Original article

JOURNAL OF REINFORCED PLASTICS & COMPOSITES

Development and characterization of high-performance kenaf fiber–HDPE composites

Journal of Reinforced Plastics and Composites
0(0) 1–10

DOI: 10.1177/0731684417739127
journals.sagepub.com/home/jrp
SAGE

Qiushi Wang[1], Joydan Jones[1], Na Lu[2], Ralph Johnson[3], Haibin Ning[1] and Selvum Pillay[1]

Abstract

Natural fiber-reinforced polymer matrix composites have been increasingly used in automotive and other fields because of their good mechanical properties, low density, excellent damping properties and biodegradability. The objective of this work is to develop and characterize a high-performance lightweight kenaf fiber composite that is processed using unconventional processing methods, wet laid process followed with compression molding process. Kenaf fiber mats produced by wet laid process are stacked with high-density polyethylene films and compression molded into plates from which testing samples are prepared. The effects of fiber length, fiber content, and area density on the tensile properties are investigated. The composite samples with the best tensile properties are also evaluated in its flexural, compression, impact, and fire resistance performance. The processing–structure–property relations of the developed kenaf fiber high-density polyethylene composite are systematically studied, which can be broadly applied to other natural fiber composites.

Keywords

Kenaf fiber, composites, compression molding, mechanical property

Introduction

Kenaf fiber-reinforced composite is one type of natural fiber composite material that has kenaf fibers as reinforcements in polymer matrix. It has drawn lots of attention owing to its good mechanical properties, low density, excellent damping characteristic and biodegradability. Kenaf fiber has high weight percentage of cellulose content that can reach up to 72%[1] and it possesses high strength up to 930 MPa.[2,3] In addition, the specific modulus of kenaf fiber favorably compares to that of E-glass.[4] The kenaf fiber composite has been increasingly used for secondary structural components in automotive. Toyota Motor Corporation used kenaf fiber polypropylene composite as the material for the interior components such as door trim and seat back board.[5,6] At General Motors, a kenaf and flax mixture has been used in package trays and door panel inserts for Saturn L300s and European-market Opel Vectras.[4] Kenaf/Ramie composite has been used as the material for automotive headliner.[7] In addition, Panasonic Electric Works adopted kenaf for structural application as the structural wall board to replace plywood which is usually fabricated using timber. It was found that the structural wall made of kenaf composite was much lighter than the one made with timber.[6]

Polyethylene (PP) and polypropylene (PE) are the common matrices used in natural fiber composites,[8–10] including kenaf fiber-reinforced composites.[11–13] Both PP and PE have low melting temperatures and their processing temperatures are generally lower than 200°C, at which cellulose in the kenaf fiber starts to degrade[3] and loses its mechanical properties. Therefore, it is important to avoid the degradation of the kenaf fibers, such as hydrolysis, oxidation, dehydration, depolymerization, decarboxylation, and

[1]Department of Materials Science and Engineering, Materials Processing and Applications Development Center, University of Alabama at Birmingham, Birmingham, AL, USA
[2]Lyles School of Civil Engineering, School of Materials Engineering, Purdue University, West Lafayette, IN, USA
[3]CetoTech Inc., West Lafayette, IN, USA

Corresponding author:
Haibin Ning, Department of Materials Science and Engineering, Materials Processing and Applications Development Center, University of Alabama at Birmingham, Birmingham, AL 35294, USA.
Email: ning@uab.edu

recrystallization,[14] by processing them in the polymers with low melting temperatures.

Different processes, such as injection molding and compression molding process, have been used to produce natural fiber thermoplastic polymer matrix composite. These processes are able to produce natural fiber composites with adequate impregnation between fibers and polymer matrix at a high production rate. However, a compounding process is normally involved initially in which the fibers and polymer go through an extruder that compounds the fibers with molten polymer. Large shear force involved in the compounding process and consequent molding process, especially injection molding, have resulted in severe fiber length attrition. Since the mechanical properties of discontinuous fiber composite are proportional to fiber length as reported by Chawla[15] (Figure 1), the fiber length attrition in the compounding process and injection molding process leads to compromised mechanical properties of the final natural fiber composite product. For example, a kenaf/HDPE composite produced by compounding kenaf fibers into HDPE has a tensile strength less than 31 MPa and a tensile modulus less than 1 GPa.[11] A kenaf fiber-reinforced (HDPE and PP) matrix composite that was produced by compounding process has a tensile strength 18 MPa and modulus of elasticity of 1.6 GPa.[16] Aji et al. studied the effect of the fiber size and fiber loading on the mechanical properties HDPE composite reinforced by kenaf hybridized with pineapple leaf fiber at 1:1 ratio. The tensile strength is approximately 30 MPa and modulus 1 GPa.[17]

To overcome aforementioned challenges, this study focuses on the development of lightweight kenaf fiber composite material that has a combination of both high performance and good processibility. The effects of the fiber length, fiber loading, and area density on the flexural properties are evaluated for the kenaf fiber composite. Other properties of the kenaf fiber composite, such as compression, impact and fire resistance, are also discussed.

Material and methods

Kenaf fibers supplied by CetoTech, Inc. and HDPE films, as shown in Figure 2, were used for molding the kenaf/HDPE composite samples. The initial kenaf fibers were in 50 mm length and normally bundled. The fibers were chopped into different lengths such as 25 mm and 12 mm for studying the effect of fiber length on the mechanical properties. The HDPE film has a thickness of 0.127 mm (0.005″) and its melting temperature is 130°C. The low melting temperature of HDPE prevents the degradation of kenaf fibers during impregnation.

The wet laid apparatus shown in Figure 3 was used to produce kenaf fiber mats. The fibers were dispersed in a water container after the fiber bundles were broken down using a blender. The water was drained and a stainless steel mesh at the bottom of the water container held the fibers in a mat form. When the water was drained completely, the hinged water container was lifted (Figure 3) and the mat, as shown in Figure 4 (a), was removed for drying process. The wet mat was then dried in an oven at 70°C for 2 h before laying up with HDPE sheets for compression molding process. Figure 4(a) and (b) shows the fiber mat before and after being dried, respectively.

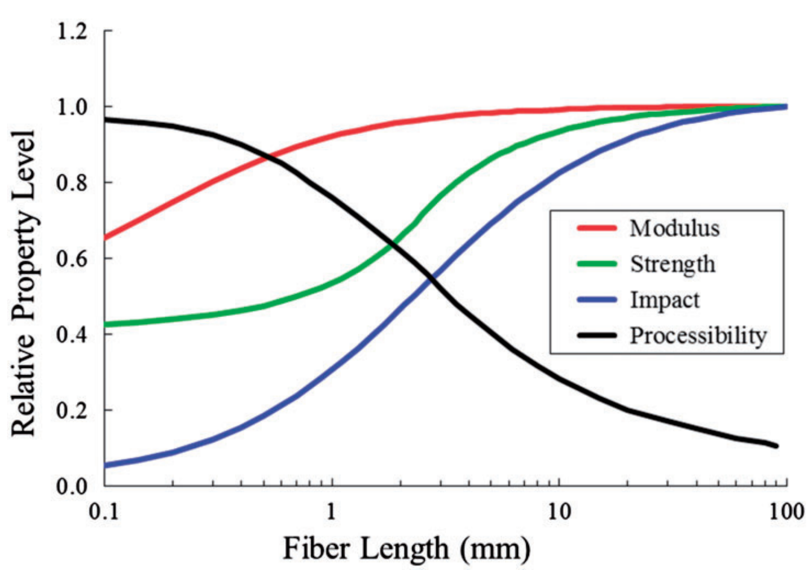

Figure 1. Dependence of composite properties on its fiber length.[15]

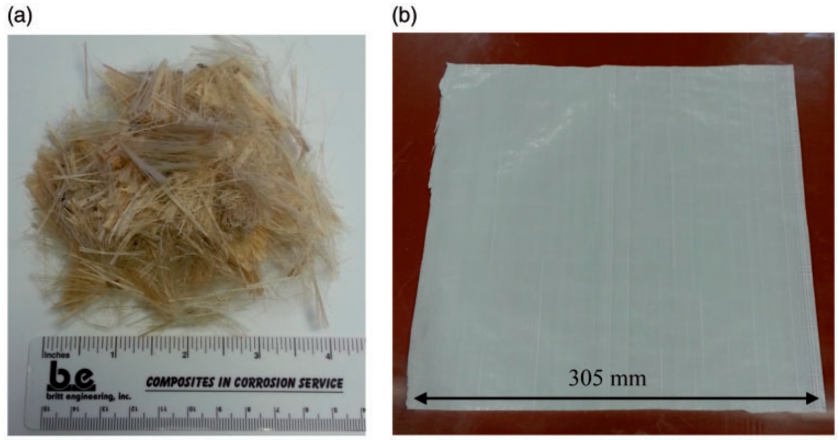

Figure 2. (a) Kenaf fibers and (b) HDPE film used for developing the high performance composite.

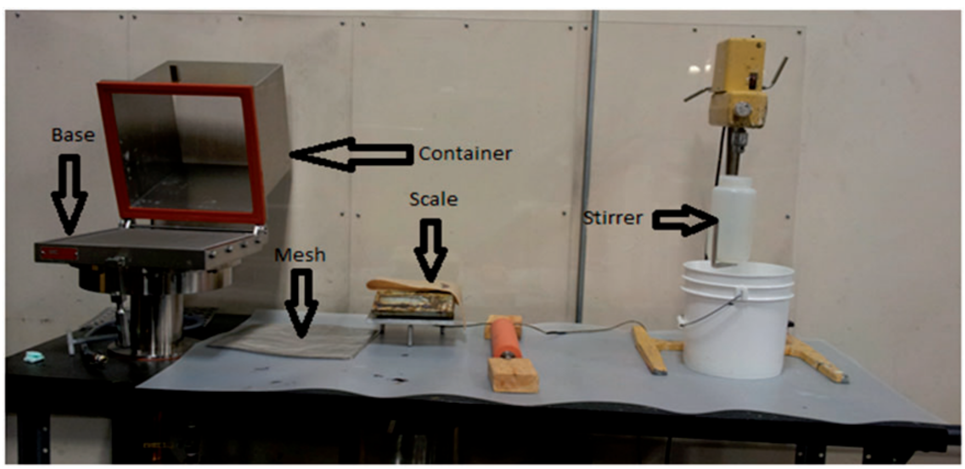

Figure 3. Wet laid apparatus for producing natural fiber mats.

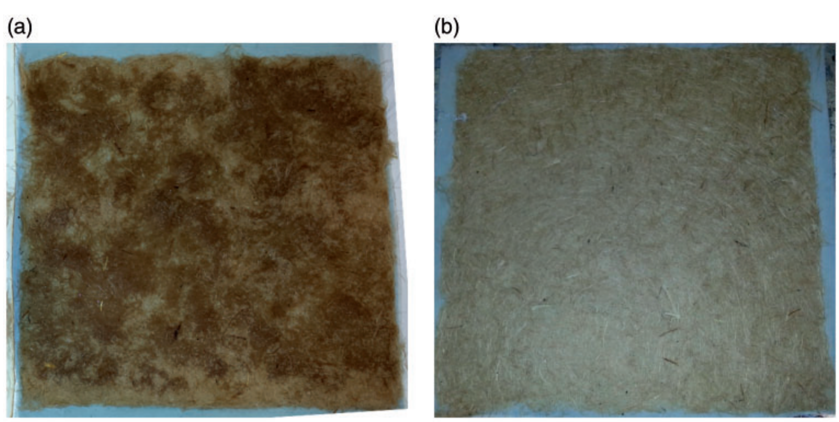

Figure 4. (a) Fiber mat formed from wet laid process; (b) fiber mat after being dried.

The dried kenaf mats and HDPE films were stacked and molded into a kenaf/HDPE composite sample using a hydraulic molding press (Pasadena Hydraulics, Inc.). The fiber loading or fiber weight percentage of the composite sample was controlled by varying the number of the fiber mats and the HDPE films. Normally, two layers of HDPE films are placed between two fiber mats for 40 wt% fiber loading. Figure 5(a) shows the stacked fiber mats and HDPE films in a steel compression mold that has a dimension

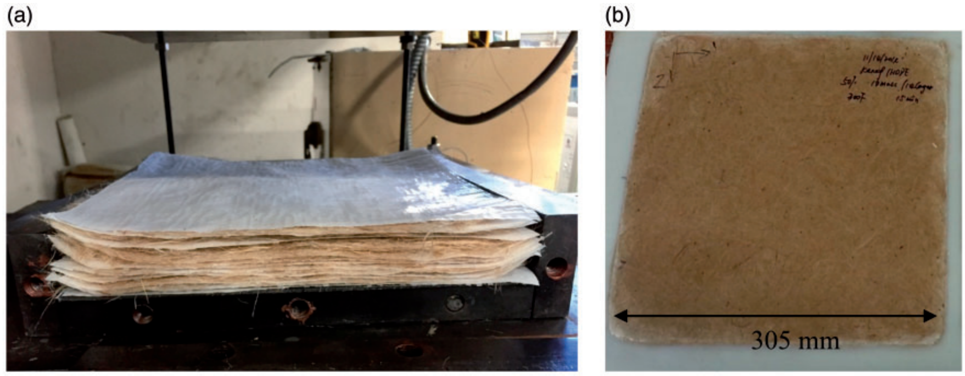

Figure 5. (a) The stacked fiber mats and HDPE films in a 305 mm × 305 mm mold and (b) compression-molded kenaf/HDPE composite sample.

of 305 mm × 305 mm (12 in. × 12 in.). The stack was heated to 150°C and held at that temperature for 15 min with a molding pressure of 1 MPa. The composite sample was demolded after it was cooled down below 40°C. Figure 5(b) shows a compression-molded composite sample with good consolidation.

Results and discussion

There are several parameters, such as fiber length, mat area density, and fiber loading, that can influence the processibility and the mechanical properties of the fiber-reinforced composite at the same time. In this project, the effects of kenaf fibers length, mat area density, and kenaf fiber loading on the processibility in wet laid process and the tensile properties are described below. All of the plates were molded with the processing conditions aforementioned. Tensile testing, one of the most important mechanical tests, has been conducted to compare composites' properties with different variables. Tensile testing was conducted according to ASTM D3039 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. Tabbed specimens were prepared with a dimension of 150 mm × 20 mm and tested at a loading rate of 1 mm/min on a MTS testing frame (MTS Systems Corp.). An extensometer (MTS Systems Corp.) was used to collect strain data to calculate tensile modulus (elasticity of modulus). The strain range between 1000 and 3000 micro strain was used for calculating modulus as specified in ASTM D3039.

Flexural testing was conducted according to ASTM D790 – Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. The flexural specimens have a width of 15 mm and thickness of 2.3 mm. The span length was 40 mm to keep at least 16:1 span length to thickness ratio. The loading rate was 1 mm/min.

Fiber length effect

Fiber length has a great influence on the composite properties and processibility. With increasing fiber length, mechanical properties such as modulus, impact and strength increase normally while their processibility decreases (Figure 1). The length of the kenaf fibers is studied in this project to understand its effect on the processibility and the mechanical properties. The kenaf fibers with three different lengths, 12 mm, 25 mm, and 50 mm, were used for molding composite samples and the properties and the processibility of the composite samples were compared.

It was noticed that fibers with shorter length (12 mm) were dispersed readily, while severe tangling occurred to the fibers with the length of 50 mm during breaking down of fiber bundles using the blender. Manual separation such as combing had to be used to break down the fiber bundles with 50 mm long fibers. In addition to the difficulty of breaking down fiber bundles, inconsistent and inadequate dispersion for the mat was resulted for the 50 mm fibers as shown in Figure 6(a). Figure 6(b) and (c) shows the mats produced with fibers of 25 mm and 12 mm, respectively. Both of them show adequate dispersion and good quality.

Composite samples were molded with all of the three fiber lengths to analyze the fiber length effect on the mechanical properties. Fiber loading (30 wt%) was used for all of the composite samples. The processing parameters (30 wt%, 20 g per mat, and 150°C) were maintained similar for all of the samples. Tensile testing was conducted and the testing results show that the composite sample with 25 mm long fibers has the highest tensile modulus (5.1 GPa) and strength (45.1 MPa) among all of the samples as shown in Figure 7. There is minimal benefit in tensile properties by increasing the fiber length from 25 mm to 50 mm. The benefit of

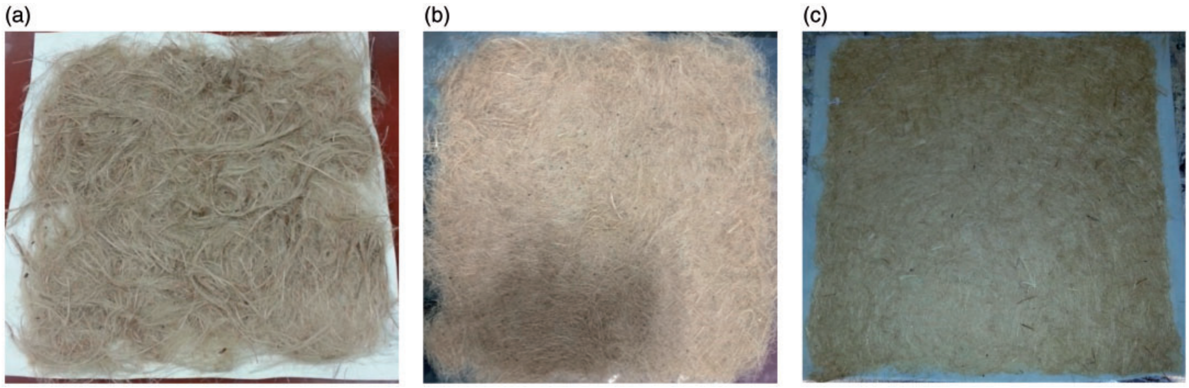

Figure 6. (a) Mat with 50 mm long fiber; (b) mat with 25 mm long fiber, (c) mat with 15 mm long fiber.

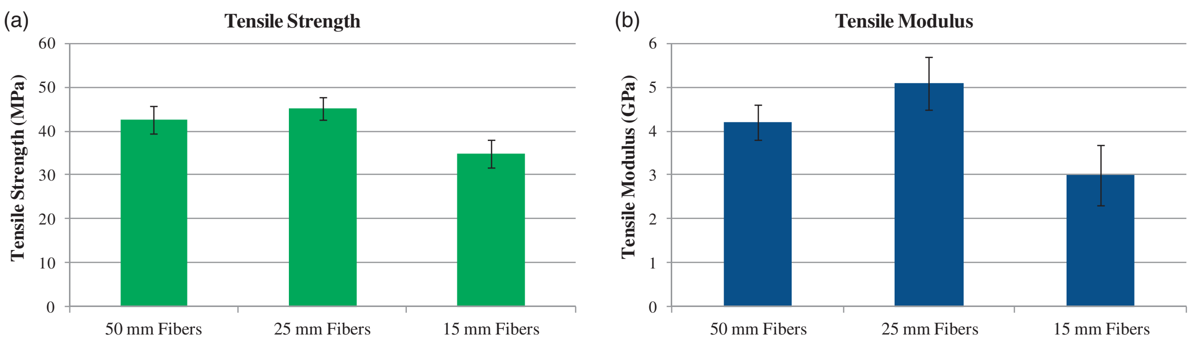

Figure 7. (a) Tensile strength and (b) tensile modulus comparison for the samples with different fiber length (all samples with 20 g mat and 30 wt% fiber loading).

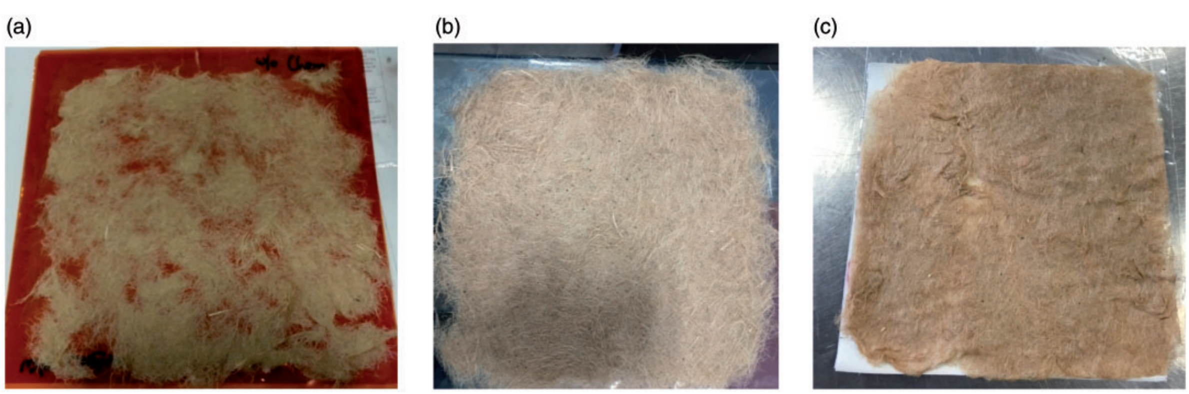

Figure 8. (a) Mat with 5 g fibers; (b) mat with 10 g fibers (c) mat with 20 g fibers.

increased fiber length was compromised by the inconsistent and inadequate dispersion of the fibers.

Area density

The effect of area density of the fiber mat was also studied. Three mat area densities, 54 g/m^2 (5 g per mat in an area of 305 mm $\times$ 305 mm), 108 g/cm^2 (10 g per mat in an area of 305 mm $\times$ 305 mm) and 215 g/cm^2 (20 g per mat in an area of 305 mm $\times$ 305 mm), were processed, and Figure 8 shows the fiber mat with different densities.

It is seen that the 5-g mat does not have adequate fibers to cover the 305 mm $\times$ 305 mm area, while the mats with both 10 and 20 g with 25 mm long fibers result in consistent and good quality. Tensile testing results are compared between the composite samples with 20 g per mat and 10 g per mat (Figure 9). There is more than 12% increase in tensile strength and comparable tensile modulus by decreasing the mat mass from 20 g to 10 g. It is believed that the lower area density results in easier resin penetration during compression molding and therefore better consolidation and wet-out.

Fiber loading

Fiber loading in a composite has a great influence on mechanical properties and processibility. In this study, different fiber loadings, such as 30 wt%, 40 wt%, 50 wt % and 60 wt% fiber loadings, were used to mold the composite samples, and tensile and flexural testing were conducted to compare their properties. Long fibers of 25 mm and a mat mass of 10 g were used based on the studies aforementioned for all of the fiber loadings.

The tensile testing results are compared for the samples with different fiber loadings in Figures 10 and 11. Figure 10 shows that the 40 wt% sample has the highest tensile strength (51.9 MPa) and tensile modulus (6.5 GPa) with minimal standard deviation. Flexural testing results are compared in Figure 11 and it is shown that 40 wt% fiber samples have the highest flexural strength (75.8 MPa) and modulus (4.1 GPa). It should be noted that 60 wt% specimens had delamination during specimen preparation, indicating poor consolidation due to inadequate HDPE matrix. Therefore, flexural testing was not conducted on the 60 wt% sample.

It is clearly seen that the 40 wt% sample shows the highest tensile strength and modulus, and flexural strength and modulus, all of which have less than 8% standard deviation, indicating consistent processing in both of the wet laid process and compression molding process, which is verified by the uniformly distributed kenaf fibers in the micrograph (Figure 12).

Overall, the studies on fiber length, mat area density, and fiber loading have shown that the kenaf/HDPE with 25-mm fiber length, 108 g/cm^2 (10 g per mat), and 40 wt% fiber loading resulted in the highest mechanical properties along with good processibility. The kenaf/HDPE composite samples with these three parameters were prepared for all of the following tests/ measurement below.

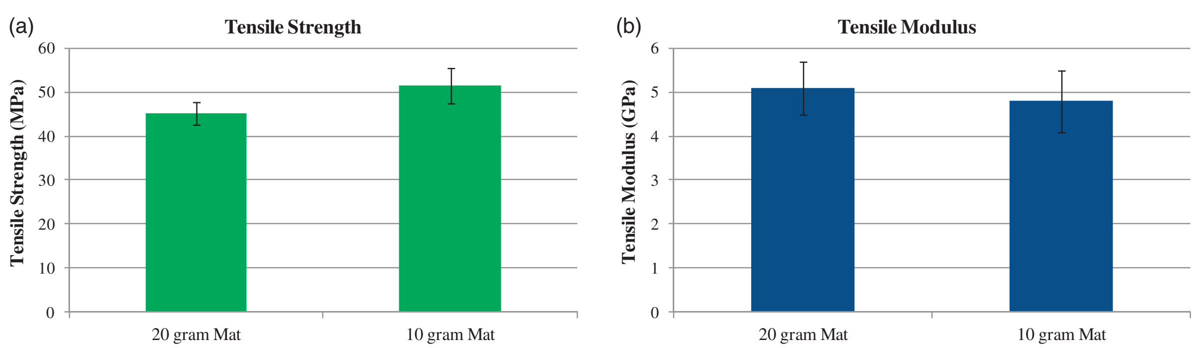

Figure 9. (a) Tensile strength and (b) tensile modulus comparison for samples with different area densities (all samples with 25 mm fibers and 30 wt% fiber loading).

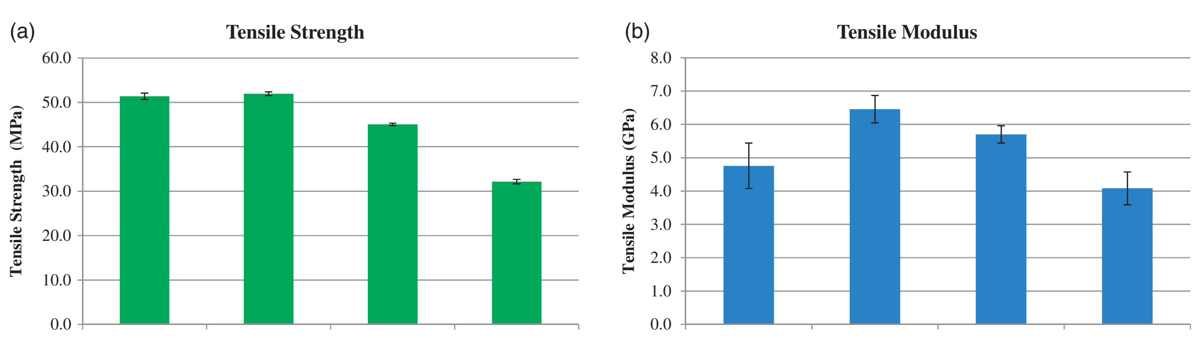

Figure 10. (a) Tensile strength and (b) tensile modulus comparison for the samples with different fiber loadings (all with 25 mm long fibers, 10 g mat).

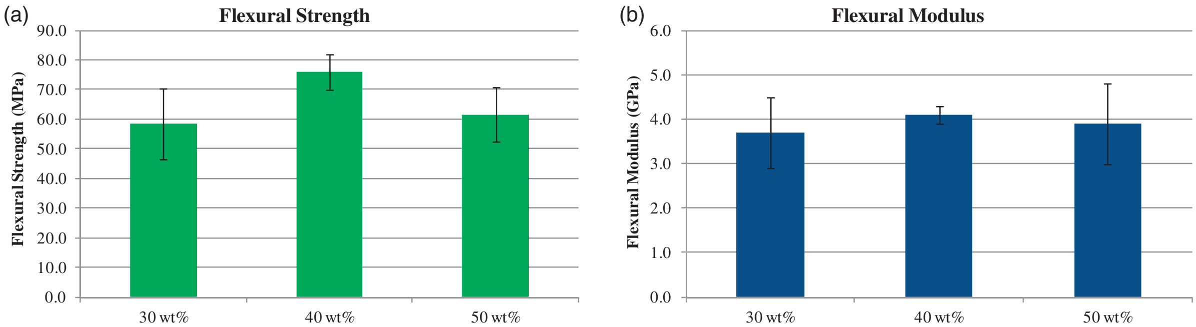

Figure 11. (a) Flexural strength and (b) flexural modulus comparison among 30, 40, and 50 wt% samples (all with 25 mm long fibers and 10 g fiber mat).

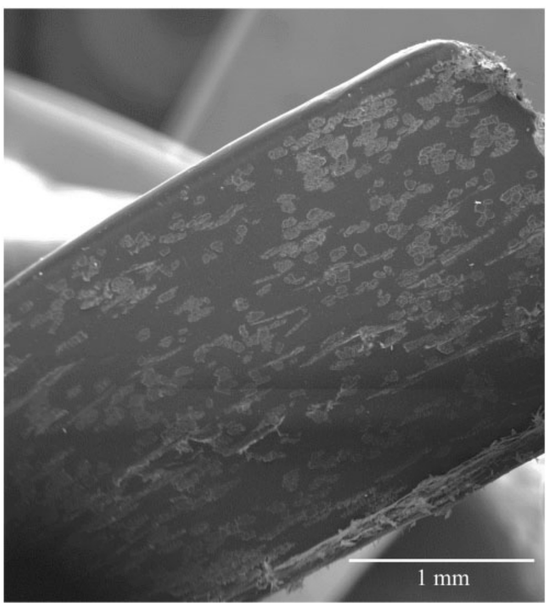

Figure 12. Uniform distribution of the fibers in the kenaf/HDPE composite.

The advantage of the approach used to produce the high-performance kenaf fiber composite is mainly to maintain the fiber length during both of the wet laid process and the compression molding process. Compared to the existing processes such as compounding process and the consequent molding processes such as the injection or compression process, the developed process is able to maintain the fiber length, which in turn results in high mechanical properties such as tensile and flexural strength. Tensile strength of 51.9 MPa and flexural strength of 75.8 MPa were achieved. The tensile strength of the kenaf fiber HDPE composite surpasses those of similar natural fiber composites with HDPE matrix aforementioned.[11,16,17] The standard deviations for the tensile and flexural properties are minimal (less than 8%), indicating the consistency in the fiber distribution and consolidation from this approach. In addition, any chemical treatment on the fibers can be integrated into the wet laid process. The compression molding process might take longer time to reach temperature required to consolidate the composite, IR heating could be used to shorten the heating time and increase the production rate.

Compression testing

Compression testing was conducted based on ASTM D6641 – Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials using a Combined Loading Compression Test Fixture. The same testing frame for tensile testing was used for the compression testing. The specimens with dimension of 140 mm $\times$ 13 mm $\times$ 2.3 mm (Figure 13(a)) were tested with the loading fixture as shown in Figure 13(b). The specimens show typical compression failure in Figure 13(c). The load vs. displacement curve in Figure 13(d) shows gradual compression failure. The compressive strength is averaged to be 39.8 MPa with a minimal standard deviation 2.0 MPa.

Izod impact

Izod impact testing was used to study the impact resistance of the kenaf/HDPE composites according to ASTM D256 – Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics. Ten un-notched and 10 notched specimens with a dimension of 64 mm $\times$ 13 mm were prepared and tested on an Izod impactor (Tinius Olsen Material Testing Machine Company). The impact strength of un-notched specimens is averaged to be 25.4 kJ/m^2 with a standard deviation of 2.4 kJ/m^2. The impact strength of notched specimens is averaged to be 16.8 kJ/m^2 with a standard deviation of 4.5 kJ/m^2. All of the specimens show complete breakage as shown in Figure 14(b).

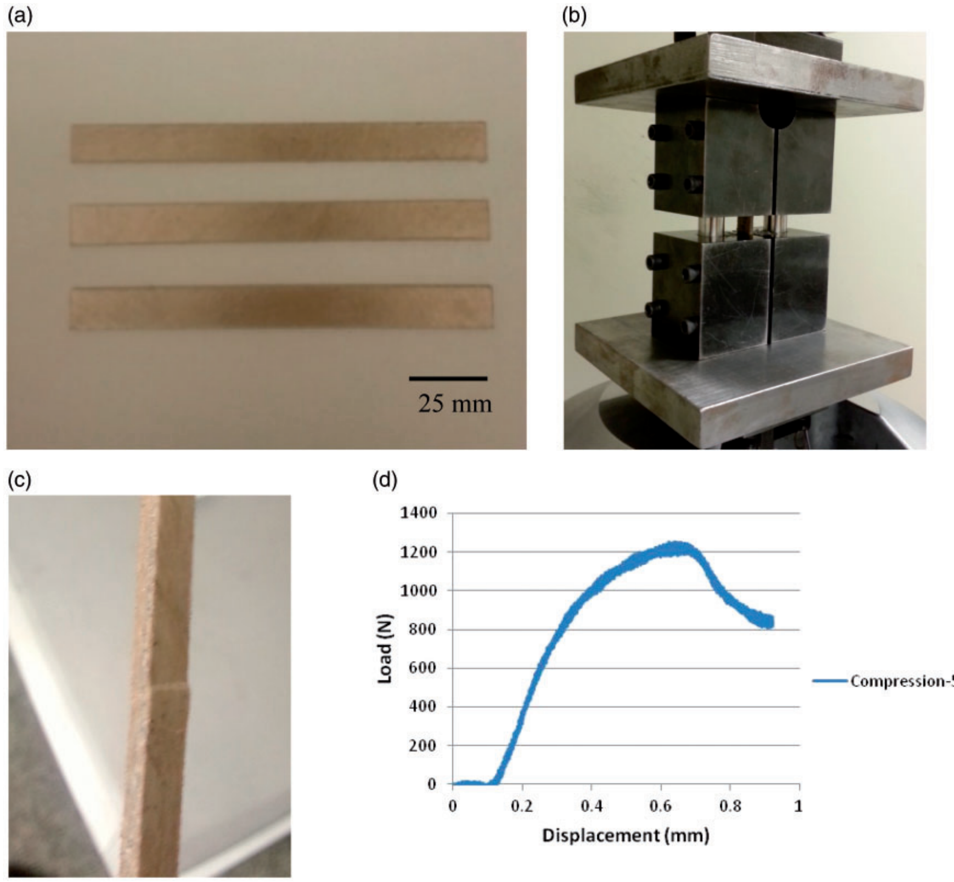

Figure 13. (a) Compression testing specimens; (b) specimen in CLC testing fixture; (c) tested specimen showing compression failure; (d) representative load vs. displacement curve.

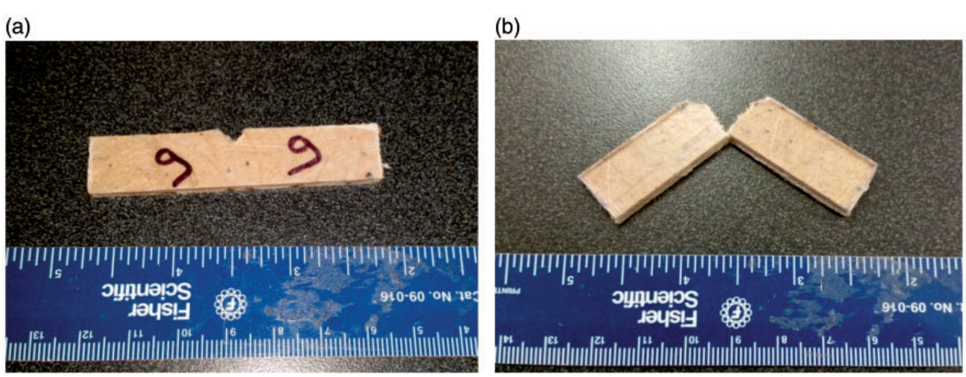

Figure 14. (a) Notched Izod specimen; (b) notched Izod specimen after being tested.

Burn test

Burn testing was conducted according to ASTM D635 Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position. Neat HDPE specimens were also tested for comparison purpose. The specimens were ignited on one end and the time elapsed is recorded when the flame reaches 75 mm mark.

It was noticed that there was considerable dripping from the neat HDPE specimens as shown in Figure 15(a). The dripping is from the molten HDPE during burning, which is normally undesired since it helps spreading fire. No dripping was noticed for the kenaf/HDPE specimens during the burn test. Figure 15 (c) and (d) shows the neat HDPE and kenaf/HDPE specimens after the burn test, respectively. The composite specimen shows obvious charred fibers which

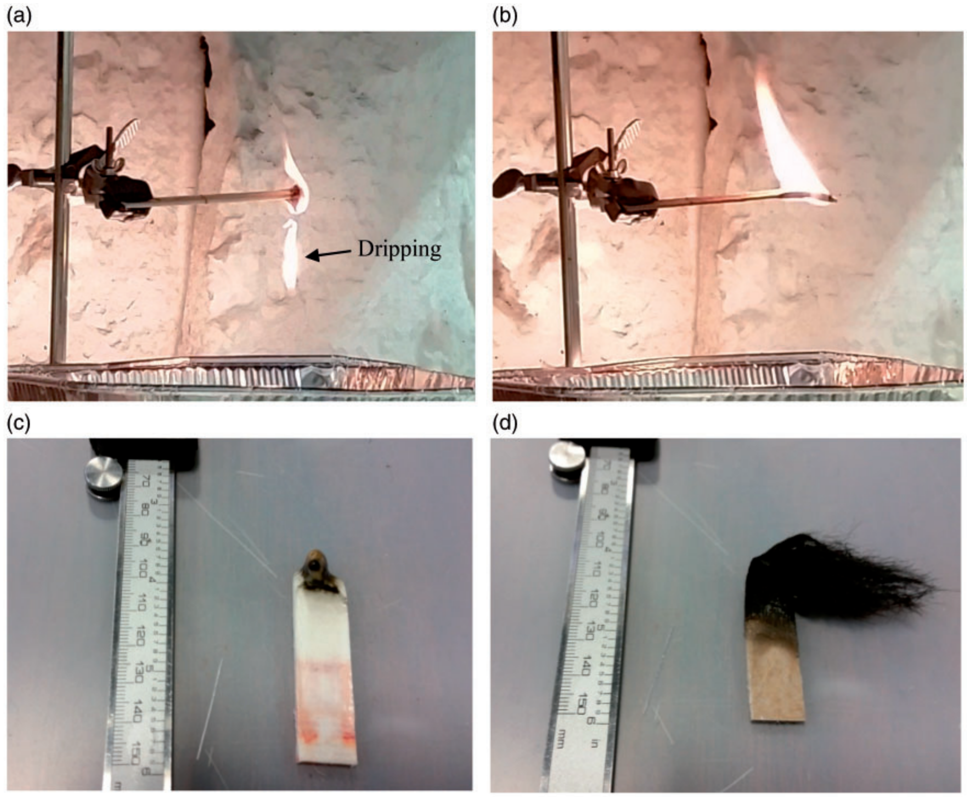

Figure 15. (a) Neat HDPE during burn testing; note the dripping from the molten HDPE; (b) kenaf/HDPE specimen without any dripping during burn test; (c) Neat HDPE after burn test; (d) kenaf/HDPE specimen after burn test; note the charred fibers.

may contribute in preventing any dripping of the HDPE matrix. The burning rate is comparable between the neat HDPE specimen and the kenaf/HDPE composite specimen.

Density measurement

Density of the kenaf/HDPE was measured according to ASTM D792 – Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement. Specimens were dried and immersed in distilled water, and dry mass and wet mass were measured. Temperature of the water was also measured to determine its density. The density of the kenaf/HDPE composite specimens is averaged to be 1.04 g/cm^3 with a standard deviation of 0.02 g/cm^3. The 40 wt% kenaf/HDPE composite sample has an averaged tensile strength of 51.9 MPa and an averaged tensile modulus of 6.5 GPa as aforementioned. Its specific tensile strength and specific tensile modulus are calculated to be 50 MPa/(g/cm^3) and, 6.3 GPa/(g/cm^3), which are comparable to those of 40 wt% discontinuous glass fiber HDPE counterpart,[18] 47 MPa/(g/cm^3) and 6.6 GPa/(g/cm^3), respectively. In addition, the specific flexural properties of the 40 wt% kenaf/HDPE are comparable to those of 40 wt% glass fiber-reinforced HDPE composite.[18]

Conclusions

A lightweight high-performance kenaf/HDPE composite was developed using unconventional processes. Wet laid process was used to produce kenaf fiber mats that are compression molded with HDPE films. The effects of the parameters such as fiber length, mat area density, and fiber loading were studied on the mechanical properties and processibility. It is concluded that the kenaf/HDPE composite with 25 mm fiber length, 108 g/cm^2 (10 g per mat), and 40 wt% fiber loading resulted in the highest tensile and flexural properties along with good processibility. Its performance in compression, flexure, and impact was quantified using ASTM standard test procedures. In addition, burn test and density measurement were conducted to evaluate the kenaf/HDPE composite. The specific tensile and flexural properties of 40 wt% kenaf/HDPE are comparable to those of 40 wt% discontinuous glass fiber HDPE composite.

Acknowledgements

The material donation from CetoTech, Inc. is greatly appreciated.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors would like to acknowledge the financial support from NSF SBIR Program (award number: 1534697).

References

1. Dittenber DB and GangaRao HV. Critical review of recent publications on use of natural composites in infrastructure. *Compos Part A: Appl Sci Manuf* 2012; 43: 1419–1429.
2. Faruk O, Bledzki AK, Fink HP, et al. Biocomposites reinforced with natural fibers: 2000–2010. *Progr Polym Sci* 2012; 37: 1552–1596.
3. Koronis G, Silva A and Fontul M. Green composites: a review of adequate materials for automotive applications. *Compos Part B: Eng* 2013; 44: 120–127.
4. Holbery J, Houston D. Natural-fiber-reinforced polymer composites in automotive applications. *J Miner Metals Mater Soc* 2006; 58: 80–86.
5. Bourguignon M. *Growth, productivity, and utilization of kenaf (Hibiscus cannabinus L.): a promising fiber and fuel crop for Iowa*. Doctoral Dissertation, Iowa State University, USA, 2017.
6. Kamal IB. Kenaf for biocomposite: an overview. *J Sci Technol* 2014; 6: 41–66.
7. Chen Y, Sun L, Chiparus O, et al. Kenaf/ramie composite for automotive headliner. *J Polym Environ* 2005; 13: 107–114.
8. Sullins T, Pillay S, Komus A, et al. Hemp fiber reinforced polypropylene composites: the effects of material treatments. *Compos Part B: Eng* 2017; 114: 15–22.
9. Lu N and Oza S. A comparative study of the mechanical properties of hemp fiber with virgin and recycled high density polyethylene matrix. *Compos Part B: Eng* 2013; 45: 1651–1656.
10. Lu N and Oza S. Thermal stability and thermo-mechanical properties of hemp-high density polyethylene composites: effect of two different chemical modifications. *Compos Part B: Eng* 2013; 44: 484–490.
11. Salleh FM, Hassan A, Yahya R, et al. Effects of extrusion temperature on the rheological, dynamic mechanical and tensile properties of kenaf fiber/HDPE composites. *Compos Part B: Eng* 2014; 58: 259–266.
12. Tajvidi M, Falk RH and Hermanson JC. Time–temperature superposition principle applied to a kenaf-fiber/high-density polyethylene composite. *J Appl Polym Sci* 2005; 97: 1995–2004.
13. Zampaloni M, Pourboghrat F, Yankovich SA, et al. Kenaf natural fiber reinforced polypropylene composites: a discussion on manufacturing problems and solutions. *Compos Part A: Appl Sci Manuf* 2007; 38: 1569–1580.
14. Gassan J and Bledzki AK. Thermal degradation of flax and jute fibers. *J Appl Polym Sci* 2001; 82: 1417–1422.
15. Chawla KK. *Composite materials: science and engineering*. New York, NY: Springer Science & Business Media, 2012.
16. Meon MS, Othman MF, Husain H, et al. Improving tensile properties of kenaf fibers treated with sodium hydroxide. *Proc Eng* 2012; 41: 1587–1592.
17. Aji IS, Zainudin ES, Khalina A, et al. Studying the effect of fiber size and fiber loading on the mechanical properties of hybridized kenaf/PALF-reinforced HDPE composite. *J Reinf Plast Compos* 2011; 30: 546–553.
18. http://web.rtpcompany.com/info/data/0700/RTP707.htm (accessed 5 July 2017).