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Water Absorption Analysis of Oil Palm Fibre Reinforced Acrylonitrile Butadiene Styrene Composites by Fick's Law

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ABSTRACT

Over the past twenty years, researchers have become increasingly interested in natural fibres reinforced thermoplastics. The major cause of hydrophilic tendency is the presence of voids and non-crystalline part of these fibres which affects the fibre and polymer matrix adhesion. Therefore, it is important to develop the proper mechanism and understanding the water absorption behaviour of these composites. The aim of this paper is to analyse the water absorption behaviour using Fickian diffusion model. The oil palm fibre reinforced acrylonitrile butadiene styrene (ABS) composites at different fibre loadings (0, 3, 5 and 7 wt %) were fabricated by FDM according to the ASTM D6980 and the water absorption was analysed by a Fickian diffusion model. The results showed that the percentage of water absorption increases with increasing of fibre loadings from 0 wt% to 7 wt%. The result of applying the Fickian model showed that when the fibre loading increased, the D value decreased. On the other hand, when the fibre loading rose, the M_∞ value rose as well. The value of the kinetic parameters, n was closer to 0.5. It showed that the absorption process behaved like a Fickian process.

1. Introduction

Additive manufacturing (AM) technology, commonly referred to as three-dimensional (3D) printing, because of its adaptable design, ease of manufacture, reduced production costs and less waste of raw materials [1]. Fused deposition modelling (FDM) is one of the most popular ones due to its affordability, low waste generation, potential for recycling and user-friendly [2]. A number of methods for AM are available for purchase on the market, including stereolithography, laminated

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object manufacturing, inkjet modelling and fused deposition modelling (FDM). But unlike other AM methods that use various laser systems, resins and powders, FDM is a commonly used technology that includes extruding semi-solid thermoplastic material via a nozzle [3]. The most widely studied thermoplastic polymers used in the FDM technique are polylactic acid (PLA), acrylonitrile–butadiene styrene (ABS), polyethylene terephthalate (PET), polypropylene (PP) and high-density polyethylene (HDPE) [4-6].

Previously, there were some researches on development of new composite material using natural fibre for FDM include wood/PLA, powder/nylon, fibreglass/ABS and carbon fibres/ABS [7]. According to the study by Yu *et al.,* [8], the water absorption (%) of rice straw/PLA composites increased as the immersion time increased. Mohammed *et al.,* [9] described the variety of internal factors influence the water absorption capabilities of natural fibre composites. Natural composite properties, fibre loading and alignment, fibre-matrix interaction, matrix type, surface area of the composites, void presence, humidity, lumen size and temperature of the immersing media are some of these factors. Furthermore, the composites' surface has an impact on how well they absorb water. Polymer composites exhibit Fickian and non-Fickian water absorption characteristics [10]. Figure 1 illustrates the contrast between Fickian and non-Fickian diffusion. The diffusion coefficient (*D*), which indicates the water molecules' capacity to permeate the material's structure, is a crucial parameter for research of water absorption behaviour. It could take a lot longer (up to several months) for non-Fickian diffusion to reach saturation.

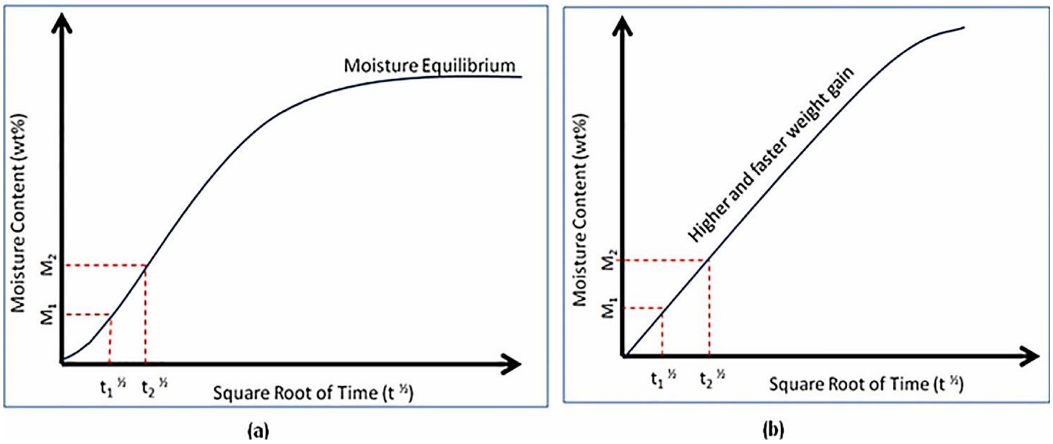


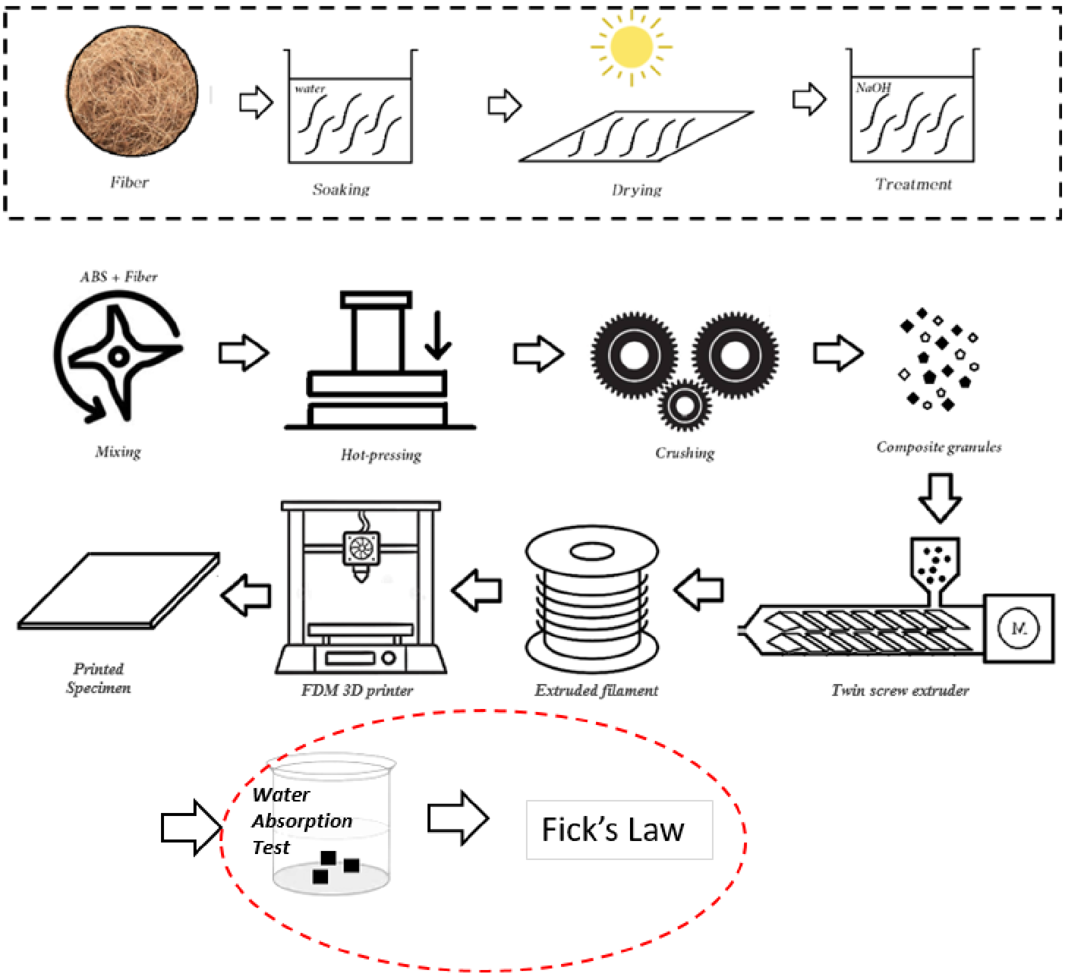
Fig. 1. (a) Fickian diffusion and (b) non-Fickian diffusion [10]

According to Yu *et al.,* [8], Mohammed *et al.,* [9] and Arya *et al.,* [10], adding the fibres to matrix had a negative impact on the printed parts' density and absorption of water. Based on these studies, none of them performed the analysis of water absorption for oil palm fibre composites printed by FDM. Thus, this paper aims to investigate the water absorption behaviour of oil palm fibre reinforced acrylonitrile butadiene styrene printed by FDM with different fibre loading. This behaviour will be analysed by using a Fickian diffusion model.

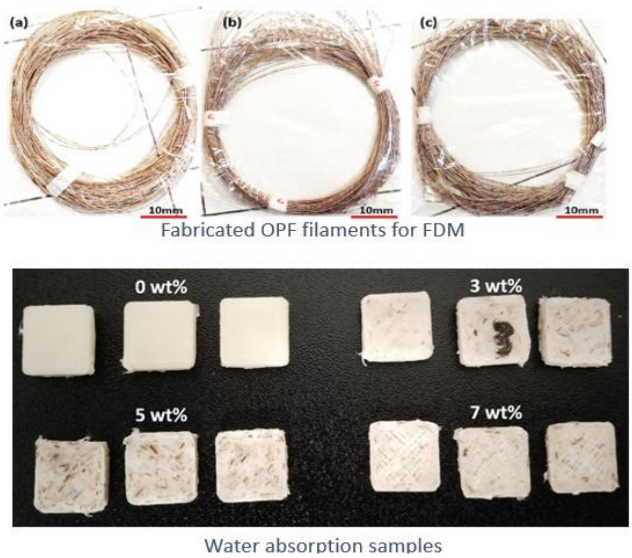
2. Materials and Methods

2.1 Materials

The oil palm fibre was obtained locally and the plastic ABS (PA-747H) was from Chi Mei Corporation, Taiwan. The fibre was immersed in sodium hydroxide, NaOH, for 2 h to remove the undesirable lignin, pectin, hemicellulose and cellulose. Figure 2(a) shows a flow chart of conducting this study, the first process was the compounding process of oil palm fibre composite in granules form. It includes the fibre treatment, mixing, hot pressing and crushing. A twin-screw extruder was used to manufacture the oil palm fibre composite filament as in Figure 2(b).



(a)



(b)

Fig. 2. (a) Flow chart of research method (b) Filaments and water absorption samples of oil palm fibre reinforced thermoplastic composites

The extruder was assembled locally that used a Siemens PLC controller supplied from China. The 3D printer FDM, FlashForge model was used to print the samples (Figure 2(b)) and the printing parameters were set as in the Table 1. After printing the specimens, the next process was water absorption test and thickness swelling test. Lastly, a Fickian diffusion model was used to analyse the behaviour of water absorption.

Table 1
FDM specification

Parameter	
Layer thickness (mm)	0.2
Build orientation (°)	0
Infill percentage (%)	100
Printing speed (mm/s)	10
Infill pattern	Rectilinear
Nozzle temperature (˚C)	240
Bed temperature (˚C)	80

2.2 Water Absorption Test

In this study, water absorption test was carried out according to ASTM D6980. Printed samples (10 mm × 10 mm × 3 mm) were dried in an air circulating oven at 105 °C ± 2 for 24 h in order to remove existing moisture and then immersed in water at room temperature (23 ± 1 °C) for 10 days [11]. The water absorption (*WA*) of the printed samples was calculated as in Eq. (1):

$$\mathrm{WA} = \frac{\mathrm{Wf}-\mathrm{Wi}}{\mathrm{Wi}} \text{ x } 100\% \quad (1)$$

where W_i is initial weight before immerse in water and W_f is the final weight after immerse.

2.3 Fickian Law

According to Azka *et al.,* [12] Fickian diffusion is a process that captures the general water absorption behaviour of composites. Eq. (2) could be used to determine the absorption of the natural fibre composites in accordance with Fick's law [13]:

$$\frac{\mathrm{M_t}}{\mathrm{M_\infty}} = \mathrm{kt^n} \quad (2)$$

where M_t is the water absorption at time (*t*), M_∞ is the equilibrium moisture content of sample and *k* and *n* are the diffusion kinetic parameters. At initial stage, the water absorption was controlled by diffusion. If *n* is equal to 0.5, the water absorption follows Fickian law of diffusion. The mass gain correlated with the diffusion coefficient (*D*) and the maximum water absorption, M_t could be acquired by two equations, if $\frac{M_t}{M_\infty} < 0.6$ using Eq. (3). If $\frac{M_t}{M_\infty} > 0.6$, the curve of absorption is calculated with Eq. (4) [13]:

$$\frac{\mathrm{M_t}}{\mathrm{M_\infty}} = \frac{4}{\mathrm{h}}\left(\frac{\mathrm{D}}{\pi}\right)^{1/2} \mathrm{t}^{1/2} \quad (3)$$

$$\frac{\mathrm{M_t}}{\mathrm{M_\infty}} = 1 - \exp\left(-7.3\left(\frac{\mathrm{Dt}}{\mathrm{h^2}}\right)^{0.75}\right) \quad (4)$$

where *D* is the diffusion coefficient and *h* is the composites thickness. The *D* could be calculated using Eq. (5) [13]:

$$D = \pi\left(\frac{kh}{4M_\infty}\right)^2 \tag{5}$$

2.4 Thickness Swelling Test

Thickness swelling test was carried out according to ASTM D6980. Printed samples (10 mm × 10 mm × 3 mm) were dried in an air circulating oven at 105 °C ± 2 for 24 h in order to remove existing moisture and then immersed in water at room temperature (23 ± 1 °C) for 30 and 120 minutes. The samples were measured before (*Ti*) and after (*Tf*) immersion using a digital vernier. The printed samples' thickness swelling ratio was determined by applying Eq. (6):

$$\text{Thickness swelling } (\%) = \frac{T_f - T_i}{T_i} \text{ x } 100 \tag{6}$$

2.5 One-Way Analysis of Variance (ANOVA)

The significant difference in the primary factors was ascertained by applying one-way ANOVA. It is used when you have a continuous dependent variable and one independent variable (factor) with several levels to see if there are significant differences between the means of two or more independent groups.

3. Results and Discussion

Since natural fibre-based composite materials were known to be water-sensitive, it was important to investigate the oil palm fibre composite's water absorption properties for FDM. Figure 3(a) and 3(b) depicts the oil palm fibre composite's water absorption and diffusion curve for fibre contents of 0, 3, 5 and 7 wt% after being immersed in water for 10 days. At 7 wt% oil palm fibre composites, the water absorption was at its highest, with values of 31.6% and 34.2% for immersion times of day 1 and 2, respectively. As compared to neat ABS (0 wt%), the graph demonstrates the significant increase in water absorption when fibre is added at a range of 3 to 7 wt%. This result was consistent with research by Kusmono *et al.,* [14], who looked at how much an ABS/cellulose composite absorbed water. They noticed that the plain ABS did not absorb as much water as the composite and that the amount of absorbed water in the composite increased as the fibre loading rose. Similar results were also reported by Wang *et al.,* [15], who found that the rate of water absorption for specimens increased with the wt% of fibre.

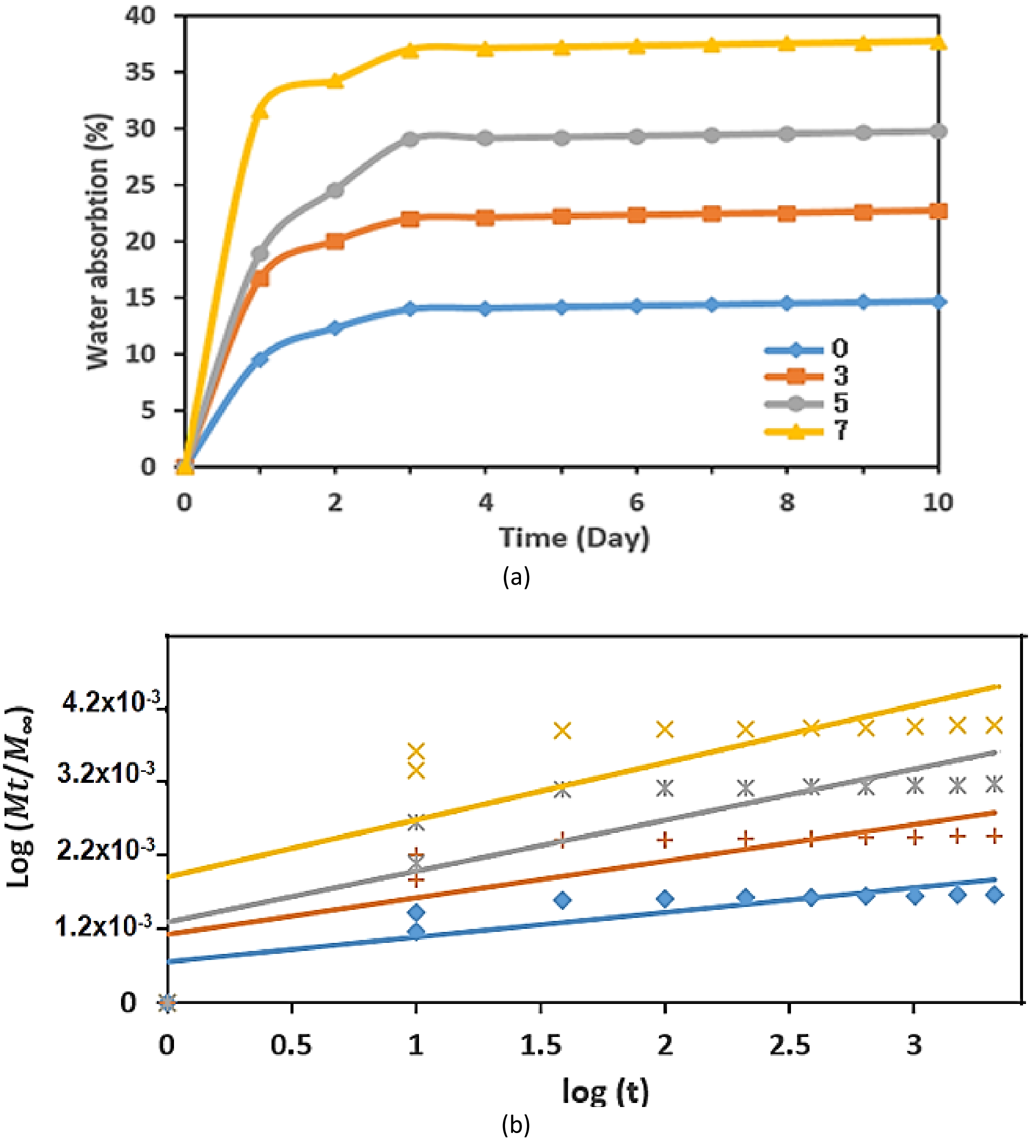


Fig. 3. (a) Water absorption (b) diffusion curve fitted plot of oil palm fibre reinforced thermoplastic composites

The relationship between water absorption and diffusion coefficients (*D*), as calculated using Fickian law, is shown in Table 2. When the fibre loading (wt%) of oil palm fibre/ABS composites increased, the *D* value decreased. On the other hand, when the fibre content rose, the $M\infty$ value rose as well. This is consistent with research by Jiang *et al.,* [13] and Tengsuthiwat *et al.,* [16] found that increasing the fibre percentage in the matrix raised the $M\infty$ value while decreasing the *D* value. In addition, Table 2 also presents the correlation coefficient (R^2) and the values of the kinetic parameters (*n* and *k*). The fact that n was approaching 0.5 and R^2 was getting closer to 1.0 shows that the absorption process behaved like a Fickian process. Therefore, the water absorption of pure ABS and oil palm fibre/ABS composites could potentially be theoretically analysed using Fickian law. An ANOVA with a confidence interval of 95% was used to examine the main effects of input parameters on the response.

Table 2
Fickian model parameters for water absorption of oil palm fibre reinforced thermoplastic composites

Fibre (wt %)	*n*	*k*	R^2	M_∞ (%)	*D* (mm^2/s)
0	0.1376	0.00115	0.9837	0.63	4.9714 x 10^{-6}
3	0.3125	0.00187	0.9931	1.11	5.0124 x 10^{-6}
5	0.3016	0.00165	0.9897	5.58	1.5437 x 10^{-7}
7	0.4062	0.00195	0.9566	6.28	3.0658 x 10^{-7}

Note: n and k are diffusion kinetic parameters, R^2 is correlation coefficient, M∞ is equilibrium water uptake and D is diffusion coefficient

Table 3 exhibits the results of a one-way ANOVA for water absorption of oil palm fibre composites. The *P*-value calculated the results' significance or how much a parameter influences the objective function. Based on the result demonstrates that there was a significant difference between the mean data of water absorption, where the *P*-value is less than 0.05.

Table 3
One-way ANOVA

Response	Source	DF	SS	MS	F-value	*P*-value
Water abortion	Wt%	3	784.9	261.6	24.92	0.000
	Error	8	84.0	10.5		
	Total	11	868.9			

Note: P-value < 0.05 is significant; DF is degree of freedom; SS is sum of square; MS is mean square

Figure 4 depicts the thickness swelling percentage of oil palm fibre composites. Over a period of 30 and 120 minutes of immersion, the thickness of all composites rose substantially. This effect can be explained by enabling more water molecules to form hydrogen bonds with the composites' sites, which speeds up swelling [17]. However, oil palm fibre composite samples show less swelling at 7 wt% fibre loading than at 3 wt % and 5 wt% fibre loading. Consequently, it shows that 7 wt% fibre loading had better dimension stability than 3 wt% and 5 wt%. Thus, 7 wt% could potentially be proposed as an FDM filament to print parts more precisely while exposing them to water for a greater period of time.

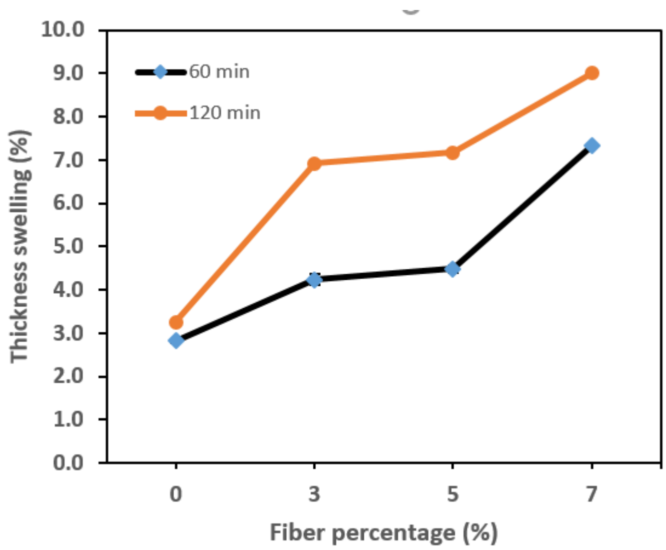


Fig. 4. Thickness swelling of oil palm fibre reinforced thermoplastic composites

4. Conclusions

The oil palm fibre reinforced acrylonitrile butadiene styrene (ABS) composites at different fibre loadings (0, 3, 5 and 7 wt %) was fabricated by FDM and the water absorption was analysed by a Fickian diffusion model. The study found that the percentage of water absorption increases with increasing of fibre loadings from 0 wt% to 7 wt%. Result of applying the Fickian model shows that when the fibre loading increased, the he diffusion coefficient, *D* value decreased. On the other hand, when the fibre loading rose, the equilibrium water uptake, $M\infty$ value rose as well. The value of the kinetic parameters, *n* was closer to 0.5. It shows that the absorption process behaved like a Fickian process. Therefore, Fickian law could potentially be used to theoretically study the water absorption of pure ABS and oil palm fibre/ABS composites.

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