

# Tensile properties of natural and synthetic fiber-reinforced polymer composites

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## 5.1 Introduction

Polymer composites are a kind of high-performance and versatile material formed from a combination of different phases of materials, at least one of which, normally the matrix, is a polymer [1]. The combination of these components results in unique mechanical and thermal properties that are infeasible to be achieved with a single material. Matrix and reinforcement are the two main phases that are essential in developing polymer composites. These two phases are usually composed of organic polymers as the matrix and fiber as the reinforcement. Generally, the strength and stiffness of the fiber materials are much higher than those of the matrix material, and thus make the fiber the major load-bearing component in polymer composites. On the other hand, the matrix serves as a load distributor by uniformly transferring the applied force to the fiber. Therefore, the matrix needs to hold the fiber firmly to establish an efficient load transfer, which in turn increases the mechanical properties of the polymer composites.

The performance of polymer composites is generally determined by:

1. the properties of the fiber,
2. the properties of the polymer matrix,
3. the ratio of the fiber to the polymer matrix in the composite (fiber volume fraction), and
4. the geometry and orientation of the fiber in the composite.

The performance is usually referred to as the mechanical properties of the polymer composites. It is considered to be the most important of the physical and chemical properties of the polymer composites. To determine the mechanical properties of polymer composites, there are numerous mechanical tests and testing instruments with standardized and nonstandardized testing methods [2]. One of the most important criteria in determining the performance of polymer composites materials is the tensile properties.

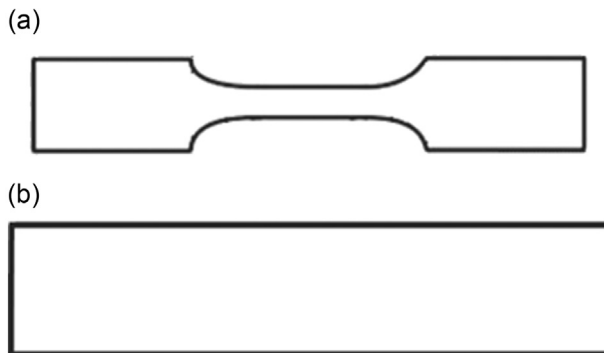
## 5.2 Tensile properties

Tensile properties are composed of the reaction of the materials to resist when forces are applied in tension. Determining the tensile properties is crucial because it provides information about the modulus of elasticity, elastic limit, elongation, proportional limit, reduction in area, tensile strength, yield point, yield strength, and other tensile properties. Tensile properties vary from material to material and are determined through tensile testing, which produces a load versus elongation curve, which is then converted into a stress versus strain curve. Tensile properties are usually determined through tensile testing, which is normally described by an ASTM standard test. The appropriate standards for tensile testing are ASTM D638 and ASTM D3039, depending on the type of polymer composite. ASTM D638 is recommended for randomly oriented, discontinuous, moldable, or low reinforcement–volume composites. Instead, ASTM D3039 is applied for highly oriented and/or high tensile modulus fiber-reinforced polymer composites. Specimens for tensile testing are usually dumbbell or dog bone–shaped and rectangular bar-shaped, as illustrated in Fig. 5.1.

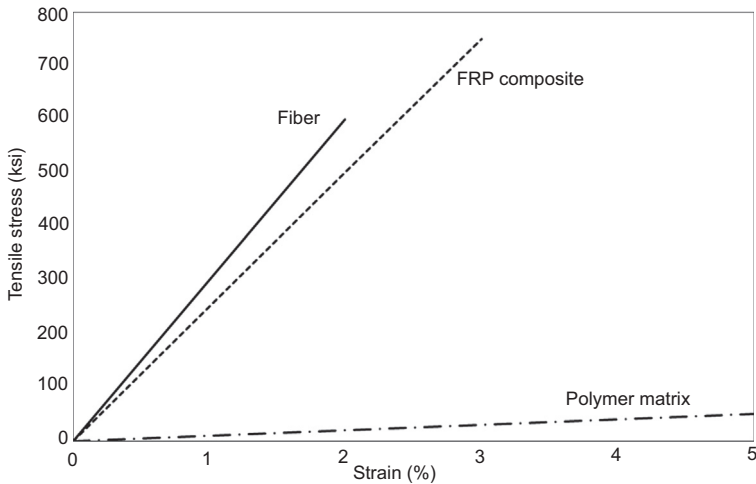
In fiber-reinforced polymer (FRP) composites, the tensile properties of the fiber, matrix, and composite are as depicted in Fig. 5.2. Fiber generally has higher strength and stiffness, whereas matrix has a higher degree of elongation. The combination of these two constituents results in the production of an FRP composite that has tensile properties lying between the two constituents.

## 5.3 Fiber-reinforced polymer composite

Polymer composites are formed from a combination of different phases of materials, at least one of which, normally the matrix, is a polymer [1]. This results in unique mechanical and thermal properties that are impossible to be achieved with a single type of material. Matrix and reinforcement are the two main phases in the production



**Figure 5.1** Specimens' shape for tensile testing: (a) dumbbell or dog bone, and (b) rectangular bar.



**Figure 5.2** Tensile properties of the fiber, polymer matrix, and fiber-reinforced polymer (FRP) composite.

of polymer composites. The reinforcements are usually fiber; the constituents within a polymeric matrix of a composite contribute to the high tensile strength, boosting properties in the final part such as improving the strength, rigidity, matrix interaction, conductivity, heat resistance, and resistance against chemical and physical corrosion while minimizing weight [3]. Several types of reinforcements are used in different composites, depending on their applications [4]. Two types of fibers are used as reinforcement in polymer composites: synthetic and natural. The classifications of the fiber are shown in Fig. 5.3 [5]. The various arrangements and assembly methods of fiber and their orientations lead to characteristic changes in its mechanical properties because the fiber performs as the major load-bearing component in FRP composites.

### 5.3.1 Natural fiber

Natural fiber as an alternative reinforcement for fabricating lightweight, low-cost polymer composites has attracted the attention of many researchers and scientists owing to its advantages over conventional glass and carbon fibers (CF) [6]. Among known types of natural fiber are flax, hemp, jute, sisal, kenaf, coir, kapok, banana, and henequen [7]. Various advantages of natural fiber over man-made glass and CF are their low cost, low density, comparable specific tensile properties, lack of abrasion to equipment, lack of irritation to skin, reduced energy consumption, less health risk, renewability, recyclability, and biodegradability [8].

Generally, the tensile strength of natural fiber is low compared with synthetic fiber [3]. Tensile properties such as tensile strength and the Young's modulus of natural fiber-reinforced polymer composites are listed in Table 5.1.

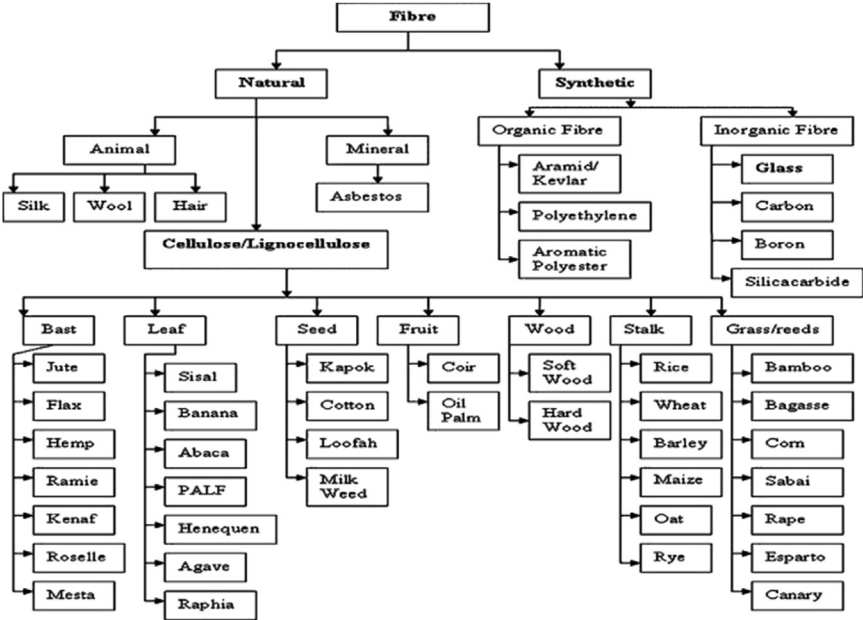


Figure 5.3 Classification of natural fibers and synthetic fibers [5].

5.3.1.1 Kenaf

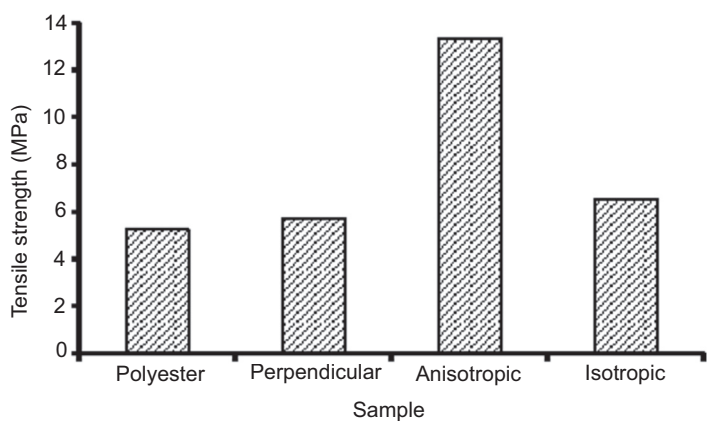
Kenaf fiber has emerged as an important plant cultivated in third-world countries and has been regarded as an industrial crop. It has a great potential for replacing synthetic fiber such as glass fiber. The use of kenaf fiber can provide mechanical properties, i.e., tensile strength, comparable to those of synthetic fiber with lower density than traditional materials, resulting in lightweight and eco-friendly polymer composites. The performance of kenaf-reinforced polymer composites is affected by several factors such as chemical treatment, fiber content, the part of the kenaf fiber used, the form of fiber, and water uptake [9]. The effect of fiber content on the tensile strength of the pultruded kenaf fiber composites was studied by Fairuz et al. [10]. They found that the tensile strength of the pultruded kenaf fiber composites increased with an increase in the percentage of fiber by 50%. Beyond 50% fiber loading, the tensile strength slightly decreased. Besides the fiber content, the tensile properties of kenaf-reinforced polymer composites are strongly influenced by the fiber orientation. Yong et al. [11] studied the effect of fiber orientation on the mechanical properties of kenaf–polyester sandwich composites.

In the study, kenaf fiber was subjected to mercerization with a 6-wt% sodium hydroxide (NaOH) solution before composite fabrication. Unsaturated polyester resin was cast into a sheet film. The composites were prepared by sandwiching a layer of treated kenaf fiber between two layers of polyester films. The final sandwich composite

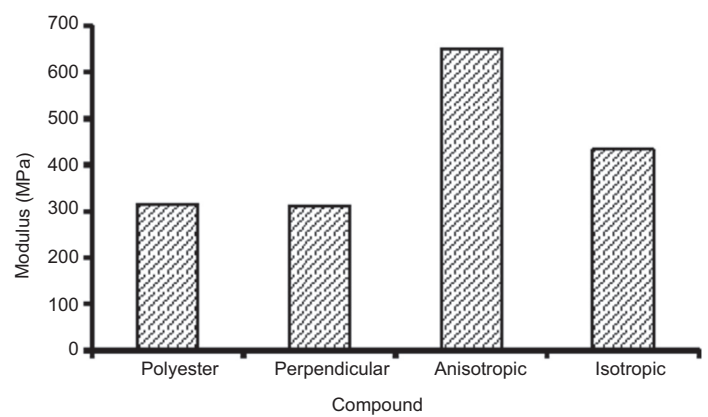
**Table 5.1** Tensile properties of natural fiber-reinforced polymer composites

Type of fiber	Type of matrix	Tensile strength (MPa)	Young's modulus (GPa)	References
Abaca	Polypropylene	29–49.8	3.1–6.2	[25]
Alfa	Polypropylene	29–32	1.1–1.7	[26]
Bamboo	Polylactic acid	223	10.5	[27]
Banana	Epoxy	21	0.62	[28]
Coconut	Polypropylene	10–25	1.7–2.8	[29]
Curaua	High-density polyethylene/ ethylene-vinyl acetate	16.9–24	0.55–1.3	[30]
Flax	Epoxy	186	18.95	[31]
Fique	Epoxy	60.26–100.94	1.61–1.86	[32]
Hemp	High-density polyethylene	12.27–17.39	16.39–22.56	[33]
Henequen	Poly(hydroxybutyrate- co-hydroxyvalerate)	14.8–16.6	0.41–0.77	[34]
Jute	Epoxy	32.9–42.14	0.054–0.059	[35]
Kenaf	Polyester	25.5–36.4	1.52–2.63	[36]
Palm	Epoxy	10.064	1.71	[37]
Pineapple	Polyester	36.22–103.25	1.32–1.99	[38]
Ramie	Polylactic acid	59.3	4.3	[39]
Sisal	Phenol formaldehyde	45–60	0.56–1.1	[40]
Vakka	Polypropylene	16.02–28.22	—	[41]
Wool	Polypropylene	24.7–34.4	1.82–2.41	[42]

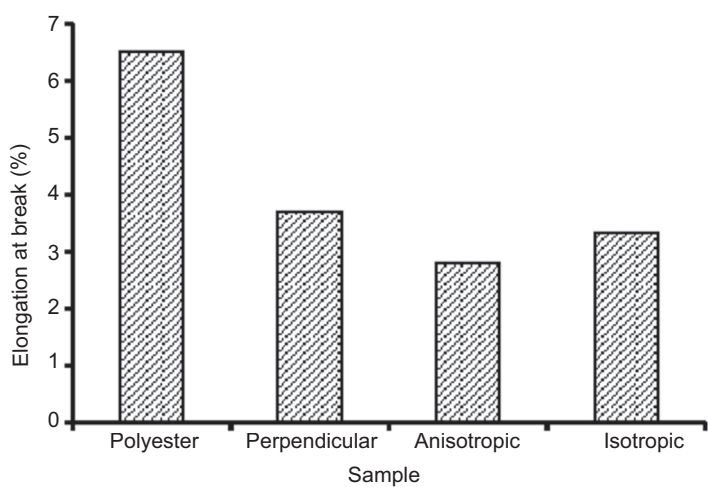
was prepared with five layers containing three layers of polyester resins and two of kenaf fibers. The volume fraction weights of polyester and kenaf fiber layers were controlled to maintain composites with a ratio of 70:30. The polyester–kenaf sandwich composite was prepared with three different fiber arrangements in perpendicular, anisotropic, and isotropic orientations. Tensile properties such as tensile strength, the Young's modulus, and elongation at break were studied. The researchers found that the composite with fiber in an anisotropic arrangement achieved the highest tensile strength and Young's modulus, as depicted in Figs. 5.4 and 5.5. However, the same specimen evidenced the lowest elongation at break, as shown in Fig. 5.6. From the tensile property results, they concluded that the strength of the kenaf–polyester sandwich composite increased with a decrease in the fiber's orientation.



**Figure 5.4** Tensile strength of polyester and kenaf–polyester sandwich composite [11].



**Figure 5.5** Young’s modulus of polyester and kenaf–polyester sandwich composite [11].



**Figure 5.6** Elongation at break of polyester and kenaf–polyester sandwich composite [11].

### 5.3.1.2 Jute

Alternative uses for biodegradable plastics and their natural fiber biocomposites have gained in popularity. This is because they are easily degraded in landfills. A number of commercially available biodegradable polymers such as polyhydroxyalkanoate, poly(lactic acid) (PLA), polycaprolactone, and polyester amide are used frequently as matrices for natural fiber to develop a new class of fully biodegradable composites. In the class of biodegradable polymers, PLA has the greatest potential in the composite industries because of its easy availability, good biodegradability, and high mechanical properties [12]. Studies on the tensile strength of natural fiber–PLA composites are summarized in Table 5.2.

Jute fiber is a commercially available and cheap natural fiber that contains a high cellulose content [13]. The mechanical properties of injection-molded jute–PLA composites were successfully improved by Arao et al. [14]. In that study, long jute fiber pellets (LFP) with a length of 6 mm and short jute fiber pellets (SFP) were compounded by using a twin-screw extruder with a control temperature set to 180°C to avoid the thermal degradation of the jute fiber. Subsequently, the LFP and SFP were fed into the injection-molding instrument. Three types of specimens were studied, depending on the type of pellet: LFP, SFP by full flight (FF), and SFP by mixing (MIX). To suppress hydrolysis during processing, LA-1 [poly(dicyclohexylmethane-carbodiimide)] was added to the PLA. A crystallization agent was also used to increase the crystallinity of the PLA composites. The weight ratio of jute, PLA, LA-1, and the crystallization agent was set to 50, 46, and 2 wt%, respectively. The initial studies focused on the effect of LA-1 to suppress the hydrolysis of PLA. By adding jute fiber to the LFP and in the absence of LA-1, the strength of the PLA composite decreased from 49.8 to 28 MPa. Adding LA-1 increased the molecular weight; thus, a higher tensile strength was observed. In the SFP specimens, SFP (MIX) gave better mechanical performance than that of SFP (FF). This indicated that for jute–PLA composites, using the pellet, which had a higher compounding intensity, led to exceptional performance. The overall tensile properties of the jute–PLA composites are listed in Table 5.3.

### 5.3.1.3 Hemp

The major difficulty that limits the extended use of natural fiber is their hydrophilic nature, which affects the adhesion to a hydrophobic polymeric matrix and decreases the mechanical properties of the resulting composite material. To improve adhesion between the reinforcement and matrix resin, the fibers were subjected to chemical treatment before use. Strongly polarized cellulose, is not inherently compatible with hydrophobic nonpolar polymers matrices. Also, poor resistance to moisture absorption makes natural fibers less attractive for use in composites to be employed in outdoor applications. The effects of the surface treatment of natural fibers on their properties are usually functions of the type and concentration of the treatment solution used. Among popular chemical treatments on natural fiber are alkali and silane treatment.

The effects of alkali and silane treatment on the mechanical properties of woven hemp-reinforced epoxy composites were investigated by Sepe et al. [15]. Woven

**Table 5.2** Comparison of mechanical properties of poly(lactic acid)-based natural composite fabricated by various processes [14]

Fiber	Fiber content (wt%)	Process	Stress (MPa)	Strength (%)	Young's modulus (GPa)	Additional information	Source
Flax	30	CM	53	106	8.3	Using extruded pellet	[43]
Hemp	40 (volume)	CM	54.6	156	8.45	Film stacking + surface treatment	[44]
Ramie	30 (volume)	CM	66.8	148	—	Compound pellet + surface treatment	[45]
Jute	40	CM	100.5	182	9.4	Film stacking method	[46]
Jute	35–39	IM	49	80	10.5	Using long fiber pellet	[47]
Cordenka	30	IM	58	130	4.85	Using compound pellet	[48]
Jute	30	IM	81.9	129	9.6	Using compound pellet	[49]
Jute	50	IM	82.2	121	—	Optimal compound process	[50]
Hemp	30	IM	75.5	148	8.18	Surface treatment	[51]

CM, compression molding; IM, injection molding.

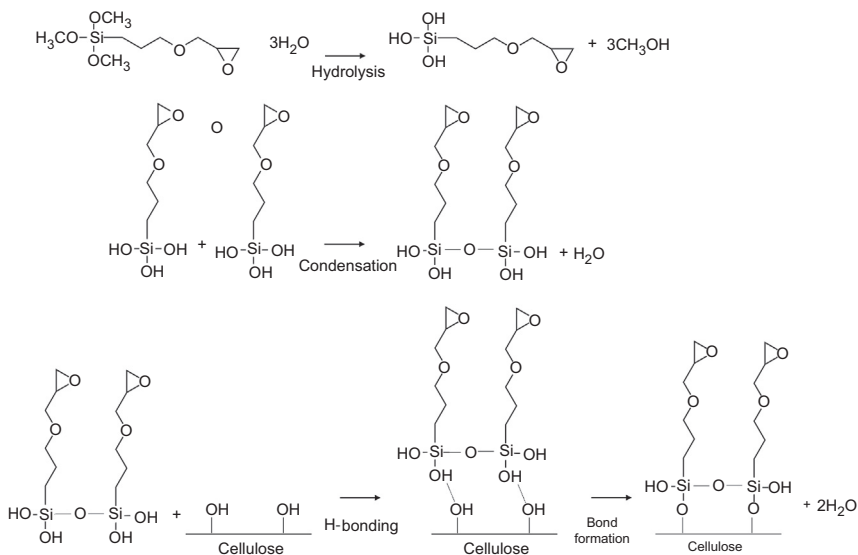


**Table 5.3** Tensile properties of PLA and jute–PLA composites [14]

Material	Tensile strength (MPa)	Tensile strength (%)	Tensile modulus (GPa)
PLA	49.8 ± 0.53	—	2.8 ± 0.1
LFP without LA-1	28.0 ± 2.3	56.2	3.85 ± 0.49
LFP	65.2 ± 2.2	131	4.39 ± 0.76
SFP (full flight)	78.6 ± 0.80	158	4.57 ± 0.29
SFP (mixing)	90.7 ± 1.3	182	4.22 ± 0.15

*LFP*, long jute fiber pellets; *PLA*, poly(lactic acid); *SFP*, short jute fiber pellets.

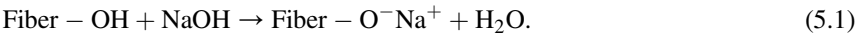
hemp fabric with a plain weave and epoxy infusion resin were used as the reinforcement and matrix, respectively. For alkali treatment, the hemp fiber was treated using 1 and 5 wt% sodium hydroxide (NaOH), whereas for silane treatment, a silane coupling agent (3-glycidyloxypropyl)trimethoxysilane was used at concentrations of 1, 5, and 20 wt%. The reactions to alkali treatment and the mechanism between the alkoxy-silanes and the fiber surface are shown in Eq. (1) and Fig. 5.7 [15]. Hemp–epoxy composites at 42% fiber weight fraction for all composites were prepared by vacuum infusion process in a mold. The composites, which were formed from four plies of textile and six different configurations, were manufactured as listed in Table 5.4.



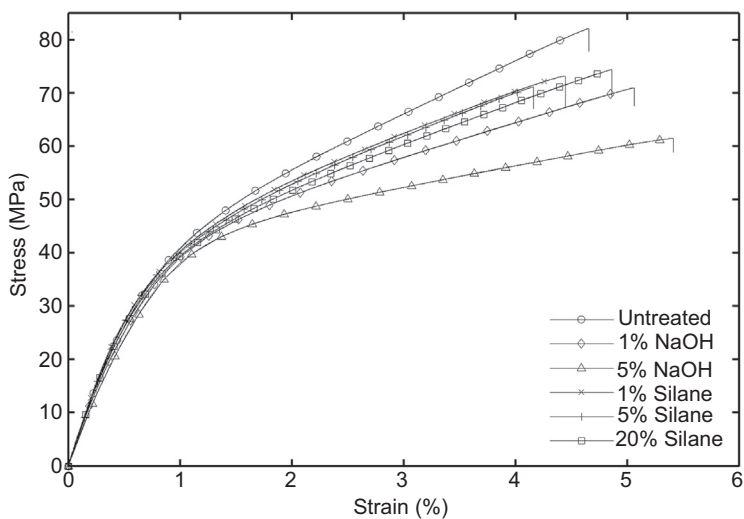
**Figure 5.7** Mechanism of linking between the alkoxy-silane and the fiber surface containing hydroxyl group [15].

**Table 5.4** Laminate stacking sequence [15]

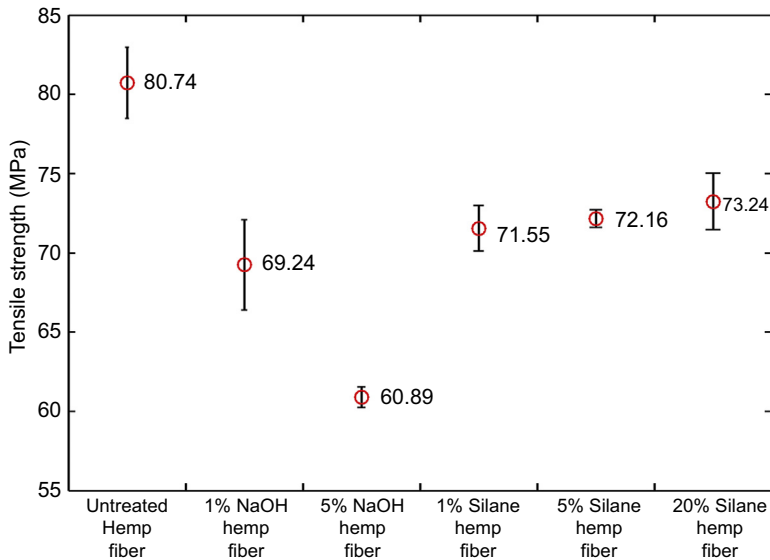
Symbol	Fiber	Treatment	No. of ply	Stacking sequence	Thickness (mm)
A	Hemp	Untreated	4	[0/90] <sub>1s</sub>	1.364
B	Hemp	Alkaline treatment NaOH 1%	4	[0/90] <sub>1s</sub>	1.511
C	Hemp	Alkaline treatment NaOH 5%	4	[0/90] <sub>1s</sub>	1.679
D	Hemp	Silane treatment 1%	4	[0/90] <sub>1s</sub>	1.471
E	Hemp	Silane treatment 5%	4	[0/90] <sub>1s</sub>	1.460
F	Hemp	Silane treatment 20%	4	[0/90] <sub>1s</sub>	1.450



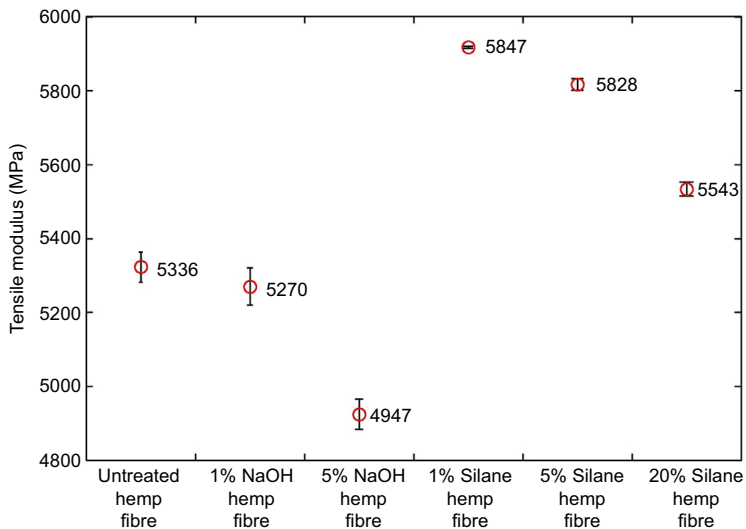
The tensile [15] stress–strain curves for six different configurations of hemp–epoxy composites are shown in Fig. 5.8. All of the curves displayed a linear range at low strain (<0.5%) followed by a hardening region that continued up to 5%. Fig. 5.8 demonstrates that the elongation at break increased with the treatments in which epoxy composites containing hemp fiber treated with 5% NaOH showed the highest elongation. The different effects of treatment on the tensile strength and tensile modulus of the composites are depicted in Figs. 5.9 and 5.10, respectively. The tensile



**Figure 5.8** Typical tensile stress versus strain curves for six different configurations of hemp–epoxy composites [15].



**Figure 5.9** Tensile strength of hemp-epoxy composites [15].



**Figure 5.10** Tensile modulus of hemp-epoxy composites [15].

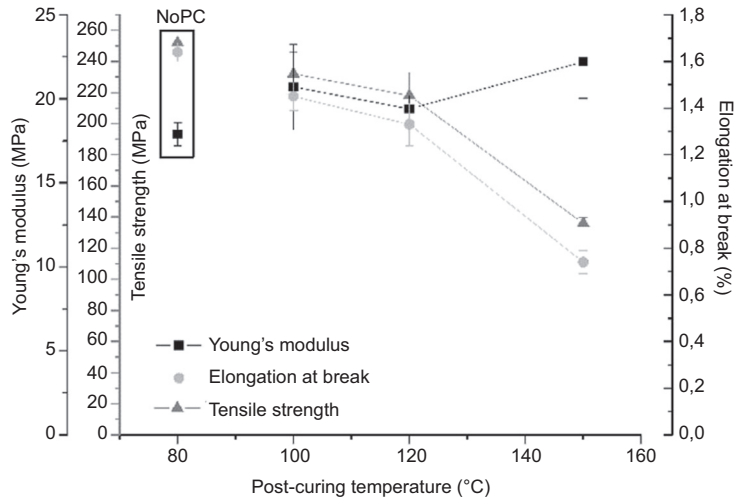
strength of composites reinforced with alkali-treated hemp fiber was lower than that of composites reinforced with untreated hemp fiber. The reduction was most significant for composites with hemp fiber treated with a 5% concentration of NaOH, for which the tensile strength was 25% lower than that of the composite with untreated hemp fiber and 12% lower compared with the composite treated with 1% NaOH. According

to the author, this may be the result of the removal of hemicellulose and lignin after 5% alkali treatment, which caused the fiber to be pulled out easily. The tensile strengths of the silane-treated composites were lower than those of the untreated hemp fiber composites, but the tensile strength of the 20% silane-treated fiber composite was 8% lower than that of untreated fiber composite. For the tensile modulus, the composite with hemp fiber subjected to 5% NaOH treatment was lower than that of the composites with untreated hemp fiber (about 7%), whereas the modulus of the 1% NaOH-treated hemp fiber composite was almost equal to that of the untreated hemp fiber composite. The tensile modulus of the composites with hemp fiber that were subjected to silane treatment was significantly higher than that of the composites with both untreated and alkaline-treated hemp fiber. The increase in modulus associated with silane treatment was attributed to improved bonding between the fiber and the matrix. Sufficient load transfer between the matrix and the fiber occurred for the higher modulus of the fiber and had a beneficial impact on the modulus of the composite.

#### 5.3.1.4 *Flax*

Thermoset polymer matrix composites are generally cured at low temperatures ranging from ambient to 100°C. To complete curing, postcuring at higher temperatures around 150°C or more is needed by the composites to reach the highest cross-linking and improve the modulus and strength. However, a postcure can also lead to thermooxidation of the resin and degrade the natural fiber reinforcement. Therefore, it is challenging to achieve complete curing of natural fiber-reinforced polymer composites without damaging the fiber. A study by Campana and coworkers [16] assessed the impact of the postcuring temperature on the mechanical properties of an epoxy composite using unidirectional flax fiber as a reinforcement.

In the study, the flax-reinforced epoxy composites were manufactured using a vacuum infusion process. Four plies of flax fiber oriented in the weft direction were infused with epoxy resin before being cured at 80°C for 24 h. Three postcurings for 2-h cycles were studied: at 100°C (PC100), 120°C (PC120), and 150°C (PC150). Uniaxial tensile tests were performed on the flax-epoxy composites and neat epoxy resin. The tensile strength, modulus, and elongation at break of the non-postcured (NoPC) and postcured (PC100, PC 120, and PC150) flax-epoxy composites are shown in Fig. 5.11. A decrease in the tensile strength from 252 MPa for NoPC to 136 MPa for PC150 was observed when the postcuring temperature increased. The higher the temperature of postcuring was, the lower the maximal stress was with a maximal decrease of 46% for the highest temperature. The decrease in tensile strength was particularly significant when the postcuring temperature increased from 120°C to 150°C with a relative variation of 40% between the two temperatures. A decrease in tensile strength despite a higher cross-linking rate evidenced that one (or both) of the composite components was modified during postcuring. The elongation at break followed the same tendency. A significant decrease was observed for PC150 with an elongation at break of 0.74% (versus 1.64%, 1.45%, and 1.33% for NoPC, PC100, and PC120, respectively). This may be explained by modification of the resin, which was more brittle when the cross-linking rate was higher. The Young's moduli



**Figure 5.11** Tensile strength (MPa), Young's modulus (GPa), and elongation at break (%) of the flax-epoxy composites postcured at 100, 120, and 150°C [16].

for all the composites were according to the NF EN International Organization for Standardization 527-4 standard. Despite the high standard deviations, the Young's modulus tended to increase when the temperature of postcuring increased from  $17.9 \pm 0.68$  GPa for NoPC to  $22.2 \pm 2.18$  GPa for PC150.

### 5.3.2 Synthetic fiber

The use of synthetic fiber composites is unavoidable in the manufacturing and production industries because their properties are known for being better than those of natural fiber. Synthetic fiber has been used to make high-performance polymer matrix composite products such as FRP tanks, aerospace components, automobile parts, and building panels. Among popular synthetic fibers that are commonly used in composites industries are glass, carbon, and aramid [17].

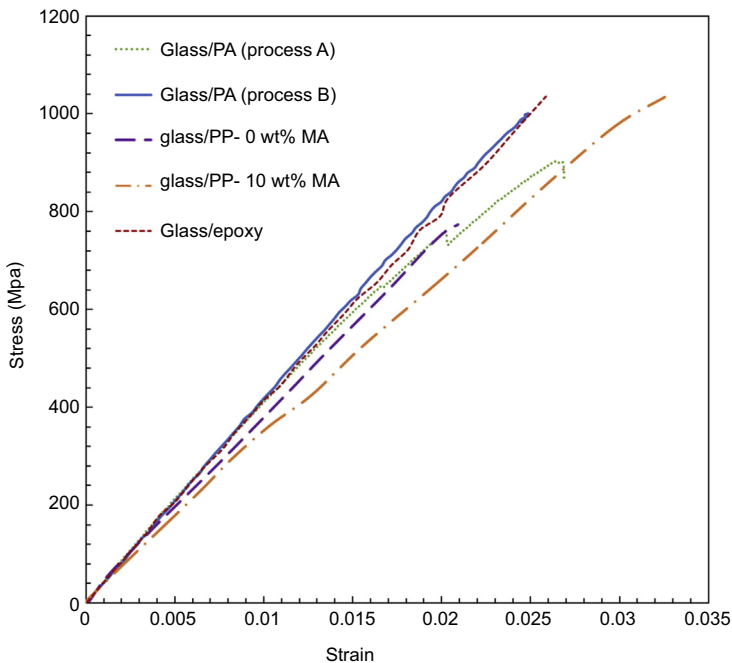
#### 5.3.2.1 Glass

Glass fiber is the most common reinforcement for polymeric composites. Major advantages of glass fiber are its low cost, high tensile strength, high chemical resistance, and excellent insulating properties. Glass fiber-reinforced polymer (GFRP) composites are the largest class of composite materials. Various forms of glass fiber, such as long longitudinal, woven mat, chopped strand fiber, and chopped strand mat, which were incorporated into the polymer matrix, have been produced to enhance the mechanical and tribological properties of polymer composites. Although glass fiber was one of the earliest reinforcement used in modern composite materials, the study of the mechanical properties of GFRP continues. Nikforooz et al. [18] examined the performance of polyamide 6 reinforced by continuous unidirectional E-glass fiber. The laminates

were processed using distinct hot press molding cycles and the results were compared with similar E-glass–epoxy and E-glass–polypropylene (PP) laminates from other works [19,20].

The study evaluated the influence of processing parameters on the in-plane tensile performance of unidirectional and cross-ply E-glass–polyamide 6 laminates. Two processes were used to fabricate the composite laminates. The first laminate was processed using a manual hot press machine and was called process-A. Process-B was performed using a Carver hot press. The tensile stress–strain curves for various laminates of glass–polyamide 6 (PA) and their comparison with glass–PP with and without maleic anhydride (MA) and glass–epoxy composites are shown in Fig. 5.12.

The results of the Young's modulus, ultimate strength, and volume fraction for the same laminates are shown in Table 5.5. As can be seen in Fig. 5.12 and Table 5.5, the strength of the glass–PA specimens was higher than for glass–PP without MA but slightly lower than for glass–PP with 10 wt% MA and glass–epoxy. However, the Young's modulus of both glass–PA specimens were approximately the same as glass–epoxy. The Young's modulus of glass–polyamide was also comparable to that of glass–PP (with and without MA), which was expected because PP and PA have comparable Young's moduli.



**Figure 5.12** Tensile stress–strain curves for various laminates of glass–polyamide 6 (PA), glass–polypropylene (PP) without maleic anhydride (MA) [19], glass–PP with 10 wt% MA [19], and glass–epoxy [20] composites [18].

**Table 5.5** Tensile mechanical properties of different composites [18]

Material	Young's modulus (GPa)	Ultimate strength (MPa)	Volume fraction
Glass—PA (process-A)	$42.1 \pm 1.6$	$835 \pm 69.5$	0.58
Glass—PA (process-B)	$41.6 \pm 3.7$	$885 \pm 78.5$	0.58
Glass—epoxy [20]	41.8	1034.8	0.6
Glass—polypropylene without maleic anhydride [19]	$43.4 \pm 1.4$	$720 \pm 50$	0.58
Glass—polypropylene with 10 wt% maleic anhydride [19]	$43.6 \pm 2.0$	$890 \pm 60$	0.58

PA, polyamide 6.

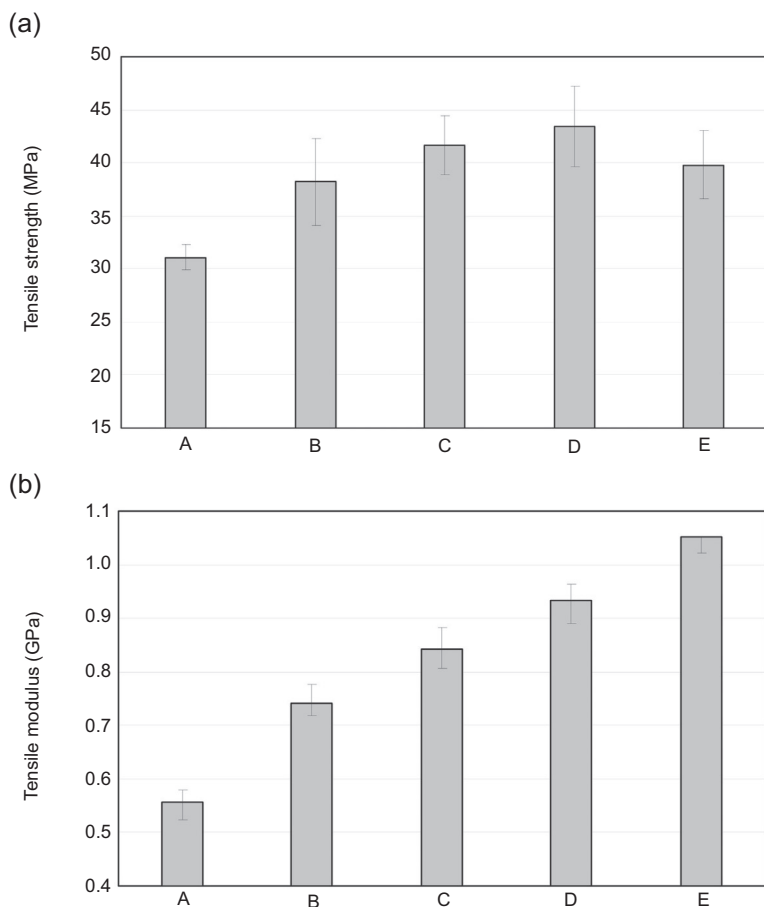
### 5.3.2.2 Carbon

Carbon fibers (CF) are regarded as multifunctional fillers because they improve the properties of the polymers. CF have a wide range of aspect ratios that can be used for different purposes such as thermal conductivity and elastic modulus enhancement. Advantages of CF include high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance, and low thermal expansion. These properties make CF an excellent reinforcement for polymers to increase their thermal and mechanical properties [21].

Short fiber-reinforced polymer composites have been widely used as structural materials for automobiles, aerospace, marine, and other industrial applications. Short CF (SCF) are attractive because of their ease of fabrication, relatively low cost, high stiffness and strength to weight ratios, and excellent mechanical properties [22]. A study on the tensile properties of SCF-reinforced PP composites was conducted by Ashori et al. [23]. In the study, SCF was coated with exfoliated graphene nanoplatelet (xGnP) before it was compounded by melt blending with PP. The formulation of the compound is shown in Table 5.6. The effects of xGnP-coated SCFs on the tensile properties of PP composites were studied.

**Table 5.6** Formulation and component weight ratio of composites [23]

Code	Polypropylene (wt%)	Short jute fiber pellets (wt%)	Exfoliated graphene nanoplatelets (wt%)
A	100	0	0
B	85	15	0
C	84.5	15	0.5
D	84	15	1.0
E	82	15	3.0



**Figure 5.13** Mechanical properties of the composites: (a) tensile strength, and (b) tensile modulus [23].

The tensile strength and tensile modulus of the neat PP and the composites are shown in Fig. 5.13. The addition of SCFs to the PP matrix increased the tensile strength. Further increases in tensile strength were observed for the xGnP-coated SCF reinforced PP composites. As the xGnP content increased, the tensile strength of the composites increased and reached the highest value at 1 wt% xGnP. The obvious increment in tensile strength of xGnP-coated SCF reinforced PP composites was believed to result from the enhancement of interfacial bonding between the SCFs and the PP matrix by xGnP treatment on the SCF surfaces, which resulted in better load transfer from the PP to the SCFs. However, at 3 wt% xGnP, the tensile strength decreased but was still higher than the uncoated SCF–PP composite. The reduction in tensile strength could be explained by the agglomeration of xGnP, which occurred because of the van der Waals' interaction between the graphene nanoplatelets.



A contrary trend was observed for the tensile modulus, in which the modulus increased as the content of xGnP increased. The composite containing 3 wt% xGnP had a higher modulus than the other composites, which suggested that adhesion between the xGnP–SCF and PP was strong enough to improve the modulus, which was determined at low loads in the linear elastic region but broke at higher loads near the ultimate strength of the matrix.

### 5.3.2.3 *Aramid*

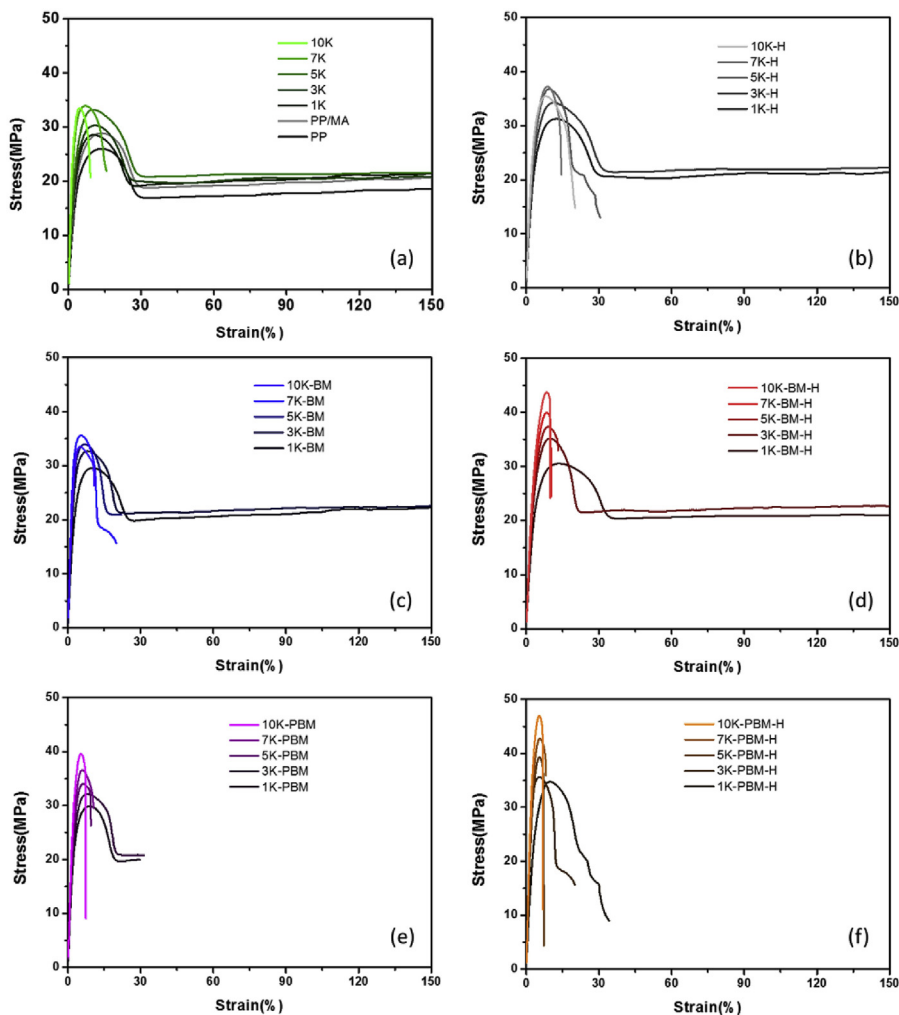
Aramid fiber, also known as Kevlar, is a synthetic fiber with high thermal properties. They are high-strength materials because of the orientation of their molecules along the axis. Their properties include good resistance to abrasion, good resistance to organic solvents, nonconductivity, no melting point, a high degradation temperature (starting from 500°C), low flammability, and good fabric integrity at elevated temperatures. Such properties made aramid fiber usable in the aerospace industry for manufacturing the body parts, for the military for making ballistic accessories and body armor, for making boat hulls and automobile parts, and for making of heat-resistant helmets and clothing.

The mechanical properties of short Kevlar fiber (KF)-reinforced PP and an MA grafted PP (MA-g-PP) composite by varying the modification process of KF were studied by Fu et al. [24]. The purpose of the modification was to improve the interfacial interaction and mechanical properties of the produced composites. Three different modification were adopted for the KF: (1) direct hydrolysis treatment of KFs with 10 wt% sodium hydroxide aqueous solution at room temperature; (2) planetary ball milling, in which predried KFs were soaked in phosphoric acid aqueous (0, 10, 20, and 30 wt%) at room temperature and then ball milled for different times at different roller speeds; and (3) hydrolysis treatment of the ball milled KFs. The nomenclature for the KFs treated with different methods is listed in Table 5.7.

The stress–strain curves of PP, PP/MA-g-PP blends, and their composites containing different types of KFs are shown in Fig. 5.14. The effects of fiber KFs obtained by different ball milling treatments without hydrolyzation are verified in Fig. 5.14a, c,

**Table 5.7** Nomenclature used for Kevlar fiber without and with various surface treatments [24]

Code	Surface treatment methods
K	Untreated KF
K–H	Hydrolyzed KF
K-BM	Ball milled KF
K-BM-H	Ball milled and hydrolyzed KF
K-PBM	Ball milled in phosphoric acid KF
K-PBM-H	Ball milled in phosphoric acid and hydrolyzed KF



**Figure 5.14** Stress–strain curves of polypropylene (PP), PP–maleic anhydride grafted PP (MA-g-PP) (97/3) blends, and PP–MA-g-PP composites containing different types of Kevlar (K) fiber: (a) K, (b) hydrolyzed K (K–H), (c) ball-milled K (K–BM), (d) ball milled and hydrolyzed K (K–BM–H), (e) ball milled in phosphoric acid K (K–PBM), and (f) ball milled in phosphoric acid and hydrolyzed K (K–PBM–H) [24].

and e. As shown in Fig. 5.14a, the samples of PP and PP/MA-g-PP had a relatively low tensile strength and high elongation at break. The yield strength of the composites increased gradually with an increase in the content of KFs but then decreased. The composite with 7 wt% KF content possessed the highest values of tensile strength with low elongation at break. Fig. 5.14c shows the stress–strain behavior of PP/MA-g-PP–ball-milled Kevlar composites. The addition of ball milled KF significantly decreased the elongation at break. The mechanical properties of composites reinforced

by KFs milled in phosphoric acid (PP/MA-g-PP/ball-milled Kevlar) are shown in Fig. 5.14e. The yield strength of the composites increased more significantly with the KF content, which was because the surface of ball-milled Kevlar was rougher and the grooves on the surface further increased the contact area with the PP matrix.

Fig. 5.14b, d, and f shows the stress–strain behavior of PP–MA-g-PP–hydrolyzed KFs. By contrast, it is obvious that the mechanical performance of the composites needed be improved. The different enhancement effects might be attributed to interfacial adhesion between the KFs and the PP matrix. By hydrolyzation, the hydroxyl and amino groups could be introduced to the surface of KFs. These active functional groups could react with MA on the MA-g-PP. The formation of these firm chemical bonds contributed much to the interfacial interaction between the KFs and the PP matrix, which led to an outstanding enhancement in the yield strength of the composites.

## 5.4 Conclusions

In the field of material science and engineering, both natural and synthetic fibers provide a useful solution to developing lightweight and high-performance polymer composite materials. Natural fibers are renewable resources that offer a number of advantages such as low cost, low density, and readily availability, and they are environmentally friendly. With the appropriate method, natural fiber-reinforced polymer composites possessing tensile properties comparable to those of conventional polymer composites can be produced. Several factors such as fiber orientation, fiber length and loading, surface modification of the fiber, and the processing or curing method should be taken into consideration during the manufacture of natural fiber-reinforced polymer composites.

As researchers focusing more on developing natural fiber-reinforced polymer composites, the use of synthetic fibers in polymer composites is inevitable because they provide exceptional mechanical strength. Synthetic fiber-reinforced polymer composites are unavoidable because they have higher tensile properties than natural fiber-reinforced polymer composites. Synthetic fibers such as glass, carbon, and aramid fiber remains relevant and are required in polymer composites for structural applications. Finally, plenty of room is available for improvement for both types of fiber-reinforced polymer composite.

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