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Investigation on an environmentally friendly biobased untreated date palm fiber composite for thermal insulation

A. Oushabi, Y. Abboud, A. El Bouari

Laboratory of Physico-Chemistry of Applied Materials, University of Hassan II, Faculty of Sciences Ben M'sik, Casablanca, Morocco.

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oushabiabdessamad@yahoo.fr
Phone: +21245729656;

Abstract

In this study, physical, mechanical and thermal properties of date palm fibers (DPFs) reinforced Epoxy resin were studied. The boards were prepared with different fiber loading: 0%, 40%, 60% and 80% (by volume) by using a melt compounding method. The effect of fiber loading on physical, mechanical and thermal properties was investigated, Epoxy-DPF composites showed an increase in water uptake percentage by increasing the fiber loading because of the hydrophilic nature of DPFs, while flexural properties was decreasing with increase in fiber content. Thermal conductivity of Epoxy-DPF composites was also measured according to ASTM C177; the results showed that the prepared boards with had the thermal conductivity values ranging from 102.39-64.66 mW/m×K at 25°C by increasing the fiber loading. Morphology observations after the composites fracture showed a good fiber-matrix adhesion.

Physical quantities:

$R = \frac{e}{\lambda}$ $E = \sqrt{\lambda.\rho.C_p}$ $D = \frac{\lambda}{\rho.C_p}$ $C = c_p \times m$	λ: Thermal conductivity in (W/m.K) R: Thermal resistance in ($m^2 \times K/W$) E: Effusivity ($J.K^{-1}.m^{-2}.s^{-1/2}$) D: Diffusivity in (m^2/s) e: Thickness in (m) C: Thermal capacity in (j/K) Cp: The specific heat in (j/K.kg) m: Mass in (kg) ρ: Density (kg/m^3)

1. Introduction

In the last few decades, the use of natural fibers such as kenaf, jute and date palm fibers as reinforcements in polymer composites became highly attractive materials due to their benefits such as low cost and weight, renewability, biodegradability and less abrasiveness to equipment [1]. Recently, many studies have been done on the development of thermal insulation materials from natural fibers used as environmental-friendly and renewable materials such as sisal, hemp and date palm fibers and polymeric matrices [2-8]. One of the most studied resins is epoxy. Indeed, epoxy resins are considered as one of the most important classes of thermosetting polymers which are widely used as matrices for fiber-reinforced composite materials and as structural adhesives thanks to their

various advantages; they are amorphous, highly cross-linked polymers and this structure results in these materials possessing various desirable properties such as greater tensile strength and modulus, uncomplicated processing, fine thermal and chemical resistance, and dimensional stability [9].
Evaluation on the thermal conductivity of insulation material is standardized into heat flux method and guarded hot plate method [10]. In general, thermal insulation materials, like other natural or man-made materials, exhibit temperature dependence of their properties which depends essentially on the operating temperature [11, 12]and the microstructure of the material [13]. For most materials, the value of the thermal conductivity increases with temperature according to many empirical relationships based on experimental data [14]. The average conductivity depends mainly on the density, temperature, and water content. The effect of the operating temperature on the thermal capacity of insulation materials has been studied by several works. Khoukhi et al. studied the effect of the operating temperature on the thermal conductivity behavior of polystyrene insulation materials in the Oman climate. The results showed that the thermal conductivity increases with the operating temperature [12].
A recent study of the fiber content on mechanical properties of kenaf fiber reinforced composite was carried out by Nishino et al. (2003) [15] who found that both Young's modulus and tensile strength increased with the increase of fiber content and showed the maximum values (Young's modulus; 6.4 GPa, and the tensile strength; 60 MPa) around a fiber content of 70 vol.%.

The aim of this paper is to investigate experimentally the thermal conductivity of environmentally friendly bio-based date palm fiber composites as new thermal insulation materials with different fiber loading and at different operating temperature, using a Lambda Meter EP500e apparatus based on the guarded hot plate method. The flexural strength of the boards is also studied. The results presented in this paper should be of great interest for new ecological material manufacturers and industrials who take an interest in the attainment of higher building thermal performance and energy efficiency.

2. Material and Methods

2.1. Materials

Date palm fibers (Phoenix Dactylifera L.) used in this study were collected from the region of Errachidia southeast of Morocco; firstly, they were washed in distilled water in order to remove salt and impurities from the surface and then dried using an oven at 80 °C. The fibers length is comprised between 10 and 15 mm. Epoxy resin used in this study (Araldite 506 epoxy resin) was supplied by Sigma Aldrich with a density of 1,168 g/cm^3.

2.2. Methods

2.2.1 Preparation of DPF -Epoxy boards

The boards were prepared using date palm fibers with different percentages (0 %, 40 %, 60 % and 80 % by volume) namely: Epoxy, Epoxy-DPF40, Epoxy-DPF60 and Epoxy-DPF80 respectively. The fibers were mixed with an epoxy resin until homogenization. After mixing, the boards were molded and pressed with the pressure of 50 kg/cm^2, and then they were stored in conditioning room and cut into various test samples.

2.2.2 Water up-take test

The samples were prepared for water up-take testing according to ASTM standards (1995) [16].; the samples were first dried at 60°C for 24 hours before being immersed in water. The water absorption percentage was then calculated by following the equation (Eq1):

$$\%\ \text{water uptake} = (Wa - Wb)/Wb \times 100 \quad (1)$$

Where Wb is the weight of samples before soaking in water and Wa is the weight after soaking in water.

2.2.3 Thermal conductivity measurement

The thermal conductivity of different samples was determined by using a λ-Meter EP500e. The thermal conductivity test tool λ-Meter EP500e is a test tool based on an embedded-PC for absolute value measurements on guarded hot plate method according to ASTM C177 standard (2010)[17] with a large measurement range between 0.001 and 3 W/m×K. A 200×200 mm^2 specimen with a variable thickness can be placed in the test section between two plates, which are maintained at different temperatures during the test. Upon achieving thermal equilibrium and establishing a uniform temperature gradient throughout the sample, thermal conductivity is determined. The thermal conductivity was determined by following the equation 2:

$$\lambda\ (W/K.m) = (Qu+Ql)/2\times D/\Delta T \quad (2)$$

Where Qu is the output of the upper heat flux transducer, Ql is the output of the lower heat flux transducer, D= 10 mm is the thickness of the sample and ΔT is the temperature difference between the surfaces of the sample.

2.2.4 Flexural properties testing

Flexural tests were performed using a three point bending set-up according to the ASTM D790 standard (1997)[18]. The samples with dimensions of 200 x 10 x 10 mm^3 (length x width x thickness) were tested using ZWICK Z50 machine with a speed rate of 1 mm/min. Flexural strength was then obtained using the following equation (Eq3):

$$\sigma f\ (MPa) = (3PL) / (2bd2) \quad (3)$$

Where L is the support span; b, the width of the specimen; d, the thickness; P, the maximum load; and m, the slope of the initial straight line portion of the load–displacement curve.

2.2.5 Scanning electron microscopy (SEM)

The surface morphology of fracture of flexural specimens was investigated using a VEGA3 scanning electron microscope from TESCAN. No preliminary preparation of samples was performed. SEM observations were used in order to visualize the Epoxy-DPF adhesion; several samples were examined to ascertain the observed phenomena.

3. Results and discussion

3.1 Water uptake behavior

The water uptake of Epoxy-DPF composites with different fiber contents is presented in Fig. 1. From this figure, it can be seen that the water uptake process for all specimens is linear in the beginning, then slows and approaches saturation after prolonged time, following a Fickian diffusion process. It is also interesting to note that the rate of absorption increases as the fiber volume fraction increases. This phenomenon can be explained by considering the water uptake characteristics of date palm fibers. These results are in accordance with those reported by Zach et al. (2013) [6] who found that the hydrophobic treatments of hemp mats significantly affected their absorbability. According to the authors, treated samples showed lower values of short-term absorbability compared to the untreated sample. Several other studies in the use of natural fiber reinforced polymeric composites have shown that the sensitivity of certain mechanical and thermal properties to moisture uptake can be reduced by the use of coupling agents and fiber surface treatments.

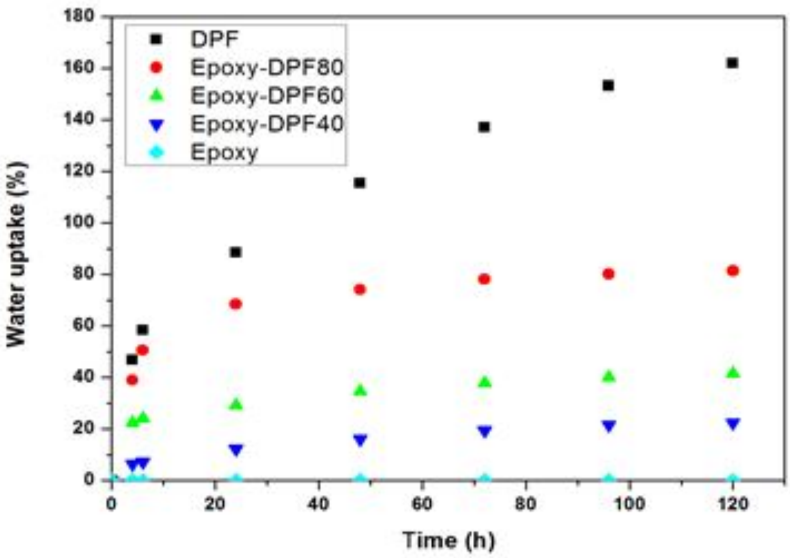

Figure 1. Water uptake behavior of Epoxy-DPF composites

3.2 Thermal conductivity of Epoxy-DPF composites

3.2.1 The effect of fiber loading

The thermal conductivity of all composites was tested in accordance with the American Society for Testing Materials (ASTM C 177). The measured thermal conductivity and thermal resistance are plotted as a function of fiber loading shown in Fig. 2. From Fig. 2, it can be clearly noted that when increasing fiber content thermal conductivity was found to decrease and consequently an increase in thermal resistance was observed. Indeed, when increasing date palm fibers load, the boards density was found to decrease due to the low density of date palm fibers compared to neat epoxy, therefore, the thermal conductivity is directly related to the board density, where the higher the board density is, the higher thermal conductivity and automatically lower insulating capacity [19]. Although in a previous work [20] date palm fibers were found to have a porous microstructure containing a lot of voids, the air within the voids leads to a lower thermal conductivity of the whole board.

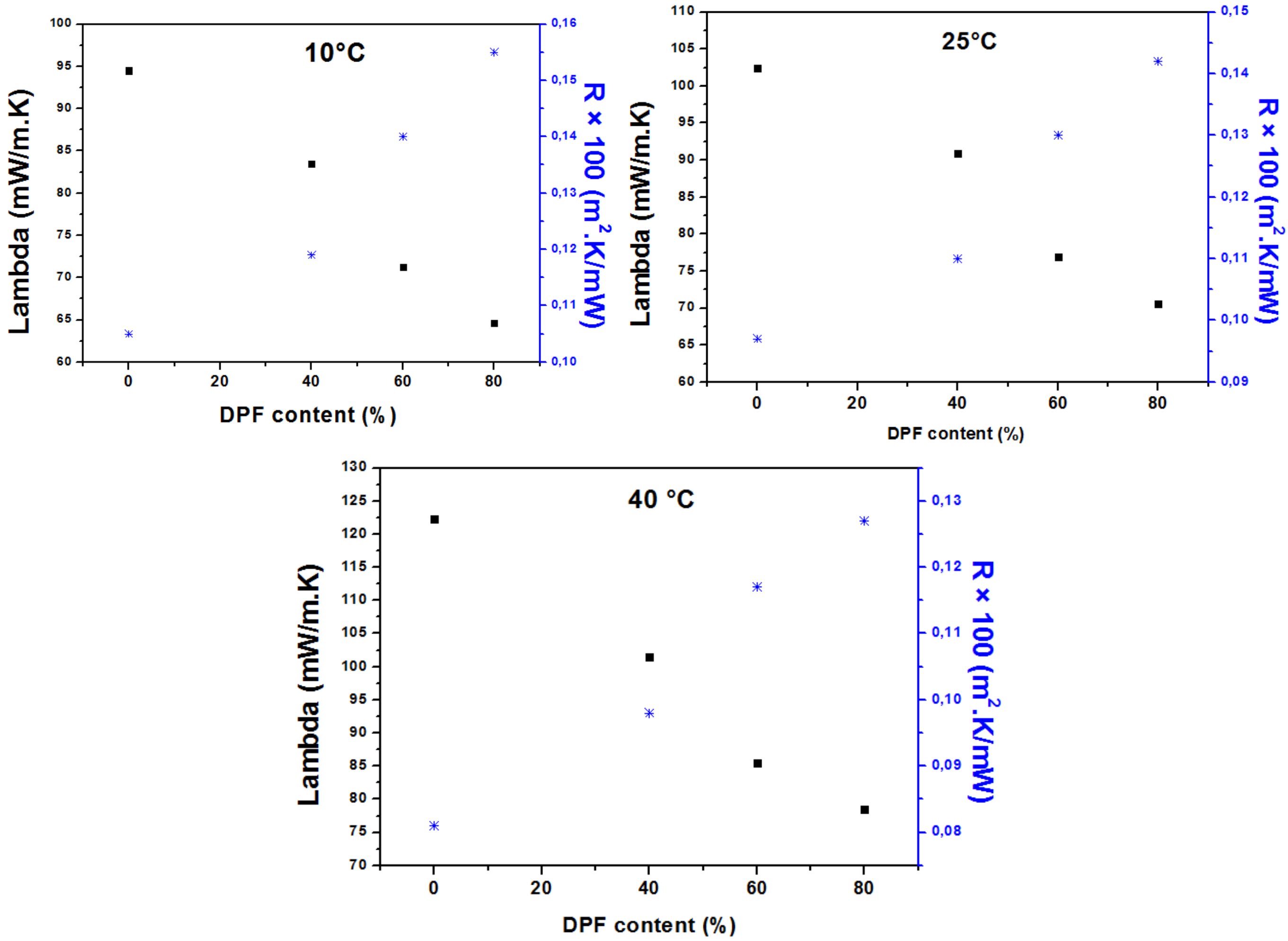

Figure 2. Effect of fiber loading on thermal conductivity and resistance of Epoxy-DPF composites

3.2 The effect of operating temperature

The effect of operating temperature on thermal conductivity of Epoxy-DPF insulation materials has been also studied. The obtained results are presented in Figs. 3 and 4. Thermal conductivity of different materials has been measured at different operating temperature: 10 °C, 25 °C and 40 °C. The result shows that the thermal conductivity is affected by the change in the operating temperature. In all cases, higher temperature leads to higher thermal conductivity values [12]. Also, the result shows clearly that the lower the material density is, the higher the effect of operating temperature on material thermal conductivity.

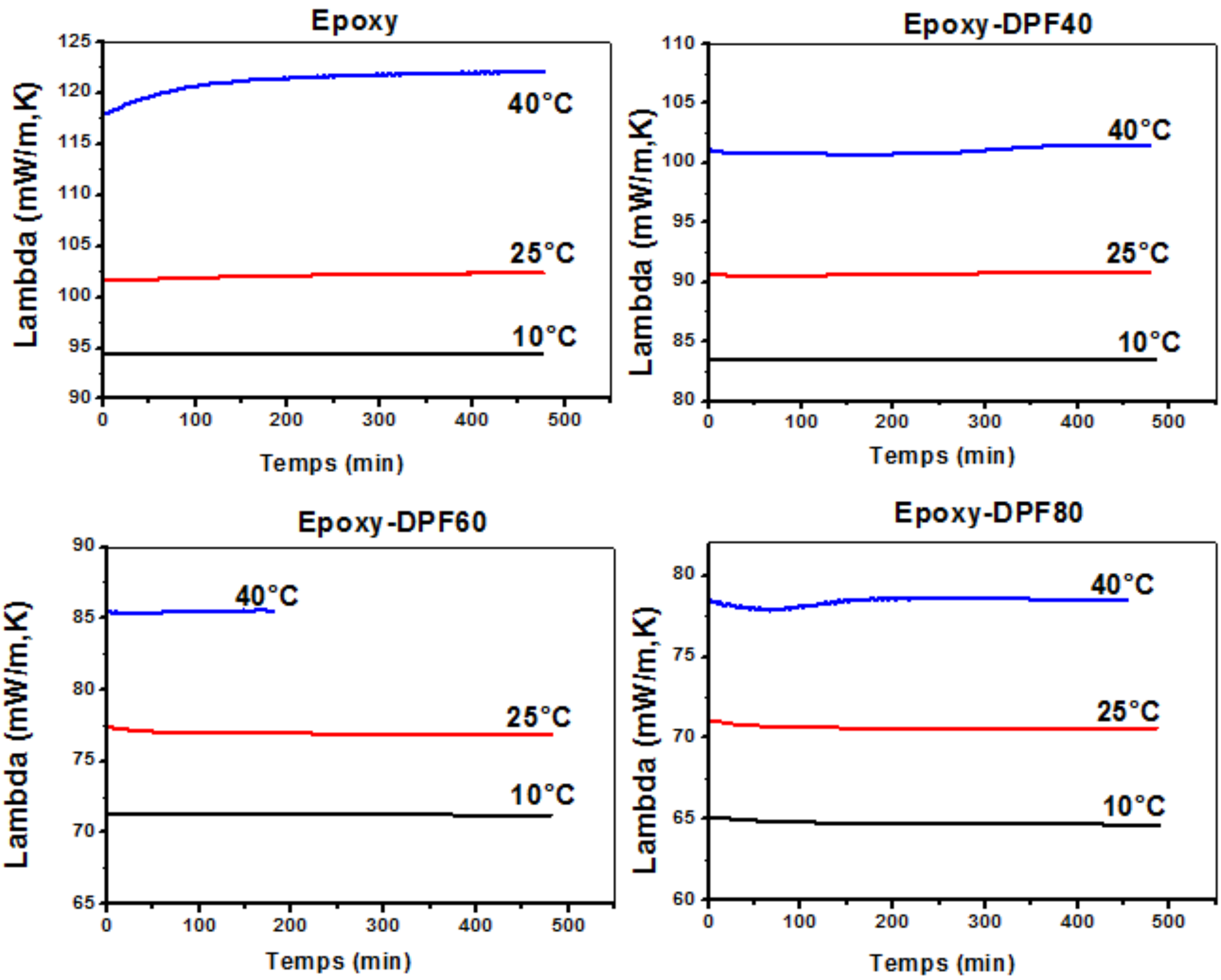

Figure 3. The effect of temperature on thermal conductivity of Epoxy-DPF composites

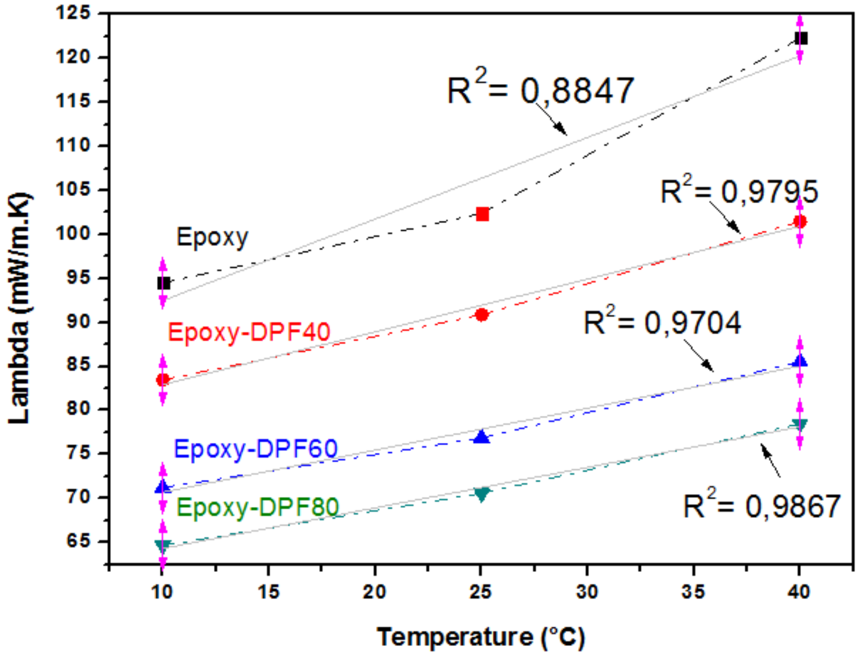

Figure 4. Variation of thermal conductivity of Epoxy-DPF composites vs operating temperature

Table 1 regroups the thermal quantities values of Epoxy-DPF composites at three different operating temperatures:

Table 1: *Thermal conductivity of Epoxy-DPF composites in different temperature*

Composites	Epoxy			Epoxy-DPF40			Epoxy-DPF60			Epoxy-DPF80		
Density (kg/m^3)	1160			1007			610			210		
Operating temperature (°C)	10	25	40	10	25	40	10	25	40	10	25	40
Lambda (mW/m.K)	4.50	102.39	122.32	83.48	90.89	101.47	71.23	76.87	85.55	64.66	70.59	78.48
Thermal capacity (j/K)	708.40	706.56	697.60	640.50	635.44	622.75	607	529.92	511.41	401.20	422.40	400.12
Diffusivity (m^2/s)	4.3	5.2	5.4	5.4	5.0	6.1	6.2	6.3	6.4	10.5	12.6	12.7
Effusivity ($J.K^{-1}.m^{-2}.s^{-1/2}$)	13.4	12.8	12.1	11.9	11.7	11.4	9.4	8.7	8.1	5.5	4.9	4.8

3.3 Flexural properties of Epoxy-DPF composites

Figure 5 shows the effect of fiber loading on flexural strength and modulus of Epoxy-DPF composites. The results are plotted as flexural strength ratio versus DPFs content. It can be clearly noted that the flexural strength increased with increasing the fiber content; the flexural strength of composite Epoxy-DPF60 showed the best flexural strength properties with flexural ratio of about 2.50 which is nearly 60 % more than that of neat Epoxy. This can be explained by the good interfacial bonding between fiber and matrix and consequently good charge transfer between fibers and the matrix. Many authors [1, 13, 21] studied the effect of vegetal fibers loading on the mechanical properties of fibers-matrix composites; they have reported several factors affecting the mechanical properties of these composites such as fiber strength, matrix strength fibers length and fiber/matrix interfacial bonding. However, it is also observed that the flexural strength of the composite Epoxy-DPF80 (80 % of fibers) was considerably lower than neat Epoxy resin about 22%. This behavior of flexural properties may be due to overloading of date palm fibers resulting in poor adhesion between the fibers and the matrix. The flexural strength ratio is 1.66, 2.50 and 0.65 for 40 %, 60 % and 80 % of DPFs respectively.

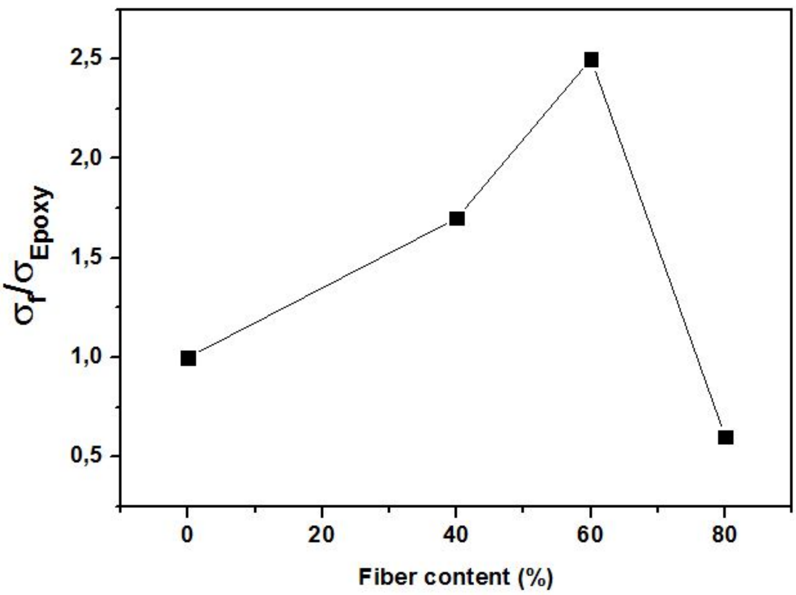

Figure 5: Flexural properties of Epoxy-DPF composites

3.4 SEM Observations

In order to examine the surface adhesion between DPFs and epoxy matrix, SEM observations of the interface fracture were carried out after flexural tests (Fig. 6).

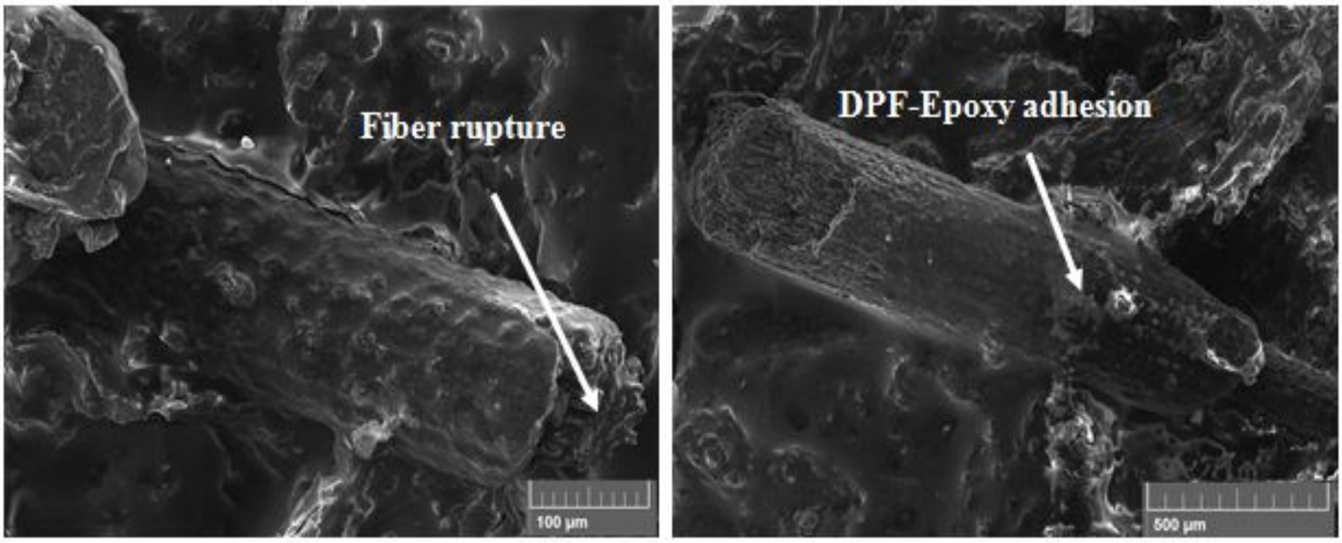

Figure 6: SEM images of Epoxy-DPF60 composite fracture

From the figure above, it can clearly be seen that there is a strong adhesion between the fibers and the epoxy matrix. This adhesion is represented by the attachment of the matrix on the surface of the fibers [13, 22]. Thus, the break observed at the level of the fiber shows that there is a transfer of charge from the matrix to the latter. These observations explain the increase in flexural strength of composites with increasing DPF content.

4. Conclusion

Natural fiber reinforced composites is an emerging area in polymer science. These natural fibers are low cost fibers with low density and high specific properties. In this paper, a friendly environmentally bio composite based on date palm fibers for thermal insulation was investigated. The effect of the operating temperature on the thermal conductivity of epoxy reinforced date palm fibers was evaluated by using a developed experimental apparatus based on the guarded hot plate. The results showed that the insertion of the DPF into the epoxy matrix has allowed to have insulating bio-composite materials having a thermal conductivity ranging from 102 to 76 mW / m×K at 25 °C for DPF contents ranging from 0 to 60 % respectively. However, up to 60 %, adhesion problems between the fibers and the epoxy matrix appeared because of an overloading of date palm fibers leading to weaken the interfacial adhesion between the fibers and the matrix. Therefore, Epoxy-DPF60 composite may be considered as a promising ecological material that can be used for thermal insulation thanks to its good mechanical and thermal insulating properties.

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