Moisture Absorption Properties and Shock Cushioning Characteristics of Bio-Based Polyurethane Foam Composites

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ABSTRACT

This paper presents the shock cushioning and water absorption properties of polyurethane (PU) foam composites filled with kenaf fibres and saw dust (SD). These properties are relevant to the use of such bio-based composites as cushioning foam for packaging materials. The PU/kenaf samples were prepared with filler size ranging between 355μm and 500μm. The PU/kenaf and PU/SD composites are fabricated with 5, 10, 15, 20 and 25 wt% filler loadings. The moisture absorption properties of the composites are determined based on the ASTM-D5229 test method. The diffusion rates from the moisture absorption test are calculated using Fick's Second Law equation. The variation in the moisture absorption curve of the samples can be attributed to their cell structure. The shock cushioning test is performed in accordance with ASTM-D4168 standard for selected composites only. In this test, the composites are subjected to five static stress loading levels, i.e. 39.22, 94.9, 225.10, 320 and 398.43 kg/m2. The shock cushioning performance of the PU/kenaf composite is compared to that of PU/SD composite. The decelerations experienced from the drop represent the fragility factor or G value of the products. The results obtained indicate that the G values generally decrease with increasing static stress loading for both types of fillers. The

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outcome of this study signifies the potential of kenaf (a trade crop) and SD (bio-waste from the timber industry) as fillers in PU foam for applications that have traditionally depended on 100% PU foams alone.

Keywords: *Polyurethane foam; Moisture absorption; Shock cushioning; Kenaf; Saw dust.*

Introduction

Polymeric composites based on natural fibres (NF) present a number of advantages including reduced dependency on non-renewable resources, lower pollutant emissions, lower greenhouse gas emission, and enhanced energy recovery [1]. However, NF are mostly hydrophilic materials that have strong affinity to moisture. The hydrophilic characteristic of NF when combined with polymer matrix makes the composites very sensitive to moisture absorption. The absorbed moisture results in issues related to dimensional stability and durability [2]. There are numerous numbers of applications in the automotive, packaging, and construction industries [3].

High moisture repellent is a desired property of NF composites in efforts to expand their scope of applications. The water absorbed of NF-polyurethane foam at saturation was found to be dependent on the amount of fibres presents in the composites [4]. Even though several reports on this subject have been discussed, the water absorption mechanism in NF composites could not be fully generalized because different NF composites possess different moisture absorption characteristics due to the cellular and macrostructure of the composites. The moisture absorption characteristics are often determined based on experiments on moisture uptake and assuming one dimension diffusion based on Fick's Law. Moisture diffusion in polymeric composites has been shown to be Fickian and non-Fickian [5],[6]. Thus, it is important that this issue to be allocated with so that natural fibres can be considered as a practical reinforcement in composite materials.

In cushioning systems, the use of cellulosic materials has been common practice for quite some time. However, the preference for plastic materials in the cushioning segment is related to the expected level of protection in contrast to bio-based composites.

Shock in packaging is often encountered during the distribution and handling processes including from drops, (a package falling from a height onto a surface), impacts, (an object falling onto a package), and sidekicks, (horizontal shocks generally occurring from packages sliding during truck transport). Shocks due to transportation by truck may happen due to the truck hitting potholes, running over curbs or railroad tracks and packages sliding during transportation [7].

The main purpose of the present study is to evaluate the suitability polyurethane (PU) foam composites for cushioning applications. This paper presents the shock cushioning and moisture absorption properties of PU foam composites filled with kenaf fibres and saw dust. These properties are relevant to the use of such bio-based composites as cushioning foam for packaging materials.

Shock Fragility Index

The two shock absorption parameters pertinent to a proper packaging solution is the fragility of the product to be protected and the maximum drop height. The fragility of an item is measured and reported numerically as its fragility index or *G* factor (expressed in *G*'s). It provides a basic parameter for packaging engineers to use in the selection of cushioning materials.

The fragility index is the maximum *G* force that an item to be packaged can withstand without Sustaining damage. This is determined by dropping test objects from increasing heights and recording the *G* force sustained by the item when damage first occurs.

In addition to the fragility index the maximum drop height must also be determined for an item to be packaged. Maximum drop height is simply how far the packaged item is expected to be dropped during typical handling and shipping procedures. Once the maximum drop height and fragility index are determined, a packaging engineer uses dynamic cushioning curves for various packaging materials to design a protective package.

Foam packaging materials are classified for packaging by determining dynamic cushioning testing or more commonly called cushion drop testing. Although similar in design, this should not be confused with the drop testing conducted to determine an item's fragility index [8]. Table 1 lists the ranges of fragility index for typical packaged articles.

Table 1. Approximate fragility index of typical packaged articles.

Application level	Products	Fragility index, *G*
Very Delicate	Hydraulic disc drive Aircraft altimeter Figurines Weapons guidance systems	15 - 40
Delicate	Thumb drive / Hard disk drive Networking hardware	40 - 80

	Personal computer Medical devices	
Moderate Rugged	Televisions Laptop computers Stereos	80 - 100
Rugged	Furniture	115

Experimental

In this study, the composite foams are formulated from a commercial isocyanate polymer and polyol manufactured for use in closed mold processes.

Material preparation

The optimum ratio of isocyanate to polyol was decided to be 2:1, after conducting a pilot study. The natural fibres (NF) used in this study as fillers are kenaf and sawdust (SD) with sizes ranging between 355µm and 500µm with a density of 0.167 g/cm3 and 0.172 g/cm3, respectively. The NF were oven dried for 2 hours at 100°C and then kept in a closed container to prevent it from absorbing environmental moisture.

Moisture absorption

In this experiment PU/kenaf and PU/saw dust (SD) foam composite were fabricated. The composite foam was prepared using rectangular plastic mold with dimension of $318 \times 227 \times 80$ mm. Specimens from 5 to 25 wt% of NF (kenaf or SD), with the increments of 5 wt% were fabricated. Two parts of isocyanate was first mixed homogenously with the NF, later one part of polyol added to the iso-NF mixture and stirred for 6s. The foam formulation was poured straightaway in an open mold and left to rise freely. Subsequently, after 10 min the foam was removed from the mold and was left to cure for three days before cut. Both PU/kenaf and PU/SD were using the same fabricating method but they were manufactured separately.

Shock cushioning

For shock cushioning sample preparation, it is same procedure as for the moisture absorption test mentioned above. The dimensions of the composite foam are11.0” × 8.5” × 3.0” (length × width × thickness). Specimens from 5 to 15 wt % of NF (kenaf or SD), with increments of 5 wt % were fabricated.

Moisture absorption test

To quantify the moisture absorption, rectangular specimen with dimensions of 80 x 80 x 30 mm were cuts from the manufactured foam. Moisture absorption test were carried out in accordance to ASTM D 5229/D 5229M-92 [9],[10]. Each specimen was placed in an individual transparent box with a top cover, containing distilled water bath at maintained room temperature of 25°C. A holding component was designed to hold the foam sample fully submersed in water during test. After 24 hours, the samples were taken out and weighed, after the weight measurement the specimens were immersed again. The process was repeated for nine days to determine its diffusivity, *D*, at early stage. The values of mass change, ΔM (in %) are calculated using the formula shown in Equation (1):

$$\Delta M\ (\%) = \frac{M_i - M_b}{M_b} \times 100\% \tag{1}$$

where M_i = current specimen mass (g), and M_b = baseline specimen mass (g).

Diffusion coefficient

The determination of diffusion coefficient is calculated from the solution of one-dimensional analysis of Fick's 2nd Law [11]. The solution to the diffusion equation can be written in terms of the amount of moisture gain at any given time, M_t normalized to the amount of saturation at infinite times, M_m as given in Equation (2):

$$\frac{M_t}{M_m} = 1 - \frac{8}{n^2}\sum_{n=0}^{\infty}(2n+1)^{-2}\exp\left[-D(2n+1)^2\pi^2 t/l^2\right] \tag{2}$$

where M_m is the moisture gain at saturation equilibrium (%), n is a known integer which varies from material to material, h is the thickness of the material, and D is the diffusivity of the material. For shorter times, this solution can be approximated as follows (see Equation (3)):

$$\frac{M_t}{M_m} = 4\left[\frac{D}{\pi h^2}\right]^2 \sqrt{t} \tag{3}$$

Thus the diffusivity, *D*, of the material can be calculated by rearranging Equation (3) to Equation (4) below:

$$D = \pi \left(\frac{h}{4M_m} \right)^2 \left(\frac{M_i - M_b}{\sqrt{t_2 - t_1}} \right)^2 \tag{4}$$

where $M_t = M_i - M_b$ = absolute value of moisture absorption, and $\sqrt{t_2 - t_1}$ is the square root of time period for the moisture gain.

Effective moisture equilibrium

A sample shall be defined to be in a state of equilibrium when the average moisture content of the material changes by less than 0.020% over reach of two consecutives reference time period spans. The change in moisture content is expressed as Equation (5):

$$|M_i - M_{i-1}| < 0.02\% \tag{5}$$

Shock cushioning test

Shock transmission characteristics of a cushioning material are normally presented in the form of cushion curves, which depict the peak acceleration (a_{max}) transmitted by the cushioning material of a given thickness in a drop from a certain height, as a function of static load. Static load stress, σ_o, is defined as the ratioof the product weight (mg) to the cushion bearing area, A, indicated in Equation (6):

$$\sigma_o = \frac{mg}{A}, \tag{6}$$

and typically is expressed in kPa (kN/m^2). The impact cushioning capacity of the bio-based foam fibre was evaluated using a shock cushioning test based on the principles and guidelines of ASTM D4168 (Test Method A) [11]. In this test, metal weight were used as static load subjected to vertical free fall under the saw dust fibres pads in order to assess the ability of fibre to slow the impact. The drop testing equipment used included a Lansmont Precision Drop Tester PDT56, a PCB model 8626M01 triaxial accelerometer attached to metal block used as static load; and a double wall carton box used as a support for the samples. The signal analysis was performed using SAVER Equipment X90 with a 1000 Hz filter. The release mechanism for drop test was set at 24 inches height. The same foam subjected to 5 times drops at the chosen test condition with the box positioned flat so that the weight rests on the test cushion as shown in Figure 1.

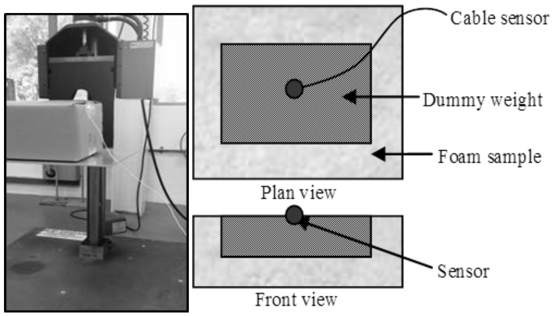

Figure 1. Test setup for shock cushioning (Method A).

Results and Discussion

Moisture absorption

In this study, the percentage of water absorption in the PU foam composite is evaluated for fibre content from 5 to 25 wt% in the interval of 5%. For both types of the PU foam composites, the results obtained indicate that moisture absorption increases with increments of fibre content. This is consistent with the general observations mentioned in earlier [12]. Higher fibre content corresponds to greater number of free –OH group resulting from the cellulose and hemicellulose inside the fibre, which lead to the increase of moisture absorption as observed here.

The percentage of mass gained, ΔM calculated by using Equation (1) as a function of square root of time is plotted in Figure 2 for both PU/kenaf and PU/SD composites. The plot in Figure 2 shows linear relationship between moisture gain and time up to the limit the samples were soaked (i.e., nine days). For all samples, the calculated average moisture content are more than 0.020%, this indicate that all samples have not yet reach the state of effective moisture equilibrium.

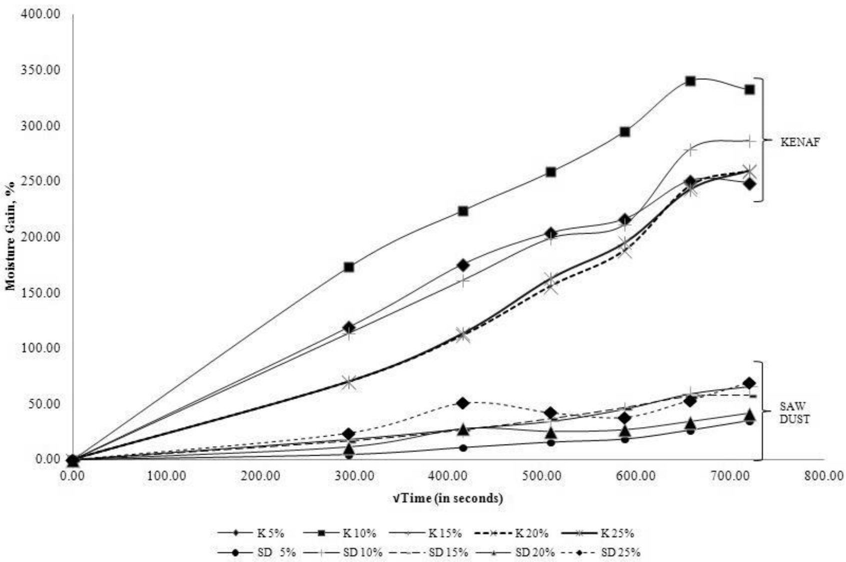

Figure 2. Moisture absorption of PU/kenaf and PU/SD immersed in water as a function of time at 25°C.

Diffusion coefficient

Diffusion coefficient, *D*, calculated by using Equation (4) as a function of fibre content is listed in Figure 3. The diffusion coefficients appear to increase slightly with the addition of fibre content. It is also to be noted that the rate of diffusion for PU/kenaf composites is far greater than that for the PU/SD composites by one order of magnitude. The highest diffusion coefficient obtained here for both types of composites is at 25 wt% filler content.

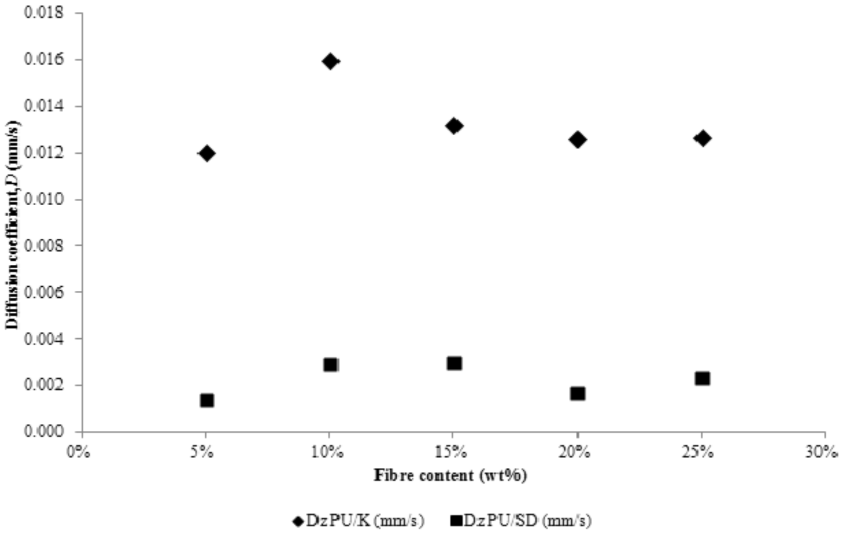

Figure 3. Variation of diffusion coefficient, *D* (mm/s) with fibre content.

Shock cushioning

The results of the shock absorption test are presented in Figure 4, which shows the *G* values of the 5, 10, 15 wt% PU/kenaf composites and 15 wt% PU/saw dust as a function of the applied static stress. For the 5%wt PU/kenaf, the *G* value captured from range 71.66*G* to 40.25*G*. This highlights the best level of shock protection from damage for product category such as hard disk and computers as described in Table 1 above.

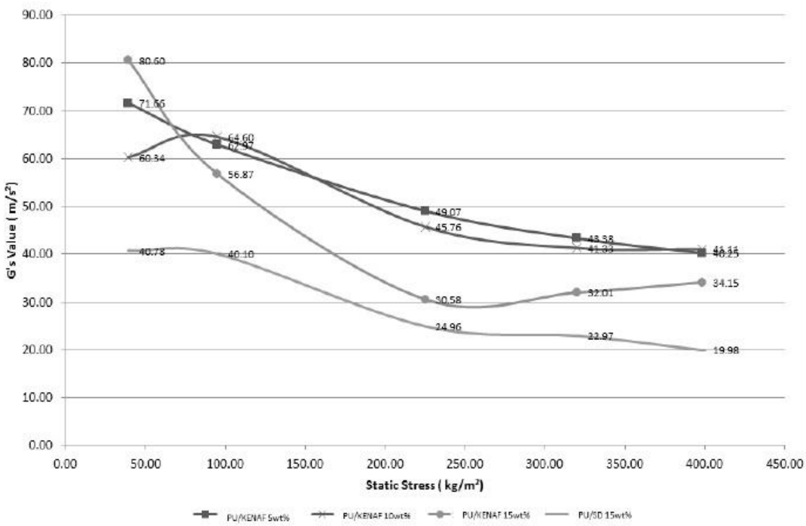

Figure 4. Shock cushioning curve for PU/kenaf (5 wt%) composite.

The setup and test parameter are same. Under these conditions, the 10 wt% kenaf fibre filled PU composite showed an increase of static stress except for point of 94.9 kg/m^3, where value for *G* is 64.60*G*. It was observed the pattern behaviour for second static stress slightly increase at 64.60*G* compare to the first static stress which gives value at 60.34*G*. For this type of fibre, as compare to the 5 wt% PU/kenaf, it shows a higher value of *G* for the last point of static stress.

The 15 wt% PU/kenaf composites recorded the *G* value range between 34.15*G* to 80.60*G*. Under these conditions, the curve showed an increase in slowing up with increasing static stress up to the 3 point of static stress. The *G* was observed slightly increased after the fourth point of static stress to the fifth point. This behaviour occurred due to the energy impact to be observed by the kenaf fibre, so that causing the deformation of the material. It was not providing a good cushioning for protection of product. As compared to 5 wt% and 10 wt% of PU/kenaf, the graph shows significant change to 30.58*G* in the same value for 225.1 kg/m^3 of static stress. In other words this material is best protection for product fragility listed in Table 1 for the moderate rugged category application.

The 15 wt% PU/SD composites were also evaluated in this test. Under the same conditions, the curve showed an increase of slowing up the *G* value with increasing number of static stress. The *G* values for saw dust compare to the kenaf for all point of static stress are observed lower. This is suitable for the production for product in very delicate category for fragility index between 15 – 40*G* in Table 1 as mentioned above.

Conclusion

The moisture absorption properties of kenaf and saw dust (SD) filled polyurethane (PU) composites were investigated. It is observed that the moisture gain generally increase with the increasing of fibre content for both PU composites. The highest value of diffusion coefficient was recorded at a filler content of 25 wt% for both PU composites: PU/kenaf, D = 10.1 mm/s and PU/SD, D = 0.56 mm/s. It is observed that all samples have not yet reached the state of effective moisture equilibrium for the nine-hour immersion period measured in this study. Thus it is expected that the moisture gain will continue to increase with time that warrants further investigation at longer duration. The shock cushioning performance of 100% PU, PU/kenaf and PU/SD composites were studied. It is observed that PU/SD composites give a good protection and cushioning for product with fragility index of 40 – 80*G*. The PU/SD composites were found to provide cushioning for products with fragility index below 40*G*. In general, the shock cushioning curve increased with the increase of the static stress for both types of composites. The main findings above highlight the prospect and utility of the bio-based PU foam composites material as cushioning foam for packaging material that can be moulded into shape of cushioning pad.

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