Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Correlative Investigation on Dielectric-Mechanical-Morphological Characteristic for Kenaf-Glass-Hybrid Fibres Reinforced Epoxy Composite

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ARTICLE INFO

Article history:
Received 17 April 2024
Received in revised form 12 June 2024
Accepted 25 June 2024
Available online 30 July 2024

Keywords:
Glass fibre; Kenaf fibre; Dielectric constant; Loss factor; Lap-shear strength

ABSTRACT

In recent years, there are many applications where synthetic fibres and natural fibres are used as reinforcing materials in composites, such as the automotive and aerospace industries, the medical industry, and the construction industry. While these hybrid fibres effectively enhance mechanical and electrical properties, research into electrical characteristics remains inadequate and is an ongoing endeavor. In this work, synthetic woven glass fibres and natural woven kenaf fibres were used to fabricate composite materials by vacuum infusion technique. The dielectric properties of three different substrates, glass fibres, kenaf fibres and glass/kenaf fibres reinforced epoxy composites were investigated at 0° orientation. The ENA Network Analyzer was used to measure dielectric properties in a wide microwave frequency range. The substrates were single-joint overlapped with an adhesive and then mechanically tested. The shear strength of the joint as a function of strain, was tested using a Shimadzu universal testing machine. Visual inspections were performed to determine the failure modes of the composites. The dielectric constant and loss factor of the glass fibre composite were the highest, while the kenaf fibre composite had the lowest value. When a small amount of glass fibres is incorporated into kenaf fibres, which is called a hybrid composite, the polarization increases and the mechanical strength also increases compared to the kenaf fibre composite. Scanning electron microscopy (SEM) of the fractured tensile tests was performed to understand the nature of the interfaces between glass, kenaf and matrix. The kenaf/matrix interface was heterogeneous but exhibited voids, resulting in low dielectric properties and mechanical strength. By inserting a small amount of glass fibres, the hybrid with kenaf fibres improve the dielectric constant by 20.7% and the dielectric loss factor by 27% compared with the kenaf fibre composite. The results also show that the composites exhibit a correlation between the dielectric properties, tensile strength, and the morphological nature of the interfaces.

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https://doi.org/10.37934/aram.121.1.135145

1. Introduction

Early research in composite materials concentrated on synthetic reinforcing fibres like glass, carbon, and kevlar fibres, which have demonstrated their efficacy across a wide range of global applications. Their commendable attributes, including durability and strong mechanical properties [1,2], have positioned them as key elements in housing, sports, electronics, and electrical engineering sectors [2]. Regrettably, the extensive utilization of these synthetic fibres introduces an environmental concern due to their non-biodegradable nature [3]. This predicament poses a significant challenge, necessitating a deliberate reduction in their usage to ensure global environmental preservation and cleanliness.

In recent times, there has been a noticeable surge in research directed towards natural fibres. These fibres exhibit the potential to replace or supplement synthetic fibres in composite materials. Polymer composites reinforced with natural fibres offer certain advantages over those composed of synthetic fibres. They emerge as a promising strategy to combat environmental pollution by mitigating carbon dioxide emissions [4], all the while maintaining comparable mechanical attributes to their synthetic fibre-reinforced counterparts [5]. Their renewability and biodegradability [6], coupled with their low density and high aspect ratio conducive to stress transfer [7], have positioned them favorably in the global market [1]. However, natural fibres come with a distinct drawback when utilized as reinforcing agents – their hydrophilic nature. This characteristic presents challenges in terms of adhesion with hydrophobic matrices [3,8], leading to differential swelling between the fibres and the matrix [9]. This phenomenon consequently results in undesirable mechanical and physical properties of the composite materials, potentially rendering them unsuitable for industrial applications.

To address the inherent mechanical limitations of natural fibres and the environmental concerns posed by synthetic fibres, numerous studies have undertaken the task of enhancing mechanical and physical properties by creating hybrid solutions that integrate a modest proportion of synthetic fibres [4]. A series of investigations have focused on developing hybrid composites that marry natural fibres with synthetic counterparts, leading to the emergence of combinations like pineapple/glass, oil palm/glass, jute/glass, sisal/carbon [10], kenaf/glass, or carbon/Kevlar [3]. By synergizing natural and synthetic fibres within the same matrix, it becomes possible to harness the optimal attributes of each component while mitigating the shortcomings that arise from individual fibre use within the composites. This approach facilitates the attainment of superior outcomes encompassing quality, reduced weight, and cost-effectiveness [11]. Simultaneously, it results in enhanced mechanical strength and a diminished hydrophilic tendency exhibited by natural fibres [5,6,12]. This strategy is grounded in the principle of capitalizing on the inherent strengths of diverse fibres while concurrently counteracting any adverse tendencies, thus yielding holistic enhancements in composite performance and functionality.

Commonly, both synthetic and natural fibres play vital roles as reinforcement materials in composite applications, spanning across industries such as automotive and aerospace sectors [13], the medical field [14], and construction domains [15]. An intriguing observation arises from the amalgamation of synthetic and natural biofibres, known as hybridization, or even the amalgamation of two distinct natural biofibres within a matrix. This practice significantly expands the potential applications, encompassing marine, power generation systems, telecommunications, construction, and thermoplastic domains [16,17]. Recent times have witnessed the integration of fibre-reinforced composites within the electrical industry, serving as dielectric materials. These materials find utility in a plethora of components ranging from printed circuit boards, microchips, connectors, terminals, to transformer components and other elements within electrical and electronic devices [7,18,19].

In this study, natural kenaf fibres were used as reinforcement material alongside synthetic fibres for the development of a hybrid composite material. Kenaf fibres (Hibiscus cannabinus L.) is a conventional third-world plant [13], are very friendly environment as they are strongly absorbing carbon dioxide and have outstanding mechanical properties compared to other natural fibres like sisal, bamboo, jute and hemp [3,10]. It is expected that the combination with glass fibres will improve the mechanical properties of the hybrid composite. Prior to fabrication, it was decided that the type of fibres would be an important factor in determining the mechanical properties. The thermosetting epoxy resin was chosen as matrix due to have distinct superiority such as excellent moisture, chemical and corrosion resistance, good dielectric materials, inexpensive as well as high mechanical and fatigue strength compared with regular thermoplastic or thermoset resins [20]. Woven kenaf fibres and woven glass fibres were selected to reinforce the matrix. Ramesh et. al. reviewed that fabricated woven hybrid composites yield higher mechanical properties when compared to random orientation hybrid composite [9]. The vacuum infusion technique was used for fabrication. This technique was chosen because it is simpler, less expensive, requires 50% of the labor time compared to the hand lay-up technique, has better mechanical properties, and thus has an impact on the production load [11,12].

This study also delves into the intricate dielectric properties of composite plates through the application of microwave non-destructive testing (MNDT). Notably, three distinct categories of composites were produced, each employing different types of reinforcing agents: synthetic fibres, natural fibres, and a hybrid combination of synthetic and natural fibres, all within an epoxy resin matrix. The primary objective is to comprehensively investigate the dielectric behavior, with a parallel exploration into potential correlations with the mechanical attributes and morphological characteristics exhibited by these composite materials. This multifaceted approach showcases a dedicated effort to uncover the interplay between dielectric, mechanical, and morphological aspects, contributing to a more holistic understanding of synthetic fibres and natural fibres hybrid fibre reinforced composite performance.

2. Methodology

2.1 Composites Plate Preparation

Kenaf yarn fibres were purchased from Innovative Pultrasion Sdn. Bhd and glass fibres were provided by Eurochem (M) Ltd. The epoxy resin and hardener were obtained from Castmech Technology Sdn. Bhd. Woven glass fibres and woven kenaf fibres were used in this study. Before sample preparation, the kenaf fibres were woven using handlooms as shown in Figure 1.

Three different types of composites were prepared: (i) glass fibres in 17 plies, (ii) hybridization of 1 ply glass fibres and 1 ply kenaf fibres, (iii) kenaf fibres in 1 ply. The matrix was prepared by mixing Epoxy Amite 100 series resin and a hardener in a ratio of 3:1. Using the AST 22 AIRSPEC high vacuum pump, the mixture was infused into the laminated layers through the resin inlet and the excess mixture was discharged through the resin outlet. The laminated panels were then dried at room temperature for 24 hours.

2.2 Microwave Non-Destructive Testing (MNDT)

The dielectric properties of the composite plates were evaluated by utilizing MNDT. To facilitate this analysis, the plates were first sectioned into 160 mm x 40 mm specimens, which were subsequently subjected to dielectric measurements across a broad range of microwave frequencies using ENA Network Analyzer E5071C. The measurements were repeated for several points and the average values are used for analysis. The composite substrates were bonded with an epoxy adhesive The volume of adhesive used and the overlapped area are constant (40 mm x 40 mm).

2.3 Mechanical Testing

The mechanical properties of the overlapped joint specimens were determined using a Shimadzu universal testing machine with a length gauge of 180 mm. After destructive mechanical testing, the damaged surfaces were visually inspected to determine the failure mode. The damaged parts were subjected to morphological examination using FESEM (NOVA NANOSEM 450).

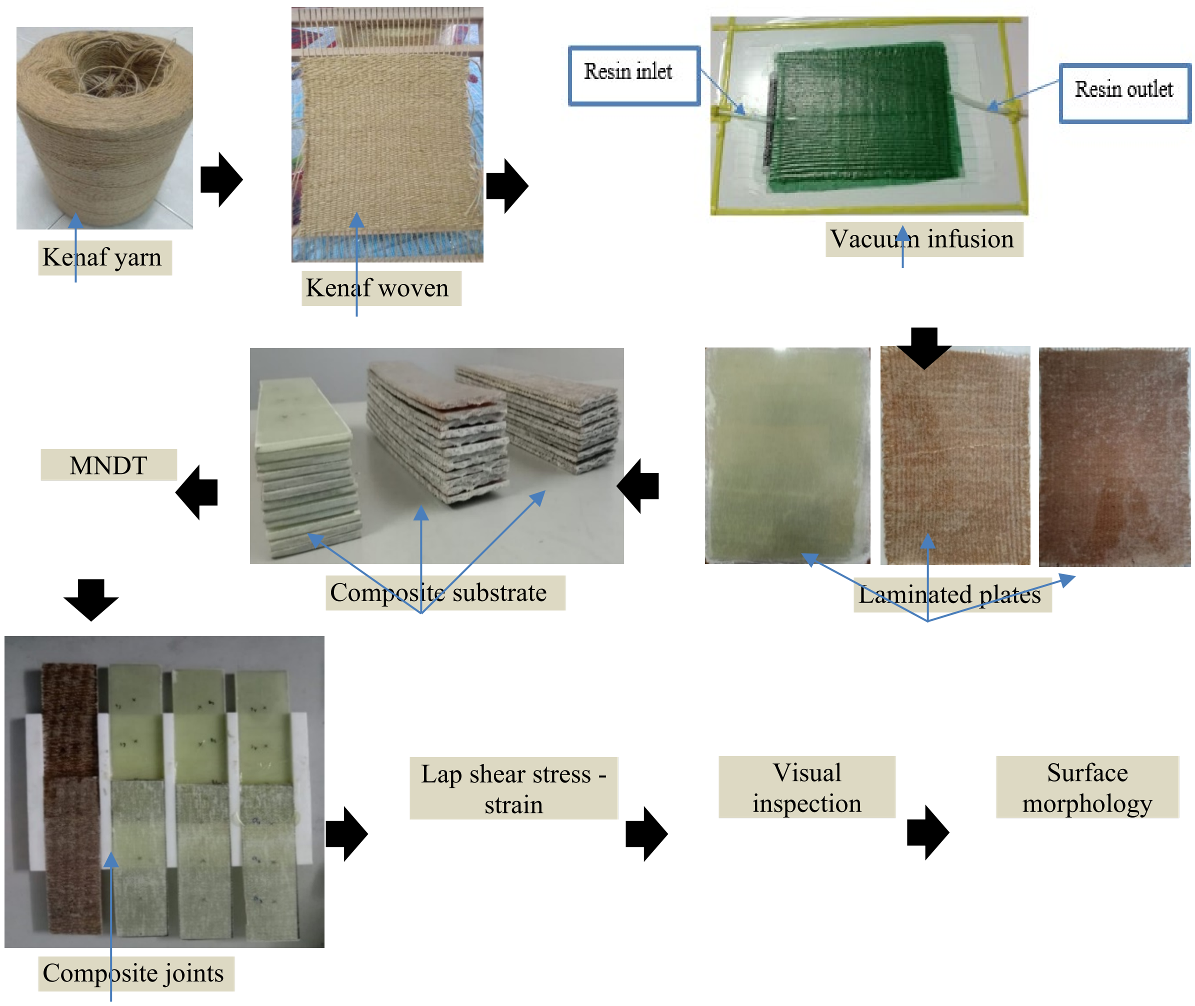


Fig. 1. Flow of the sample preparation and testing

3. Results

3.1 Dielectric Properties

In general, the dielectric constant can be interpreted as a measure of a material's ability to polarize and store charge when an external electric field is applied to the material via parallel plates that act like a capacitor [21]. Figure 2 shows the effect of fibre content on the dielectric constant of epoxy composites reinforced with glass fibres and kenaf fibres as a function of frequency in a broad microwave range. The pure epoxy matrix composite exhibited the lowest dielectric constant. This is due to the fact that the C-H bond has a small difference in electronegativity and is therefore considered nonpolar and hydrophobic. Therefore, the permanent dipoles do not occur in the epoxy matrix and the dielectric constant is lowest, which is due to atomic and electronic polarizations. Natural kenaf fibres are hydrophilic by nature and have the ability to absorb moisture. The interaction between polar - OH - groups contributes to orientation polarization, which increases the dielectric constant of non-hybrid kenaf fibre reinforced composites (KF-RE), to 3.21 on average compared to pure epoxy, 3.04. However, the poor interfacial adhesion between kenaf fibre and matrix is due to the different nature, hydrophilic or hydrophobic. The dielectric constant is highest with the content of synthetic glass fibres in the composite, with the average ε' of GF-RE being 5.10, which can be attributed to the strong interfacial adhesion of 17 layers of glass fibres with the matrix due to the hydrophobic property.

It was found that the dielectric constant values of the hybrid kenaf-glass fibre reinforced composites (HF-RE), reached an average value of ε' as 4.05, which was between the values of KF-RE and glass fibre reinforced composites (GF-RE). Compared to a non-hybrid kenaf composite, a layer of glass fibres with a layer of woven kenaf fibres as reinforcing material was incorporated into a matrix epoxy composite, which increased the heterogeneity. The heterogeneous surfaces contributed to the interfacial polarization in the hybrid composite and led to an increase in the dielectric constant of ε' 4.05 on average. The different interfaces between kenaf, glass, and matrix caused heterogeneity in the hybrid composite system, which led to the accumulation of free charges at the interface and caused the interfacial polarization. According to Ellamaran [22], interfacial polarization occurs when the free charges within the composite material migrate between two electrodes when an electric field is applied, and the charges accumulate and trap at the interface between two materials. Due to the polar and hydrophilic nature of the kenaf fibre, orientation polarization also occurs, allowing current to flow and making the composite material more conductive. The orientation and interfacial polarization contributed to the improvement in the dielectric constant of the hybrid composite compared to KF-RE.

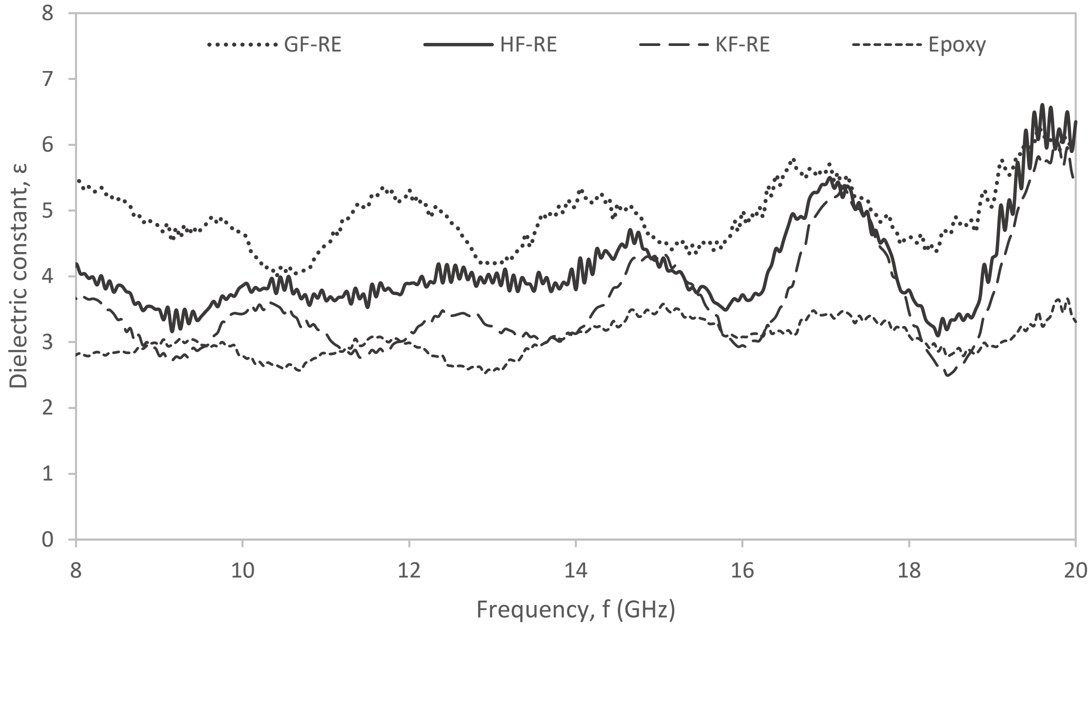


Fig. 2. Dielectric constant of the epoxy composite reinforced with glass and kenaf fibres in different layers

There were peaks at certain frequencies, possibly due to changing polarizations [23]. It was found that the dielectric constants were higher for KF-RE and HF-RE and then decreased with frequency increase. This could be due to the fact that the dipole-dipole orientation remains polarized before the molecular vibration becomes more intense and the dipoles of the full orientation cannot keep up with the applied frequency [24]. It has been observed that the dielectric constants of HF-RE show a stable trend over a wide frequency range compared to the non-hybrid composites GF-RE and KF-RE. This suggests that the hybrid composite is an advantageous material for charge storage and is suitable for electrical and electronic applications.

Dielectric loss factor usually expresses losses in industrial transmission and distribution and can be explained as the average power factor over a period of time. It is an evaluation of the energy loss in a dielectric material due to the phenomena of polarization, conduction, and other dissipation [6, 25]. The loss factor of epoxy composite material reinforced with kenaf and glass fibres as a function of frequency at different layer sequences at room temperature is shown in Figure 3. The average values of loss factor are 0.14, 0.08, 0.11 and 0.52 for the pure epoxy matrix, KF-RE, HF-RE and GF-RE, respectively. The results show that the kenaf fibres have the lowest dielectric loss factor and the glass fibres have the highest.

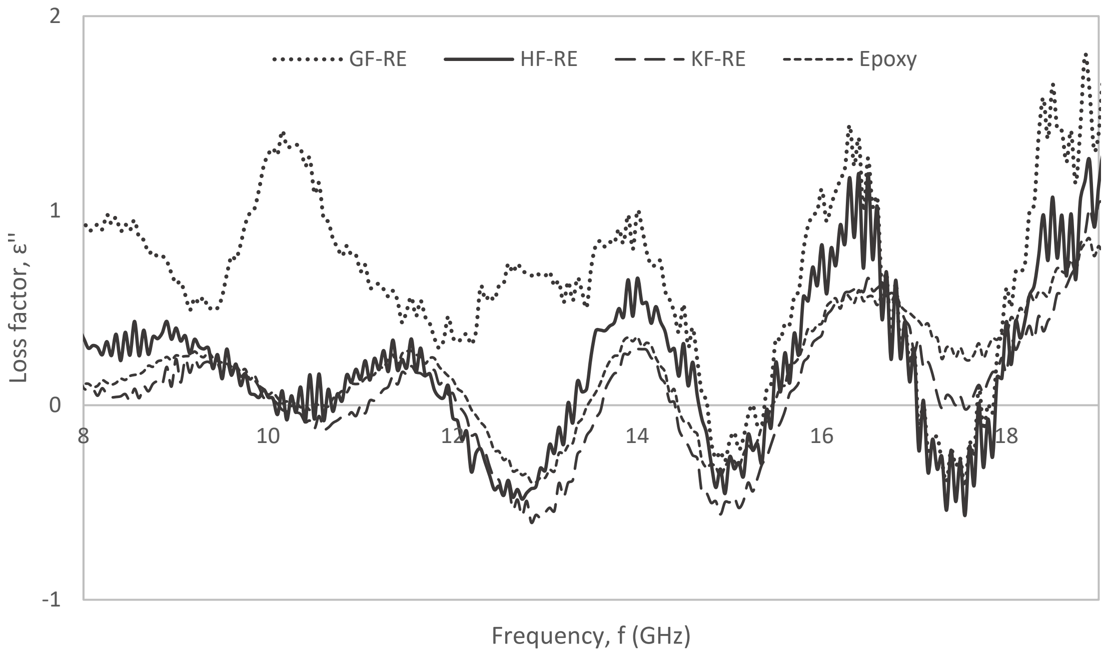


Fig. 3. Loss factor of the epoxy composite reinforced with glass and kenaf fibres in different layers

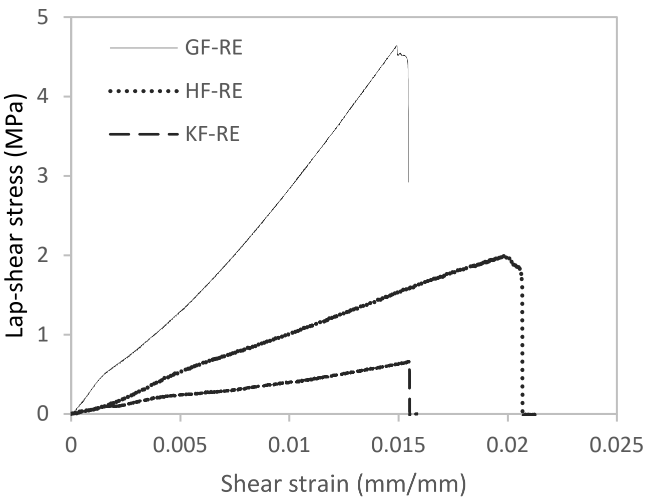
It can be observed that the composites KF-RE and HF-RE show almost similar trend as the pure epoxy matrix. The trend is higher at high frequencies, which is due to the fact that the loss factor is mainly determined by the atomic and electronic polarizations. However, the hybrid composite shows an increase in loss factor at low frequencies compared to KF-RE and the epoxy matrix. It can be explained that the increase in orientation polarization along with interfacial polarization leads to an increase in loss factor when a glass fibre with kenaf fibres was incorporated into a composite. The glass fibre contributes to the hybrid composite becoming heterogeneous, which can lead to interfacial polarization and thus an increase in loss factor. From these results, the hybrid composites can reduce the energy loss by 78% compared to GF-RE and 21% compared to the epoxy matrix. However, the energy loss of HF-RE is 27% higher than that of KF-RE, which has the lowest energy loss.

It can be concluded that the hybrid kenaf-glass fibre composite can utilize the advantages of both fibre components, kenaf and glass fibre. The hydrophilic nature of the kenaf fibre could reduce the energy loss due to polarization, conductivity and dissipative phenomena. The glass fibre, on the other hand, helps the composite to be a good electrical insulator even at low thickness.

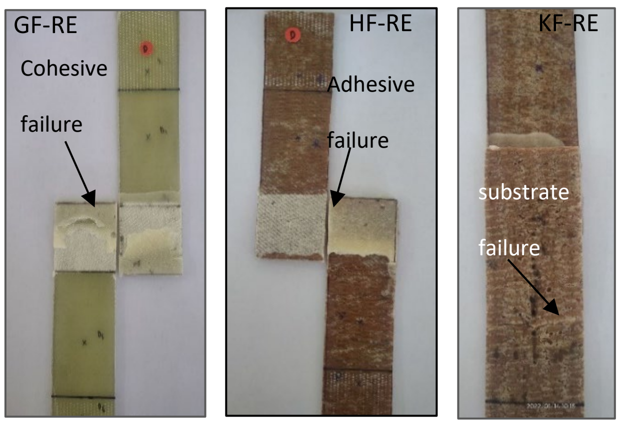
3.2 Mechanical Properties and Failure Mode

All composite specimens were made in a single lap joint and used to measure tensile strength, which is presented as a plot of lap shear strength versus strain. Lap shear strength can be defined as the potential of a material to resist stress when the applied shear force moves the two substrates in opposite directions. In application, it is usually measured at the bonded joint. Shear strain, on the other hand, is commonly known as the deformation or displacement of the material due to an applied shear stress. Figure 4(a) shows plots of lap shear strength as a function of strain for kenaf fibre and glass fibre reinforced epoxy resins, which increasing to a certain point before failure. The GF-RE has high lap shear strength and the KF-RE has the lowest values. From the figure, it can be seen that the strength and strain of the hybrid composite are higher than KF-RE. This can be explained by the fact that the hybrid composite was strengthened by the glass fibre. The lap shear strength increases by 65% when a layer of glass fibres is incorporated together with kenaf fibres. At the same time, the hybrid composite exhibits 25% higher of strain than KF-RE and GF-RE.

The failure mode was determined by visual inspection of the tensile specimens. The GF-RE, HF-RE and KF-RE composite substrates were bonded together with an adhesive that held the two surfaces together by placing it between them. After performing the mechanical test, the failure point for each composite type was observed to predict the probable failure mode. Figure 4(b) shows the type of failure, where GF-RE resulted in cohesive failure, indicating that the composite type was hard and strong. At HF-RE, adhesive failure occurred because the substrate of the hybrid composite was soft and tough. In contrast, at KF-RE, the substrate failed due to its soft and brittle nature. It can be said that GF-RE and HF-RE exhibit adhesive failure, while KF-RE causes substrate failure. This indicates that the different reinforcing materials of the composites affect the mechanical properties and the nature of the damage.



(a)



(b)

Fig. 4. (a) Lap-shear stress vs. strain curve and (b) failure mode of epoxy reinforced with glass fibre (GF-RE), kenaf fibre (KF-RE) and hybrid glass/kenaf fibres (HF-RE) composites

3.3 Morphology Properties

Figure 5 shows the microscopic images of the fracture surfaces of three types of composites, GF-RE, HF-RE, and KF-RE, subjected to tensile loading. From the image of KF-RE, it can be seen that the kenaf fibres are well bonded to the matrix. This is due to the fact that the kenaf fibres have a rough surface, which contributes to good adhesion between kenaf and the matrix. However, in some places, large voids can be seen, leading to detachment of the fibres from the matrix and cracks in the matrix due to air entrapment in the woven kenaf structure, resulting in brittle behavior and thus low mechanical properties. The image of HF-RE shows that there are sections consisting of kenaf fibre/matrix, matrix, and glass fibre/matrix. The kenaf fibre/matrix region exhibits fibre breaks, voids, and fibre/matrix delamination. The glass fibre/matrix region, on the other hand, exhibits fibre/matrix debonding, fibre breaks, and fibre splits. There is a matrix region that serves as a support for the kenaf and glass fibre regions. The presence of these three regions makes the hybrid composites tough and increases the mechanical properties compared to the non-hybrid kenaf fibre composites. The glass fibre reinforced epoxy composite GF-RE has a very homogeneous rough surface and no voids were observed, which makes the pure glass fibre composite hard and strong. This morphological explanation can support the results of electrical and mechanical properties.

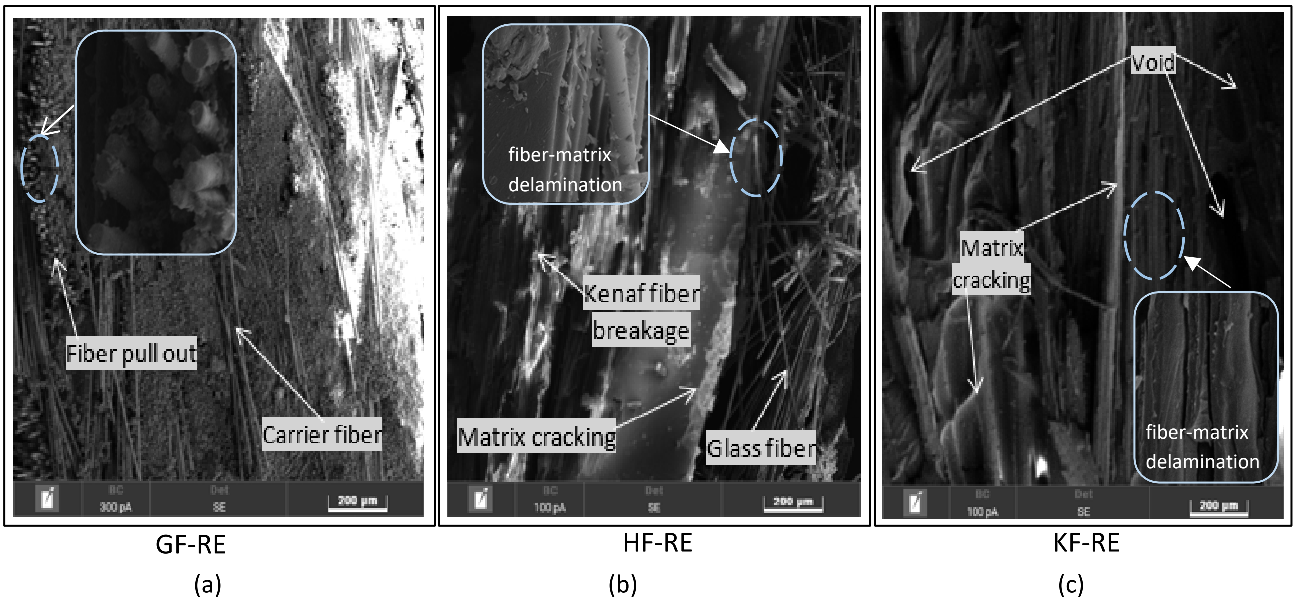


Fig. 5. SEM microscopic image of fracture surface for (a) glass fibre, (b) hybrid glass/kenaf fibres and (c) kenaf fibre reinforced epoxy composite

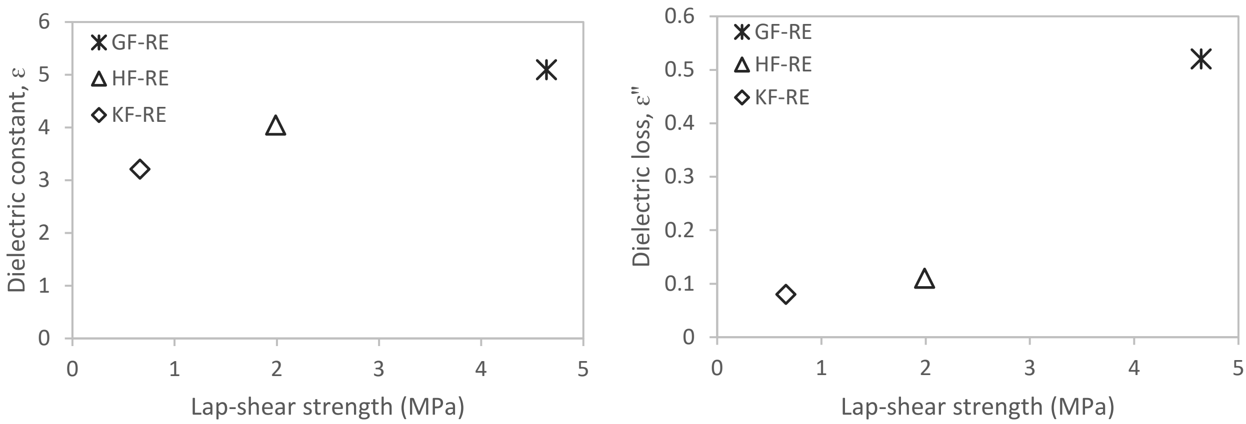
3.4 Correlation Between Dielectric and Mechanical Property

Figure 6 shows the plot of dielectric properties against shear strength. It was found that there is a correlation between dielectric constant and dielectric loss and mechanical properties of lap shear strength. The dielectric constant and dielectric loss increase as the overlap shear strength increases. The GF-RE has the highest values due to its excellent mechanical and electrical properties as it is synthetically produced. The matrix reinforced with natural kenaf fibres has the lowest values because the hydrophilic nature of kenaf fibres results in poor adhesion between the kenaf fibres and the matrix, leading to low mechanical performance. However, compared to KF-RE, both properties are improved when a layer of synthetic glass fibres is incorporated into the natural kenaf fibres, resulting in stronger mechanical performance due to stronger adhesion between fibres and matrix. The glass fibre, which has a hydrophobic property, helps to increase the heterogeneity behavior, which increases the interfacial polarization, and at the same time, the polarization of dipole orientation also helps to improve the dielectric properties of HF-RE. From the figure, it can be deduced that there is a correlation between these two properties, where the dielectric values can determine the shear strength of the composites and predict their failure.

The glass fibre composite has the highest electrical properties and the kenaf fibre composite has the lowest. In the interest of environmental protection, a hybrid composite material consisting of 1 layer of kenaf fibres and 1 layer of glass fibres out of a total of 17 layers of glass fibres was manufactured. By inserting a small amount of glass fibres, the hybrid with kenaf fibres improve the dielectric constant by 20.7% and the dielectric loss factor by 27% compared with the kenaf fibre composite. The hybrid composite can reduce the energy loss by 78% compared with the glass fibre composite.

The glass fibre composite has the highest lap shear strength and the kenaf fibre composite has the lowest. Hybridization of glass fibres and kenaf fibres increases the lap shear strength by 65% compared to the kenaf fibre composite. The strain of the hybrid composite is 25% higher compared to the composite of glass fibres and kenaf fibres. The substrate of the hybrid composite failed by adhesion to the bonded joint, but the kenaf fibre composite failed on its substrate.

These three types of composites have different morphological surface, with the glass fibre composite being very homogeneous and having high dielectric and lap shear strength-strain properties. In contrast, some voids were observed in the kenaf fibre and matrix adhesion contributes to the lowest of the properties. In the hybrid composite, a heterogeneous surface was observed, which contributes to be better properties compared to the kenaf fibre hybrid composite.



(a) (b)

Fig. 6. Correlation between dielectric properties and mechanical properties of the epoxy composite reinforced with glass fibres and kenaf fibres

4. Conclusions

Woven glass fibres and woven kenaf fibres were selected as reinforcing agents in the epoxy matrix, which were successfully prepared by the vacuum infusion technique. The composite substrates with 0° orientation and standardized thickness were used for testing. The electrical, mechanical and morphological properties of the composites were investigated. It is clear that there is a correlation between the mechanical lap shear strength and the dielectric behaviour. As the dielectric values increase, the lap shear strength also increases. These results were confirmed by visual inspection of the damage pattern and morphological observations. Ultimately, MNDT was deemed a suitable preliminary method prior to conventional destructive mechanical testing in predicting the mechanical strength through dielectric results.

Acknowledgement
This research was funded by a grant from Ministry of Higher Education of Malaysia (MTUN Matching Research Grant; (Ref: 9028-00014 / 9002-00106 / 9030-00004)

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