposites. The enhanced mechanical and morphological properties of the nano OPEFB/kenaf/epoxy hybrid nanocomposites indicates a high possibility in high end constructional and structural applications where renewable resource and high performance are required, with the addition of relatively minor amounts of coupling agents, compatibilizers or additives. Thus it can be concluded that the developed hybrid nanocomposites will acts as a low cost, lightweight and environmentally friendly composites to be used as a building material, on account of their better morphological and mechanical properties.

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