Elastic and dynamic response characteristics of kenaf/polypropylene composites

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Abstract

The elastic and dynamic characteristics of natural fibre based materials are of particular concern for packaging applications. In this study, the tensile and flexural behaviour of kenaf filled polypropylene (kenaf/PP) composites are experimentally studied. The mass fraction of kenaf is varied from 0wt% to 60wt% in 10% increments. Two rates of extensions, namely, 2mm/min and 10mm/min are used for the tensile test. The flexural test is conducted at a rate of 1mm/min with reference to the ASTM D790-10 standard. The results obtained indicate that the elastic modulus of the kenaf/PP composites increases while the Ultimate Tensile Stress (UTS) of the composites decreases with increasing fibre loadings. It is found that the elastic modulus of the 60wt% composite increases from 1.89GPa to 2.64GPa when the extension rate is increased from 2mm/min to 10mm/min. For this same increment of extension rate, it is observed that the UTS of the composites reduces when the fibre loadings are increased with the 10mm/min rate registering higher UTS values than that by the 2mm/min rate. The stiffness of the composites in tension thus increases at the expense of their strength when the extension rate is increased. A semi-empirical model employed in this study also predicts similar responses. The stiffness of the composites in bending mode is found to be little affected by the fibre content in the neat PP. The fracture toughness of the kenaf/PP composites decreases by 56% as the fibre fraction is increased from 10wt% to 60wt%. The first three modes of vibration of the composites are simulated using ANSYS® ver. 12.1 program. The natural frequencies corresponding to the elastic response of the composites at the two extension rates for these modes fluctuate between 208Hz and 725Hz.
Keywords: kenaf, agro-waste, bio-composites, tensile properties, dynamic characteristics, empirical models.

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1 Introduction

Advancement in materials science and engineering during the past three decades were driven mainly by the need to produce lightweight materials that are comparable in performance to their contemporaries (e.g., Huntington [1], Chalmers [2], McConnell [3], Wambua *et al.* [4]). There is recently an increased concern for the development of not only functionally well-designed but also sustainable materials. Material sustainability is associated with the extraction of renewable resources and disposal procedures that would not injure our ecosystem (Mohanty *et al.* [5], Jering *et al.* [6]).

Natural fibres are obtained from renewable natural resources including oil palm empty fruit bunch, coconut shell, rice husk and the kenaf plant as opposed to synthetically produced petroleum-based fibres. The growing interest in using select natural fibres over synthetic fibres to reinforce polymer based composites is mainly due to the salient advantages such as low specific weight, low cost, ease of processing and good thermal and acoustical insulating properties of the former (e.g., John and Thomas [7], Ashori [8]).

In Europe, for example, the increased usage of natural fibres especially in the automotive industry is driven by their low density and environmental concerns related to the disposal of synthetic fibres. Composite materials made of natural fibres and polypropylene, polyester or polyurethane matrix are being used in producing components such as door or trunk liners, parcel shelves, seat backs and headrests (Suddell [9]).

Packaging materials for logistical use are designed to protect fragile consumer goods from damages due to shock and/or excessive vibrations during handling and transportation. At present, expanded polystyrene (EPS) is the predominant packaging and packing materials in the market (e.g., Tolinski [10]). The disposal of the entirely polymeric, non-biodegradable and photolysis-resistant EPS often causes environmental and health concerns (e.g., Ross and Evans [11], Peter and Gerd [12]). Production of petroleum-based packing foams like EPS releases ten times the volume of carbon dioxide and consumes up to eight times the energy than that needed to produce a sample of agro-based packing material [13].

Engineering materials made from low cost indigenous agricultural wastes or by-products thus has the potential to substitute fully petroleum-based materials especially for non-load bearing applications such as packaging and packing in logistics and transportation of goods. The elastic and dynamic characteristics of natural fibre based materials are essential to and of particular concern for packaging and other shock cushioning applications.

This study presents a preliminary investigation of the tensile and flexural behaviour of kenaf filled polypropylene (kenaf/PP) composites. The mass fraction of kenaf is varied from 0wt% to 60wt% in 10% step increments. The tensile strength and modulus of the samples were experimentally measured at two rates of extensions, namely, 2mm/min and 10mm/min. The flexural test is conducted at a rate of 1mm/min. The variations of tensile and flexural strength as a function of fibre content are empirically modelled. The first three modes of vibration of the composites are simulated using ANSYS® ver. 12.1 program.

2 Experimental

Plain polypropylene (100% PP) and kenaf/PP composite samples were fabricated using the standard hot press method. The temperature of the upper and lower plates in the hot press machine is set to 200°C and a pressure of 10MPa is applied to the manually mixed kenaf/PP inside a mould for 20 minutes. The mass fractions (wt%) of kenaf used in the kenaf/PP composites are 10%, 20%, 30%, 40%, 50% and 60%. The elastic modulus and strength of the 100% PP and kenaf/PP composites are determined in tensile and flexural modes based on the BS EN ISO 527-5: 2009 and ASTM D790-10 test standards, respectively. INSTRON3382 Universal Testing Machine is used to conduct both the tensile test and the flexural test. The rate dependency of the tensile and flexural properties is measured. Two constant rates of extension (crosshead speed), namely, 2mm/min and 10mm/min are used for the tensile test. The flexural test is conducted at a crosshead speed of 1mm/min. Five samples were used for each round of test and the average values of the properties measured are reported below.

3 Results and discussion

3.1 Tensile properties

Fig.1 shows that the tensile modulus of the kenaf/PP composites measured at the extension rate of 10mm/min is greater than that recorded at the 2mm/min rate. The modulus of the kenaf/PP composites at both the extension rates are generally

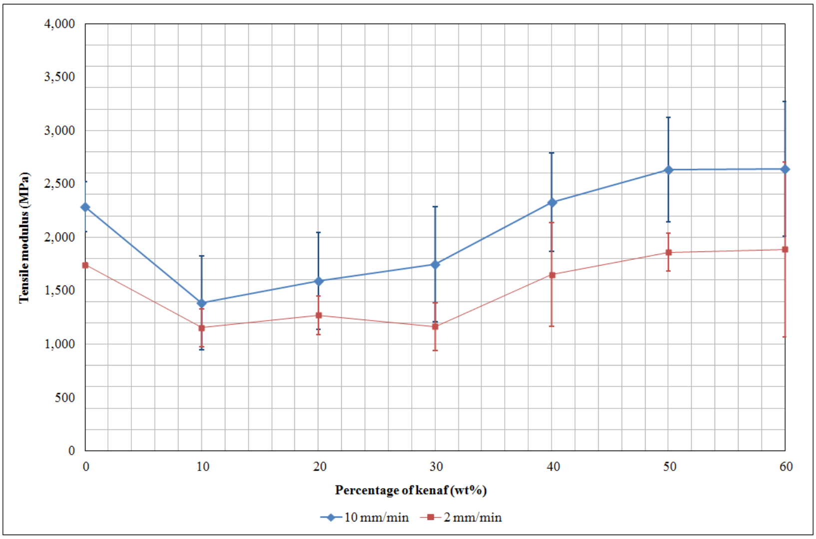

Figure 1: Comparison of elastic modulus (in tension) of the kenaf/PP composites for different extension rates.

lower than the stiffness of the plain PP with the 10% increment of fibre content up to 30wt% loading. Increasing the amount of kenaf fibre content in the PP matrix beyond 40wt% would increase the elastic modulus of the kenaf/PP composite as seen in Fig. 1. The stiffness of the plain PP is thus enhanced with a fibre addition greater than 40wt%. The highest values of elastic modulus of 1887MPa and 2640MPa were recorded at the 2mm/min and 10mm/min extension rates, respectively, for a 60wt% fibre content.

The distribution of the fibre lengths present in the composite may influence the shape of the curve, since the load taken up by the fibres decreases as the strain increases. Addition of fibres restricts the mobility of the polymer molecules to flow freely past one another and hence cause premature failure (Hull and Clyne [14]). The formation of fibre aggregates by hydrogen bonds at the surface form a bigger structure called agglomerates. This causes the mobility of macromolecule chain be affected, where the reduction in elongation at break happens which increases the tensile modulus (David *et al*. [15]).

Fig. 2 shows the values of ultimate tensile stress (UTS) of the kenaf/PP composites at the extension rates of 2mm/min and 10mm/min. Higher values of UTS were observed for the extension rate of 10mm/min. The trends of both UTS curves are the same where the UTS values continually decrease with increasing percentage of kenaf. At the strain rate of 2mm/min, the highest UTS value of 14.9MPa was recorded for the 100% PP sample while the lowest value of 4.17MPa is registered for the composite with 60wt% of kenaf. Similarly, the greatest UTS value recorded at the 10mm/min rate is 33.7MPa for the plain PP and the lowest value of 6.37MPa was measured for the 60wt% sample.

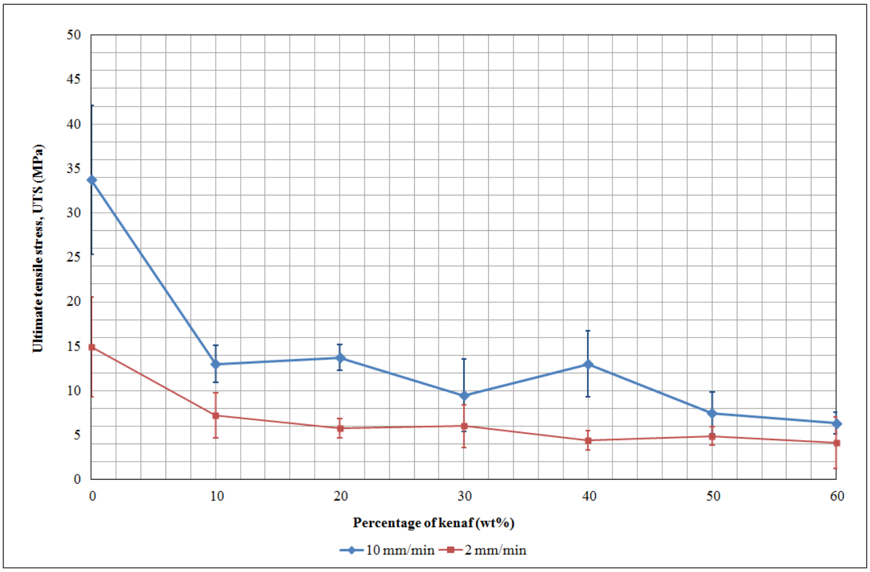

Figure 2: Comparison of ultimate tensile stress (in tension) of the kenaf/PP composites at different extension rates.

The different surface properties of the fibre (hydrophilic) and the matrix (hydrophobic) cause discontinuities at the fibre/matrix inter-phase bonding. The distribution of kenaf fibres in the PP matrix may not be uniform due to the natural traits of fibre and matrix where the opposing natures of the fibre and the matrix surfaces may weaken the interface adhesion. Stress concentration spots are created owed to poor stress transfer from fibre to matrix. Restricted polymer chain mobility by the dispersion (i.e., fibres) and poor fibre/matrix adhesion cause stress concentration spots in the composite (David *et al.* [15]). Chemical treatment of the fibre surface had achieved various levels of success in improving fibre-matrix adhesion in natural fibre-reinforced composites (Li *et al.* [16]). Chemical treatment such as maleated coupling agents may improve the adhesion between the fibre surface and the polymer matrix. The treatment modified the fibre surface and also increased the fibre strength.

The increase in tensile modulus and the decrease in UTS of the kenaf/PP composites when the extension rate is upped from 2mm/min to 10mm/min is consistent with general change in the tensile behaviour of polymeric materials from *ductile* to *brittle* as the strain rate is increased (Bower [17]).

3.2 Modelling of ultimate tensile stress

Fu *et al.* [18] studied on the effects of particle size, particle/matrix interface adhesion and particle loading on mechanical properties of particulate-polymer composites. An expression to predict the UTS of a particulate-filled composite from the UTS of the composite (σ_c) and the matrix (σ_m) is given by

$$\sigma_c = \sigma_m (1 - V_f), \tag{1}$$

where V_f is the volume fraction of particles, i.e., fibre. Eqn. (1) indicates that the strength of a particulate-filled composite such as the kenaf/PP composite in the present study decreases linearly with the increase in particle loading. A modified form of this equation is obtained by replacing the particle volume fraction by a power law function of the volume fraction (converted from wt%) as

$$\sigma_c = \sigma_m (1 - aV_f^b) \tag{2}$$

where a and b are constants that are related to particle shape and arrangement in the composite (Fu *et al.* [18]). Eqn. (2) still predicts a decrease in strength with increase of particle loading as eqn. (1) but the former considers fibre features and dispersion via the two constants. Figs. 3 and 4 shows the experimentally measured UTS values compared to that predicted by eqn. (2).

Fig. 3 shows that both the experimental and the predicted UTS values decrease with the addition of kenaf with an average error of 3.4%. The semi-empirical model given by eqn. (2) supported the experimentally observed mechanism of deformation as discussed in Section 3.1 above. The value of σ_m is constant at 14.9MPa while the constants a and b are 0.55 and 0.2, respectively.

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Fig. 4 confirms the same trend as the experimental observation with an average error of 2.7%. Value of σ_m is constant at 33.7MPa while the constants *a* and *b* are 0.6 and 0.2, respectively. It is apparent that constant *a* increases from 0.55 to 0.6 when the extension rate is increased from 2mm/min to 10mm/min, whereas constant *b* remains the same for both the extension rates.

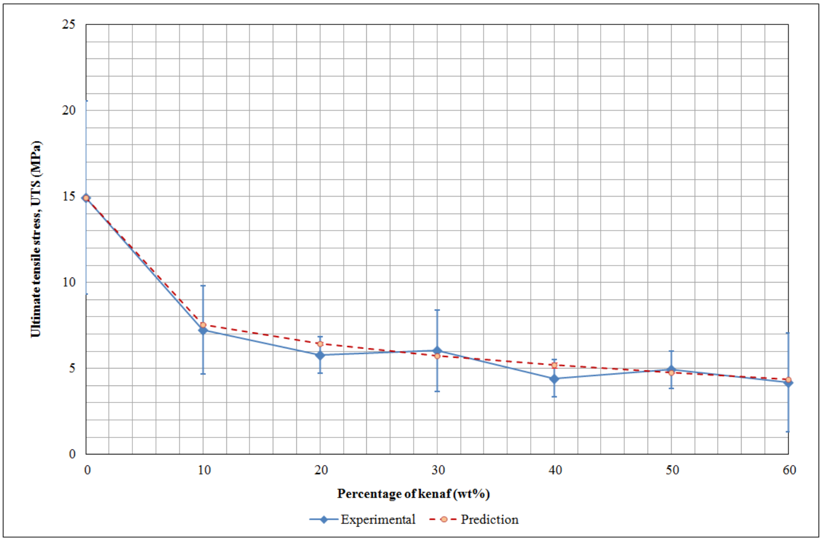


Figure 3: Experimental and predicted UTS at 2 mm/min extension rate.

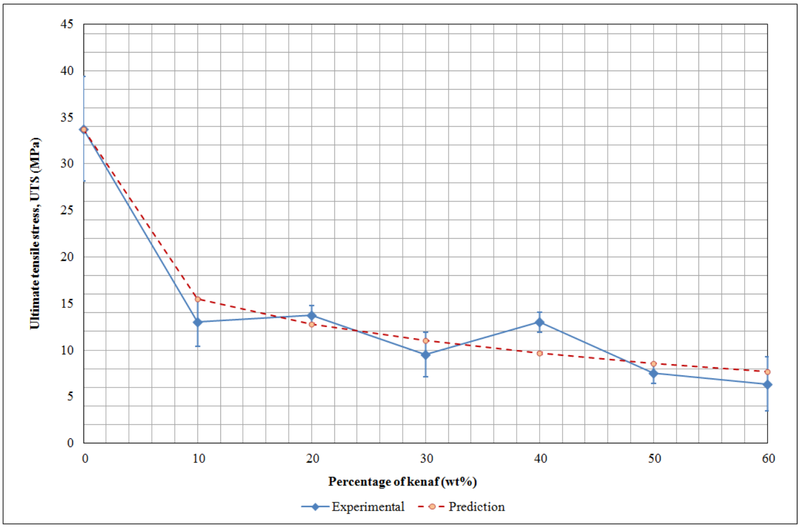


Figure 4: Experimental and predicted UTS at 10 mm/min extension rate.

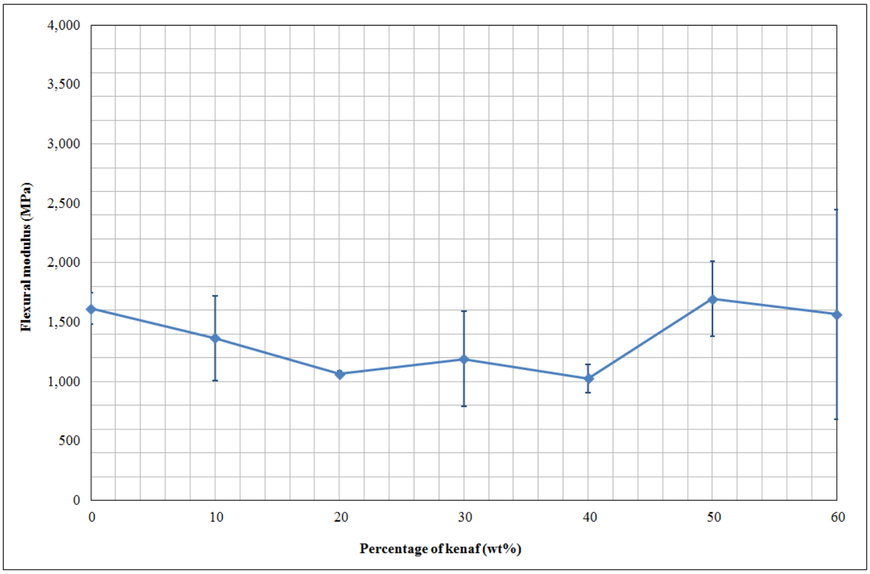


Figure 5: Elastic modulus (in bending mode) of the kenaf/PP composites.

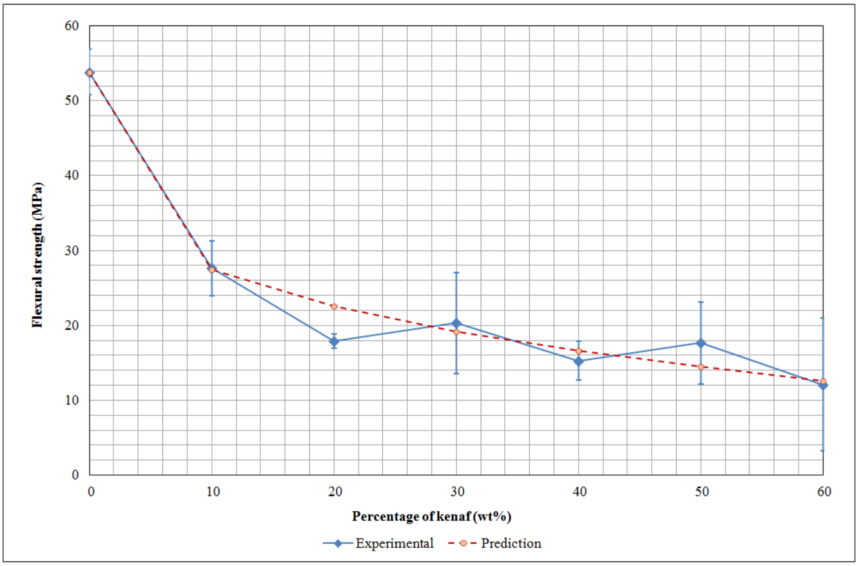


Figure 6: Experimental and predicted flexural strength of the kenaf/PP composites.

3.3 Experimental and predicted flexural properties

The variation of flexural modulus at the loading (*bending*) rate of 1mm/min illustrated in fig. 5 is found to be similar to tensile test elastic modulus graph (see fig. 1). The highest and lowest average values of flexural modulus of 1696MPa and 1027MPa were recorded for 50wt% and 40wt% fibre content, respectively.

The predicted flexural strengths of the composites shown in fig.6 conform to the trend obtained experimentally with an average error of 1%. The flexural strength decreases with the fibre content. The semi-empirical model given by eqn. (2) supports the experimentally observed deformation mechanism as depicted in fig. 6. It could be observed that the value of σ_m is constant at 53.8MPa while the constants *a* and *b* are 0.45 and 0.25, respectively.

4 Simulation of dynamic response

4.1 Simulation parameters

The first three modes of free vibration of two composites, namely, the 50wt% and 60wt% samples, and the plain PP are simulated using ANSYS® ver. 12.1 software. These composites exhibited improved stiffness over the 100% PP sample and at the higher extension rate of 10mm/min, as experimentally observed above. The experimental tensile modulus values of the composites and the plain PP for the two extension rates (see fig. 1) are used as Young's modulus of the test specimens for simulation purpose. The Poisson's ratio of the test specimens is taken as 0.3. The volume and mass of the composites and the plain PP are measured to determine their densities. The test specimens in this modal analysis are modelled as isotropic membranes of 4mm thickness. Uniform Quad Method is applied for the meshing of the models with an element size of 0.05.

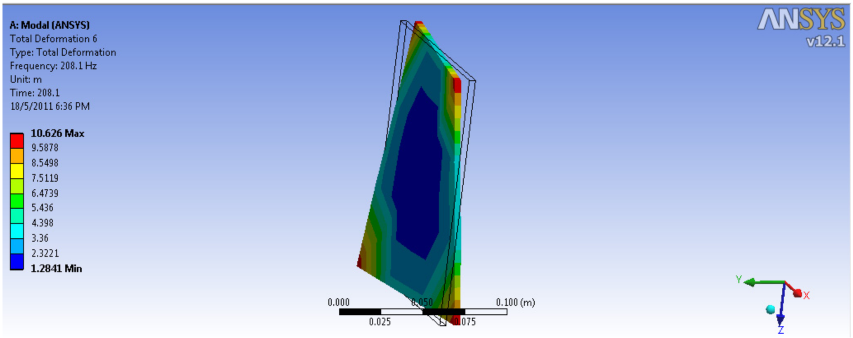
4.2 Results

The results of the modal analysis are tabulated in table 1. The natural frequencies corresponding to the elastic response of the composites at the two extension rates for first three modes of vibration of the selected samples fluctuate between 208Hz and 725Hz.

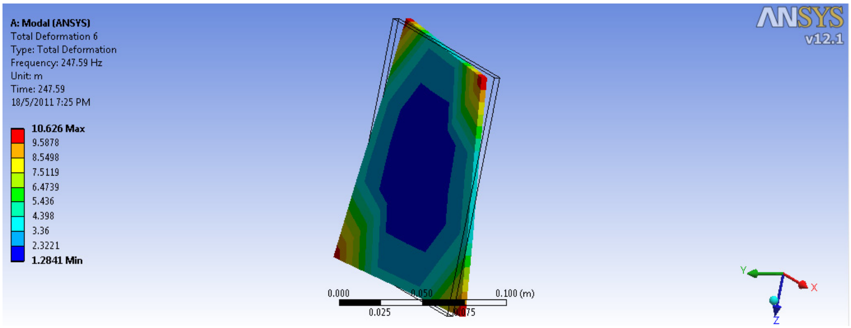
Table 1: Natural frequencies (in Hz) of the first three modes of selected samples.

Mode	2 mm/min (*lower stiffness*)			10 mm/min (*higher stiffness*)		
	100% PP	50 wt%	60 wt%	100% PP	50 wt%	60 wt%
1st	254.2	208.1	213.06	291.16	247.59	252.06
2nd	320.03	261.99	268.24	366.56	311.71	317.34
3rd	633.7	518.78	531.15	725.84	617.24	628.38

It is observed that the natural frequency increases at the higher extension rate of 10mm/min for which the tensile modulus is greater. This is consistent with general linear relationship between natural frequency and material stiffness. The deflection shapes of the first mode of the 50wt% composite sample at the two extension rates are shown in fig. 7. These mode shapes correspond to 208.1Hz and 247.59Hz for the 2mm/min and 10mm/min extension rates, respectively.



(a)



(b)

Figure 7: The deflection shapes of the first mode of the 50wt% composite sample at (a) 2mm/min, and (b) 10mm/min extension rates.

5 Digest

The tensile and flexural properties of kenaf filled polypropylene (kenaf/PP) composites with 0wt% to 60wt% kenaf content are experimentally determined. It is found that elastic modulus of the kenaf/PP composites increased while the tensile strength (UTS) of the composites decreased with increasing fibre content. The elastic modulus of the composites generally increased when the extension rate is increased from 2 mm/min to 10mm/min with the 60wt% composite registering 40% increment. For the same increment of extension rate, it is observed that the UTS of the composites reduces when the fibre loadings are increased with the 10mm/min rate registering higher UTS values than that by the 2 mm/min rate. The stiffness of the composites in tension thus increases at the expense of their strength when the strain rate is increased. The effect of strain rate on the elastic behaviour of the composites is the limited ductility and enhanced stiffness. The semi-empirical model used in this study closely predicted the experimentally measured tensile and flexural strength of the composites. These observations were utilised to simulate the first three modes of free vibration of two composites, namely, the 50wt% and 60wt% samples, and the plain PP using ANSYS® ver. 12.1 program. The natural frequencies corresponding to the elastic response of the composites at the two strain rates for these modes fluctuate between 208Hz and 725Hz. The results of the simulation are in agreement with the general linear relationship between natural frequency and material stiffness. The strain rate effect, which is not accounted for in the semi-empirical model used for predicting the UTS, and the influence of fibre surface treatment(s) on the elastic behaviour of the kenaf/PP composites, will be studied as part of future work.

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