

Pineapple Leaf Fiber Reinforced Thermoplastic Composites: Effects of Fiber Length and Fiber Content on Their Characteristics

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Received 8 April 2009; accepted 8 June 2010

DOI 10.1002/app.32910

Published online 23 August 2010 in Wiley Online Library (wileyonlinelibrary.com).

ABSTRACT: Pineapple leaf fiber (PALF) was used as a reinforcement in polyolefins. Polypropylene (PP) and low-density polyethylene (LDPE) composites with different fiber lengths (long and short fibers) and fiber contents (0–25%) were prepared and characterized. The results showed that the tensile strength of the composites increased when the PALF contents were increased. It was observed that the composites containing long fiber PALF were stronger than the short fiber composites as determined by greater tensile strength. An SEM study on the tensile fractured surface confirmed the homogeneous dispersion of the long fibers in the polymer matrixes better than dispersion of the short fibers. The unidirectional arrangement of the long fibers provided good interfacial bonding between the PALF and polymer

which was a crucial factor in achieving high strength composites. Reduction in crystallinity of the composites, as evident from XRD and DSC studies suggested that the reinforcing effect of PALF played an important role in enhancing their mechanical strength. From the rule of mixtures, the stress efficiency factors of the composite strength could be calculated. The stress efficiency factors of LDPE were greater than those of PP. This would possibly explain why the high modulus fiber (PALF) had better load transfers to the ductile matrix of LDPE than the brittle matrix of PP. © 2010 Wiley Periodicals, Inc. *J Appl Polym Sci* 119: 1952–1960, 2011

Key words: fiber; mechanical properties; polyethylene (PE); polypropylene (PP); composites

INTRODUCTION

Nowadays, biomaterial sources are renewable, widely distributed, locally accessible, environmentally recyclable, conveniently available in many forms and biodegradable. Natural fibers, such as kenaf, flax, jute, hemp, sisal, and pineapple are abundant worldwide as biomaterial sources. They have received much interest as probable reinforcing materials for plastic composites in many applications such as automotive and packaging.¹ The advantages of these biomaterial sources, compared with traditional reinforcing materials such as glass, aramid, and carbon fiber, are low cost, low density, high toughness, acceptable specific strength properties, reduced tool wear, reduced dermal and respiratory irritation, good thermal properties, enhanced energy recovery and especially biodegradability.^{1,2}

Pineapple leaf fiber (PALF) was chosen as a reinforcement material due to its high cellulose content

of 70–82% and high degree of crystallinity.^{1,2} PALF is composed of fine quality fiber, and unlike jute, its structure is without mesh. Their filaments are well separated and it is two and a half times more extensible with superior fiber bundle strength.³ In addition, pineapple canning is the main export business in tropical countries, especially Thailand. Plantation areas for pineapple are plentiful, about 93,120 hectares in 2008, which can produce 14.58–23.69 Mtonnes of fresh shoots. Farmers are interested in postharvest utilizations of all parts of a pineapple plant. After harvesting, pineapple leaves remain about 40–50 leaves/shoot or 2.73 kg/shoot. Hence, PALF could be a possible cellulose fiber source in Thailand. Besides, there has been much research in PALF utilization for reinforcement in some materials such as low density polyethylene (LDPE) and polypropylene (PP).^{4–10} These works reported the properties of fiber-reinforced composites depend on many factors i.e., fiber-matrix adhesion, volume fraction of fiber, fiber aspect ratio, fiber length, and fiber orientation.

Melt mixing in an extruder and solution mixing were the two techniques most often used to prepare the composites.^{6–9} However, the fiber lengths used in these techniques were limited to the maximum of 100 mm. Composite preparation for PALF (>100 mm) has been studied very little using the heat

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Contract grant sponsors: Thailand Research Fund (TRF), Kasetsart University Research and Development Institute (KURDI).

TABLE I
Physical Properties of PALF, LDPE, and PP

Properties	PALF	LDPE	PP
Density (g/cm ³)	1.30	0.92 ⁷	0.90 ⁵
Tensile strength (MPa)	125.0	12.7	35.2
Elongation at break (%)	4.2	389.6	11.6

press method.^{4,5,10} In addition to the mixing process, fiber-fiber interactions as well as fiber-matrix interactions plays a crucial role in the properties of composites.^{11,12} Incorporation of natural cellulosic fibers in the composite may lead to poor dispersion of the fibers due to strong interfiber hydrogen bonding that holds the fibers together. Therefore, the chemical treatment of fibers for improved adhesion between the hydrophilic surface of the fibers and the hydrophobic surface of the polymer can solve this problem. A previous study on chemical modification of PALF surfaces¹³ found that an improvement of interfacial properties between the fiber-matrix of composites with these modifications led to the enhancement of the mechanical and thermomechanical properties of PALF/poly (lactic acid) composites. One of the chemical treatments used generally and most often was the alkaline treatment. This treatment removed an amount of lignin, wax and oils, recovered the external surface of the fiber cell wall, depolymerized cellulose and exposed the short length of the fiber.¹⁴ Moreover, the alkaline treatment disrupted hydrogen bonding in the network structure, thereby increasing surface roughness which resulted in better mechanical interlocking.¹⁵ In this study, PALF was prepared using a decorticating machine and subsequently degummed with a NaOH solution.¹⁶

In this study, we have studied the effects of PALF length (orientation) and content on mechanical and physical properties of composites based on LDPE

and PP matrices. A method of laying a mat of fibers into a compression mold was used to prepare these composites because little equipment was needed and machine costs were minimized.¹⁷

EXPERIMENTAL

Materials

Two types of PALF preparation, long fibers (L) and short fibers (S), were studied and prepared.¹⁶ Long fibers (L) along the leaf length (>300 mm) were used for the uni-direction arrangement, which were extracted by a decorticated machine and then non-cellulosic components were removed by chemical treatments (degumming and bleaching). The long fibers were cut to a length of 140 mm, which was longer than the window frame to have the extra length for tape attachment with the frame. The other fiber type, short fibers (S), had a cut length of 40 mm. They were cut from long fibers which were used for the multidirectional arrangement.

Two types of thermoplastic polymers, LDPE and PP, were selected as a polymer matrix due to their good recyclability. They provided the best possible protection against water with widespread usage.¹⁸ The properties of PALF, LDPE, and PP studied here are given in Table I.

To study the decomposition pattern of PALF, thermogravimetry (TG) and derivative thermogravimetry (DTG) were carried out with Mettler thermogravimetric analysis (TGA 851E, USA). PALF was scanned from 30 to 600°C at a heating rate of 10°C/min in nitrogen atmosphere.

Preparation of composites

Fiber mats (Fig. 1) were prepared with different directions depending on the fiber length. The long

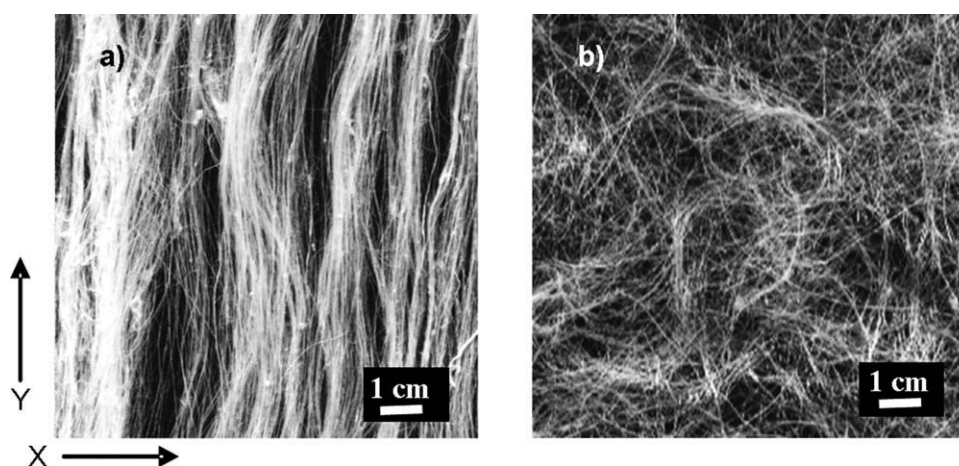


Figure 1 Photograph of PALF for different arrangements in fiber mats. (a) Uni-directional arrangement of long fibers (L). (b) Multidirectional arrangement of short fibers (S).

fibers were aligned along leaf length direction. PALF (140 mm long) was arranged separately in parallel arrays covering a stainless steel plate with a window of $100 \times 100 \text{ mm}^2$ [Fig. 1(a)]. The short fibers (40 mm) were arranged randomly using a mini card machine to form a nonwoven mat [Fig. 1(b)]. The fiber weights per unit surface area for both fiber lengths were controlled at $50\text{--}250 \text{ g/m}^2$ of the laying mold, corresponding to fiber weights (5–25 wt%).

The LDPE and PP sheets were prepared by a heat press machine at a temperature of 180 and 240°C, respectively, with a constant pressure of 12.5 MPa for 3 min. The specimens were repeatedly depressurized and pressurized at each melting temperature for 3 min to eliminate voids and air bubbles. The specimens were cooled down to room temperature at the pressure of 12.5 MPa for 30 min. The thickness of the polymer sheets was controlled at 0.25 mm. Composite laminates having a 0.5 mm thickness were made by sandwiching one layer of the fiber mat between two layers of either LDPE or PP sheets at the melting temperatures of 160 and 185°C, respectively.

Characterization of thermoplastic composites/PALF

Composites of LDPE and PP at different fiber lengths and fiber contents were determined for their mechanical properties, e.g., tensile strength and elongation, according to ASTM 638 (Type II) using the Autograph (AGS5kN, Shimadzu, Japan). The gauge length and crosshead speed were 60 mm and 100 mm/min, respectively. At least eight measurements were taken for each system.

A scanning electron microscope (SEM) was used to study the morphology of the specimen prepared. The surface fractured in liquid nitrogen and the tensile fracture surfaces were observed with a scanning electron microscope (JEOL JSM-5310, England) at 10 KV acceleration voltages.

X-ray diffraction (XRD) was used to study the crystallinity of the PALF composites as compared with the pure polymer. The XRD pattern was taken with a JEOL diffractometer (JDX-3530, England) with the $\text{CuK}\alpha$ radiation operating at 30 kV, 40 mA and a run rate of $30^\circ \text{ min}^{-1}$. The percent crystallinity was calculated by a ratio of intensity curve areas of crystalline and total regions. The crystallite sizes (D) were calculated according to the Scherrer's equation as shown in eq. (1):

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

where β is the full width at half maximum (FWHM) in radian of a diffraction peak, λ is the wavelength of the X-ray radiation (1.541 for Cu), K is the Scher-

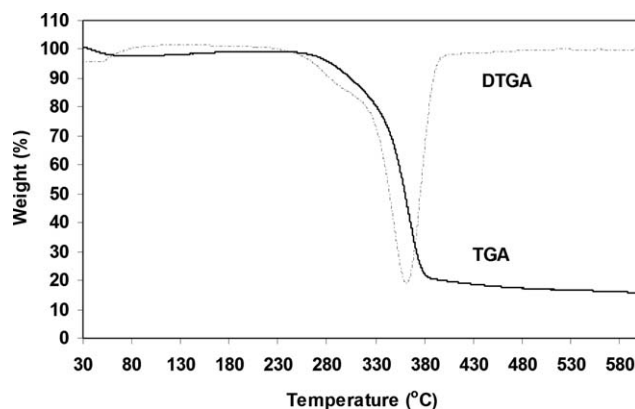


Figure 2 TGA and DTGA curves of PALF.

rer constant taken here assuming ~ 1 and θ is the Bragg angle.¹⁹

In addition, the melting temperature and internal enthalpy of the polymers with and without the PALF reinforcement were determined by differential scanning calorimetry (DSC, DSC7, Perkin-Elmer, USA) at a scanning rate of $10^\circ\text{C}/\text{min}$ with a temperature range of $0\text{--}200^\circ\text{C}$.

RESULTS AND DISCUSSION

The thermogravimetric analysis (TGA) and the derivative thermogravimetric analysis (DTGA) curves of PALF are presented in Figure 2. The temperature range from 60 to 100°C shows a weight loss of $\sim 1.6\%$ due to dehydration. The degradation of the PALF was in two stages. In the first stage, the degradation started from 250 to 294°C , and about 7% weight loss of the PALF corresponds to the thermal degradation of lignin and dehydrocellulose.⁸ For the second stage which was the main peak, the maximum degradation temperature was 364°C with a weight loss of $\sim 56\%$. This weight loss corresponded to the thermal degradation of dehydrocellulose.⁸ Thus, we can use this data to select temperature processing for the composite.

Fiber dispersion in the composite

SEM images of the fractured surfaces of the composites at 15% PALF content were taken to investigate the fiber-matrix interaction. Figure 3 shows the fracture surface of the composites with different fiber lengths (L and S) and different polymer matrices (LDPE and PP). The long fibers as shown in Figure 3a and 3b were homogeneously dispersed in a continuous polymer matrix as compared to the short fibers with smaller fiber bundles. These pictures indicated the strong fiber and thermoplastic matrix interaction were in good agreement with the literature review.⁷ On the other hand, the distribution of

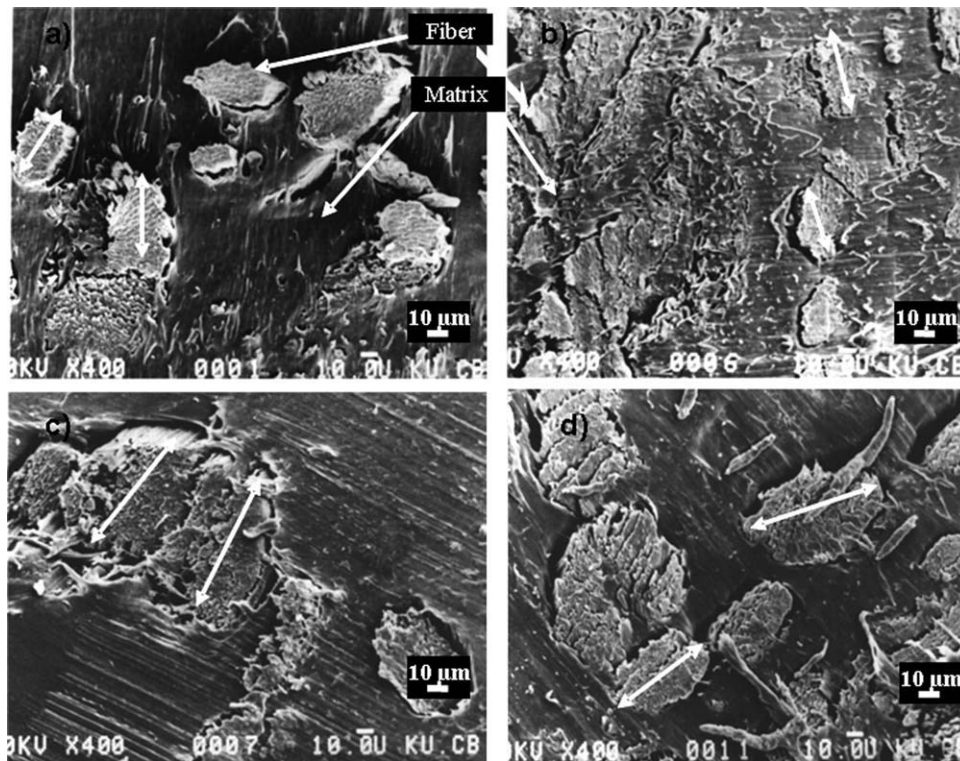


Figure 3 SEM micrographs of fractured surface of composites with 15% PALF at different fiber lengths (*L* and *S*) at magnification of x400 and scale bar of 10 μm . (a) LDPE/PALF-*L*, (b) PP/PALF-*L*, (c) LDPE/PALF-*S*, (d) PP/PALF-*S*.

short fibers in a nonwoven mat was heterogeneously dispersed which could be noticed by the polymer matrix surrounding big bundles of fibers [Fig. 3(c,d)].

X-ray diffraction study

Figure 4 shows the XRD patterns of the crystalline structure of the thermoplastic and the PALF/thermoplastic composites with a 15% PALF content. In the case of the LDPE matrix, their scattering curves had two main peaks at 2θ of 21.4 and 23.8°. Adding PALF for polymer reinforcement resulted in a decreasing of %crystallinity in the composites (Table II) as compared with the pure polymer mentioned in a previous study.²⁰ LDPE polymer molecular chains were difficult to migrate and diffuse to the surface of the growing polymer crystal with having the PALF dispersion in the composites. In the case of the fiber length effect, the percent crystallinity of the LDPE composites with short fibers decreased marginally. On the other hand, the crystallite sizes of the composites tended to increase when the PALF contents were increased; suggesting nucleation and growth were favored in the case of PALF in the LDPE matrix.²⁰

Concerning the PP matrix (Table II), the crystallinity of the PALF/PP composites was relatively unchanged with the PALF inclusion in the matrix.

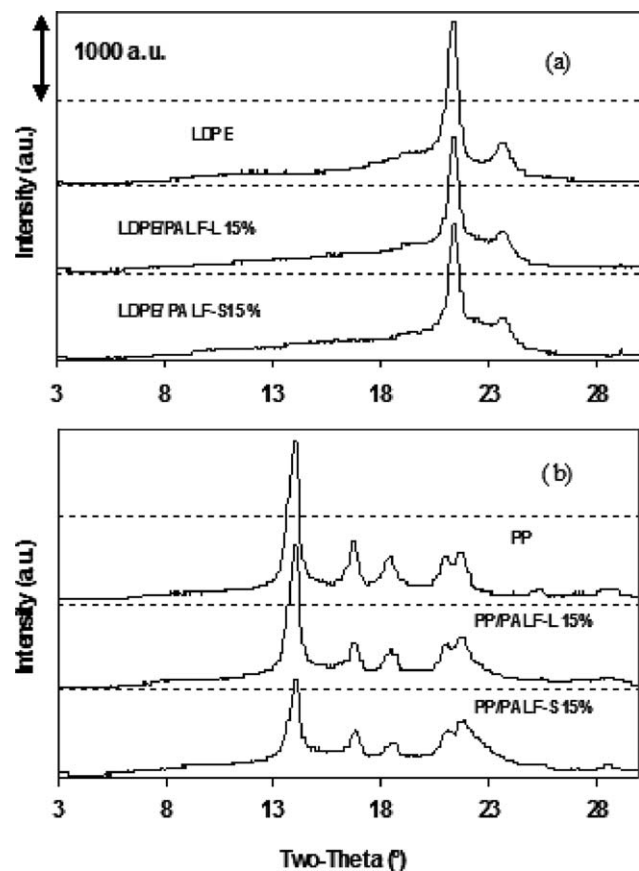


Figure 4 XRD profiles of composites with 15% PALF at different fiber lengths (*L* and *S*). (a) LDPE/PALF, (b) PP/PALF.

TABLE II
Crystallite Size and %Crystallinity of Composites with 15% PALF
at Different Fiber Lengths (*L* and *S*)

Composite	Crystallite size at 2 θ (nm)		% Crystallinity
	21.3	23.6	
LDPE	2.71	2.24	61.94
LDPE/PALF-L15%	3.12	1.99	47.03
LDPE/PALF-S15%	3.29	2.00	45.04

Composite	Crystallite size at 2 θ (nm)					% Crystallinity
	14.0	16.8	18.4	21.0	21.7	
PP	2.86	3.71	3.05	2.37	2.39	63.92
PP/PALF-L15%	2.86	3.38	3.09	2.46	2.10	66.17
PP/PALF-S15%	2.96	3.71	3.19	3.07	1.95	66.93

Also, the crystallite size of all the composites did not have a significant difference in all the peak angles. This suggested that the crystallinity of the PP matrix with PALF at different fiber lengths was still maintained.

DSC study

Thermal properties of the composites studied by DSC are summarized in Table III. Pure LDPE and PP had the heat of fusion of 75.0 and 50.5 kJ/mol, respectively. The heat of fusion (ΔH) of the composites corresponding to the melting endotherm decreased upon the incorporation of PALF to the thermoplastic composites. The decrease in the heat of fusion was observed in the composite samples with different fiber lengths. This result was in good agreement with the trend of crystallinity of the composites obtained from the XRD study. The molecular motion of the thermoplastic matrix could be restricted by the addition of fiber, resulting in a decrease of crystalline melting enthalpy. Moreover, the addition of long fiber in the LDPE matrixes exhibited a higher melting enthalpy than the addition of short fiber. This may also be attributed to the strong interfacial interaction between the thermoplastic matrix and long fiber, confining polymer chain orientation.²⁰ In the case of the PP matrixes, fiber addition at different lengths provided no significant difference in melting enthalpy. Similarly, the

TABLE III
Thermal Parameters of Composites with 15% PALF at
Different Fiber Lengths

	T_{onset} ($^{\circ}\text{C}$)	T_{peak} ($^{\circ}\text{C}$)	ΔH (kJ/mol)
LDPE	101.1	107.9	75.0
LDPE/PALF-L15%	101.4	106.6	62.7
LDPE/PALF-S15%	101.7	107.5	53.0
PP	153.9	161.0	50.5
PP/PALF-L15%	153.3	163.0	35.4
PP/PALF-S15%	154.8	162.8	34.5

melting temperatures of pure PP and their composites were not significantly different.

Mechanical properties

The mechanical properties of the composites at different fiber orientations (fiber lengths), fiber contents, and thermoplastic types are shown in Table IV and V. The effect of PALF with the uni-direction of long fiber in the thermoplastic matrix is presented in Table IV. It could be seen that the tensile strength increased with increasing the PALF content in both LDPE and PP while the elongation at the break decreased sharply. Thus, the inclusion of PALF made the thermoplastic matrix stiffer, especially for the LDPE composites. The tensile strength of the composites with 15 wt% long fiber extensively increased more than four fold for the LDPE matrix as compared to that of the PP matrix. PP is more crystalline than LDPE so that PP and its composites had a greater tensile strength as compared to LDPE. However, the reinforcing effect of PALF on PP was less than that of LDPE (Table IV). This was

TABLE IV
Mechanical Properties of Thermoplastic/PALF
Composites with %PALF Contents and Long
Length Fibers

	Tensile strength (MPa)	%Elongation
LDPE matrix		
PALF-L, % by wt. 0	12.73 \pm 1.36 d	389.6 \pm 39.0 a
5	22.73 \pm 3.72 c	4.6 \pm 0.8 b
10	33.16 \pm 4.96 b	3.2 \pm 0.4 b
15	51.27 \pm 8.95 a	4.0 \pm 0.8 b
PP matrix		
PALF-L, % by wt. 0	35.17 \pm 1.99 b	11.6 \pm 5.2 a
5	35.86 \pm 3.34 b	6.7 \pm 2.1 b
10	39.26 \pm 5.78 b	4.8 \pm 1.5 b
15	53.14 \pm 7.60 a	3.5 \pm 1.3 b

Different letters (a, b, c) in the same column at different fiber contents mean that the results are significantly different at $P \leq 0.05$.

TABLE V
Mechanical Properties of Thermoplastic/PALF
Composites with %PALF Contents and
Short Length Fibers

LDPE matrix	Tensile strength (MPa)	% Elongation
LDPE matrix		
PALF-S, % by wt. 0	12.73 ± 1.36 c	389.6 ± 39.0 a
5	21.69 ± 2.52 b	3.4 ± 0.3 b
15	35.15 ± 5.17 a	3.2 ± 0.2 b
25	40.43 ± 7.21 a	3.1 ± 0.2 b
PP matrix		
PALF-S, % by wt. 0	35.17 ± 1.99 b	11.6 ± 5.2 a
5	37.09 ± 6.58 b	3.9 ± 1.1 b
15	47.11 ± 7.58 a	3.6 ± 0.9 b
25	54.96 ± 5.29 a	3.4 ± 0.2 b

Different letters (a, b, c) in the same column at different fiber contents mean that the results are significantly different at $P \leq 0.05$.

consistent with the results of sisal fiber reinforced PP and the LDPE composites.²¹

Concerning the effect of the multidirectional orientation of the short fiber (Table V), the tensile strength of the LDPE/PALF composites was found to increase when the fiber content was increased. However, the increase in tensile strength of composites with higher proportion of PALF (25%) was not significant in both LDPE and PP ($P > 0.05$). The elongation decreased with increasing the PALF content for both thermoplastics, interpreting that the composites became stiff and brittle upon fiber loading.

It is well established that sodium hydroxide used for fiber preparation is commonly used for surface treatment of the plant fiber. This made the fiber surface rough and enhanced the interfacial interaction between the hydrophilic surface of the fiber and the hydrophobic polymer matrix. Therefore, this possibly explained an increase of tensile strength of the composites when the fiber content was increased.

It should be noted that composites containing long fiber were stronger than short fiber composites for both thermoplastic types. The long fiber with uniaxial orientation gave greater strength in both thermoplastic matrices. In the case of short fiber, the fiber ends acted as stress concentrators and were ineffective in transmitting load from the matrix to the fiber.²² Moreover, it was difficult to control the degree of orientation of short fibers compared with that of the long fibers. However, in the case of the multidirectional orientation of the short fiber (Table V), it was easy to make the composite and could increase the fiber content up to 25 wt% fiber. Improvement in the strength of the matrix was attributed to the reinforcing effect of the PALF. This resulted in a stress transfer from the thermoplastic matrix to the fiber during tensile failure, giving rise

to increased strength as described in previous research.²²

The typical stress-strain curves of LDPE and LDPE composites with different PALF contents are shown in Figure 5. They were representative of continuous composites with ductile matrices. As can be seen from Figure 5, LDPE exhibited a flexible and tough behavior having a very high ultimate elongation (strain) while modulus and tensile strength were low. It was confirmed that the tensile strength of the composite increased when the PALF content was increased. Addition of fibers rapidly increased the modulus of the composite (slope of stress-strain curve) and the system became more brittle. This phenomenon was in good agreement with the study of the rubber/PALF composite.²³ This result suggested an effect of reinforced PALF seemed to enhance the structural properties of the composites. However, this effect was less pronounced in the PP matrix. PP showed a stiffness and resistance to crack, which was higher than the LDPE matrix. Thus, the PP/PALF composites gave a similar stress-strain curve to that of pure PP (data not shown here).

The rule of mixtures was used to predict the tensile strength of fiber-reinforced composites. As referred in,^{24,25} theoretical calculations of the tensile strength in both uni-directional and multidirectional composites were carried out using a simple rule of mixture as shown in eq. (2)

$$\sigma_c = \varepsilon_s \Phi_f \sigma_f + \Phi_p \sigma_p \quad (2)$$

where, σ_c is the stress of the composite, ε_s is the stress efficiency factor for composite strength considering the effects of fiber length and orientation, Φ_f is the fiber volume fraction which is calculated using

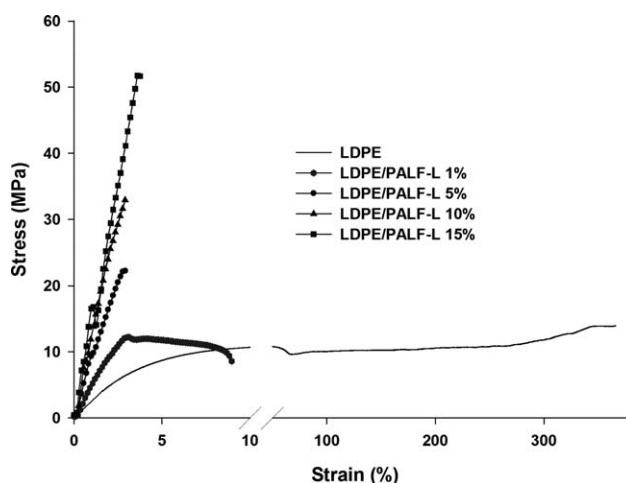


Figure 5 Stress-strain curves of LDPE/PALF composites with %PALF contents and long length fibers.

TABLE VI
Stress Efficiency Factor for Composite Strength in Both Composites for Long and Short Fibers

Fiber % by wt	Fiber volume fraction (Φ_f)	Stress efficiency factor (ϵ_s)	
		LDPE matrix	PP matrix
Long fiber			
5	0.04	2.18	0.42
10	0.07	2.23	0.71
15	0.12	2.77	1.53
Short fiber			
5	0.05	1.97	0.68
15	0.12	1.66	1.11
25	0.19	1.25	1.10

the relationship of fiber weight divided by fiber density, σ_f is the stress of fiber, Φ_p is the polymer matrix volume fraction ($1-\Phi_f$), and σ_p is the stress of the polymer matrix.

The stress efficiency factors (ϵ_s) for the different composites with long fibers were calculated by eq. (2). The stress efficiency factors of the composite strength of LDPE were greater than those of PP for uni-directional composites (Table VI). It can be implied that the high modulus fiber (PALF) had better load transfers to the ductile matrix of LDPE than the brittle matrix of PP. This result of stress efficiency factors supported the stress-strain curve of LDPE/PALF composites with a high slope. Moreover, the stress efficiency factor for long fibers in both composites increased with increasing of the fiber volume fraction (Table VI). Increasing the fiber volume fraction in the thermoplastic matrix led to an improvement of stress transfer between the fibers and the matrix. Since the high-modulus pineapple fiber increased, the reinforcement supported a higher load in the thermoplastic matrix.²⁶

In the case of short fibers with multidirectional arrangement, the fiber efficiency factor for strength decreased moderately with increasing the fiber volume fraction only for the LDPE composite (Table VI). A decrease in the fiber orientation along the flow direction of the matrix, due to fiber aggregation, led to a decrease in the fiber reinforcement efficiency factor in the LDPE matrix. The fiber efficiency factors of short fiber were less pronounced compared to the long fibers effect in the composites. This effect of poor transmitting load from the matrix to the short fiber was in good agreement with the results of the tensile strength. However, the fiber efficiency factor for PP composite strength did not decrease with increasing the fiber volume fraction. This could be explained by the effect of stress concentrations due to the difference in modulus between fibers and matrix, which may contribute to a lesser degree in the brittle matrix composites of PP.

Therefore, the presence of defects such as poor fiber to matrix adhesion, voids and other matrix flaws may override other lesser influences on decreasing of the fiber efficiency,²⁶ especially for PP composites. For further study, PALF after other chemical modifications should be investigated to improve interfacial adhesion and should result in greater composite strength.

Morphology of tensile fracture surface

SEM photographs of the tensile fracture of LDPE/PALF composites at different fiber orientations are shown in Figure 6. PALF with uni-directional orientation of long fibers can be well dispersed in the matrix with the amount of PALF at an appropriated proportion with polymer [Fig. 6(a)]. Therefore, the tensile fracture mainly occurred in the matrix with good interfacial adhesion of fiber which was mainly observed by breakage at the ends of the fibers with no fiber pull-out in the matrix. However for this long fiber, there was also some fiber breakage with pull-out in the matrix [Fig. 6(b)]. But its breakage surface was still brittle at the end of the fibers. Failure of the tensile test appeared at the matrix with extensive fiber pull-out and splitting as also previously reported on the study of PE/banana fiber with 10% fiber content.²⁷ In the case of short fibers, SEM photographs of the LDPE/PALF composite showed fiber debonding and fiber pull-out [Fig. 6(c)]. In addition, the surface of the fiber breakage exhibited a splitting appearance which was due to severe fiber breakage [Fig. 6(d)] as also noticed from the tensile fracture surface of the LDPE/PALF composite in the previous results.⁷ Concerning the PP matrix, the long fibers were fractured without retarding due to high stiffness of PP and with some fiber pull-out in the matrix [Fig. 7(a)]. The extent of contact between the fibers and the PP matrix was enhanced, and when stress was applied, the fiber breakage did not wholly pull-out of the matrix. Its breakage surface had a brittle appearance as shown in Figure 7(b). For this reason, the PP/PALF composite for uni-directional orientation of long fibers yielded higher strength. For the PALF-short fibers dispersing in the PP matrix, the random network of fibers affected the fracture with pull-out and debonded fibers (Fig. 7(c)]. In addition, the surface of the fiber breakage exhibited a splitting appearance, the same results described in the LDPE/PALF composites.

It was noticed from the SEM results of long fiber in both the LDPE and PP matrices that there were some evidence of fiber pull-out and debonding from the tensile fracture surface although the mechanical properties of the composites were enhanced. Further improvement using surface treatment of fiber would be necessary to carry out to optimize the fiber-

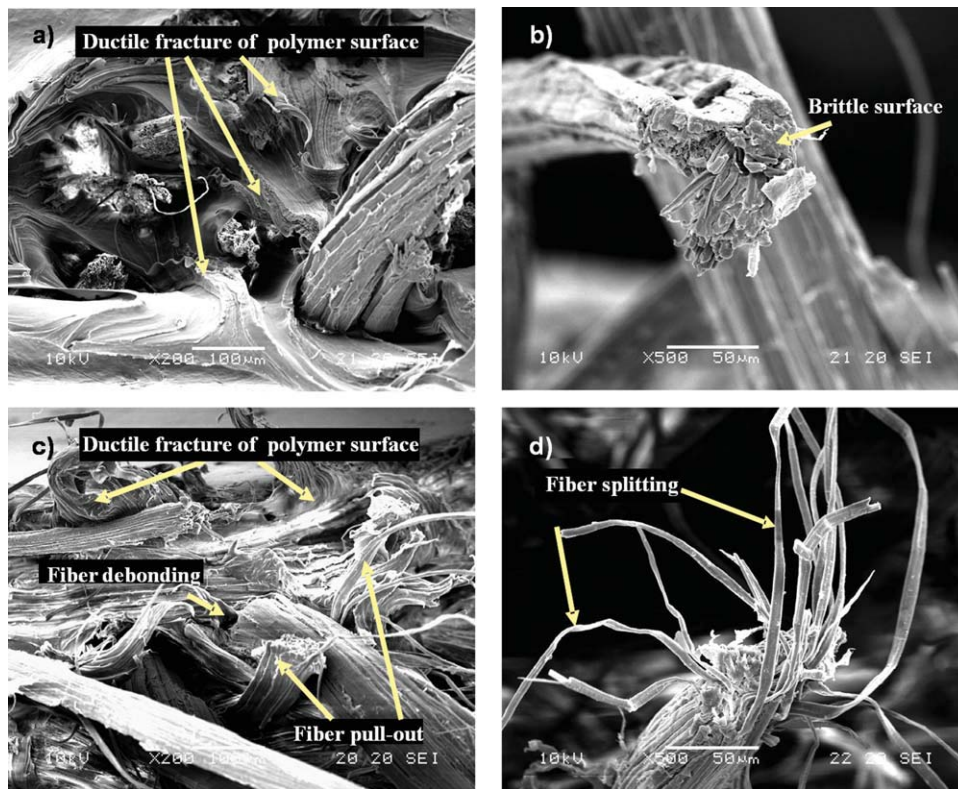


Figure 6 SEM photographs of tensile fracture of LDPE/PALF composites with 15% PALF. (a) LDPE/PALF-L at magnification of $\times 200$. (b) LDPE/PALF-L at magnification of $\times 500$. (c) LDPE/PALF-S at magnification of $\times 200$. (d) LDPE/PALF-S at magnification of $\times 500$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

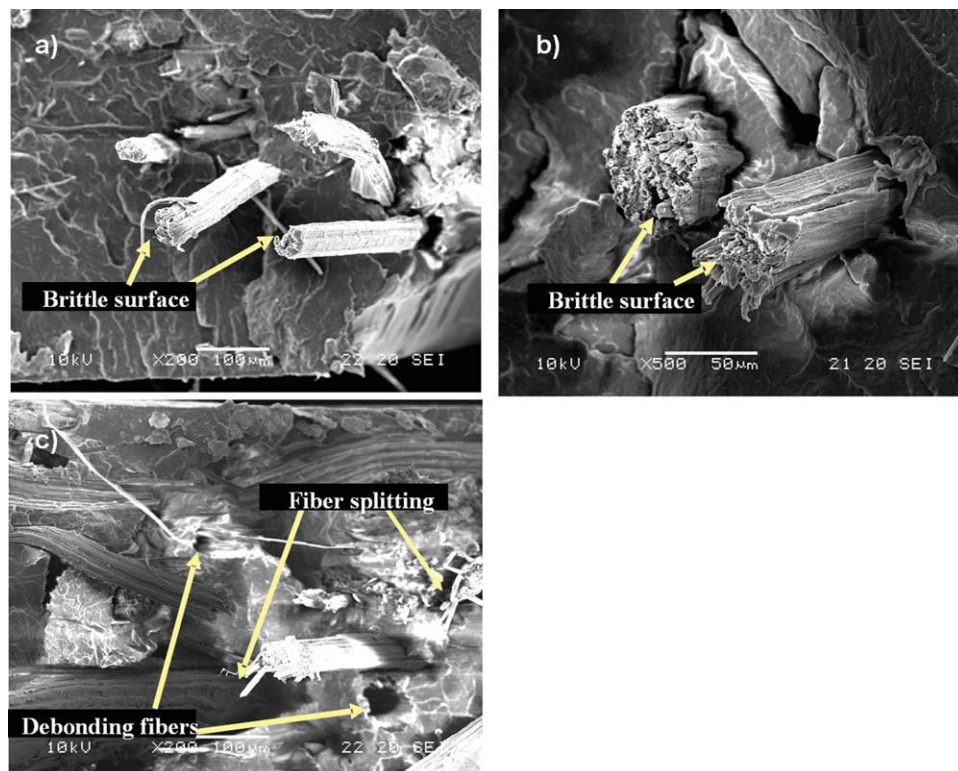


Figure 7 SEM photographs of tensile fracture of PP/PALF composites with 15% PALF. (a) PP/PALF-L at magnification of $\times 200$. (b) PP/PALF-L at magnification of $\times 500$. (c) PP/PALF-S at magnification of $\times 200$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

polymer matrix interfacial interaction as well as polymer-polymer blending.^{28,29} Then the fiber should be covered with the thermoplastic matrix, and the fiber pull-out should be relatively smaller, in good agreement with the results of surface treated hemp fiber in polyester resin.²⁹

CONCLUSIONS

PALF utilization as a high-strength reinforcing agent for LDPE or PP matrix with varying fiber length (fiber orientation) and fiber content was studied. An increase in the tensile strength with the PALF content made LDPE and PP-based composites stiffer and stronger than pure polymers. The effect of reinforcement of long fiber (uni-direction) had more distinctive evidence than that of short fiber (multidirection), resulting in higher strength. In addition, the SEM fracture surface confirmed homogeneous dispersion of long fibers in polymer matrices which was better than the dispersion of short fibers. The X-ray and DSC results confirmed that the decrease of crystallinity in the thermoplastic/PALF composites was due to the interruption of fiber migration and diffusion of polymer chains in the crystal formation. Therefore, the main reason for the strength improvement in the composites was the reinforcement effect of PALF in the matrix, which was not due to the crystallinity change of thermoplastic. However, this study shows that the PALF reinforced composites can be achieved by both uni-directional and multi-directional orientation of the fiber mat in the middle of the polymer matrices. In addition, the LDPE or PP/PALF composites could be successfully developed in the conventional process with minimal modification, which was critical to the growing applicability of these composites in automotive and building products industries. Future work will focus to improve the thermoplastic/PALF by chemical modification and uniform distribution of fiber in the matrix.

The authors would like to deeply thank Dr. Wirasak Smitthipong for helpful discussions and Miss Wanida Pasukdee for useful suggestions.

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