

Research Article

Mechanical and Morphological Properties of Poly-3-hydroxybutyrate/Poly(butyleneadipate-co-terephthalate)/Layered Double Hydroxide Nanocomposites

Yen Leng Pak,¹ Mansor Bin Ahmad,¹ Kamyar Shameli,^{1,2} Wan Md Zin Wan Yunus,³ Nor Azowa Ibrahim,¹ and Norhazlin Zainuddin¹

¹ Department of Chemistry, Faculty of Science, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

² Nanotechnology and Advance Department, Materials and Energy Research Center, Meshkin-Dasht Road, Karaj 3177983634, Iran

³ Faculty of Defence Science and Technology, National Defence University of Malaysia, Sungai Besi Camp, 57000 Kuala Lumpur, Malaysia

Correspondence should be addressed to Mansor Bin Ahmad; mansorahmad@gmail.com and Kamyar Shameli; kamyarshameli@gmail.com

Received 1 September 2013; Revised 1 November 2013; Accepted 5 November 2013

Academic Editor: Haiqiang Wang

Copyright © 2013 Yen Leng Pak et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Nanocomposites of poly-3-hydroxybutyrate/poly(butyleneadipate-co-terephthalate)/layered double hydroxide (PHB/PBAT/LDH) were prepared from a binary blend of PHB/PBAT and stearate-Zn₃Al LDH via a solution casting method using chloroform as solvent in this study. The pristine Zn₃Al LDH was synthesized from nitrate salts solution at pH 7 by using coprecipitation technique and then was modified by stearate anions surfactant via ion exchange reaction. As a result, the basal spacing of the LDH was increased from 8.77 to 24.94 Å after the modification. Intercalated nanocomposites were formed due to the presence of diffraction peak in XRD diffractograms. The infrared spectrum of stearate-Zn₃Al LDH exhibited the existence of stearate anions in the synthesized Zn₃Al LDH. Mechanical properties with 2 wt% stearate-Zn₃Al LDH loading nanocomposites showed 56 wt% improvements in elongation at break compared to those of the blend.

1. Introduction

Great contributions have been made by introducing polymers into the market to enhance the grade of living and lifestyle. Plastics are being used throughout the world. Plastics are extremely important to the job market especially packaging field. Production of ecofriendly plastics that are more compatible with the environment is needed since plastics created ecological concern due to the lack of deprivation. Therefore, biodegradable plastics began being of sparking interest. Creating of biodegradable materials draw high attention as oil prices increased and they are considered to assist in reducing the waste issue.

Poly-3-hydroxybutyrate (PHB) is produced by controlled bacterial fermentation [1]. It is a high melting temperature and a high degree of crystallinity of semicrystalline polymer. It is not soluble in water and 100% biodegraded. PHB has a few points of weakness that limited its applications such as inefficient and high cost of the fermentation and extraction process, poor mechanical properties, and poor formability. Cracking and brittleness properties of PHB are because of the large spherulites in its structure. Efforts have been made by worldwide researchers to overcome those problems and to improve different properties. The most cost effective and generally used method is blending of PHB with another kind of polymers, [2–5] such as starch, polycaprolactone (PCL),

poly (vinyl acetate) (PVAc), and cellulose derivatives which have been studied to modify the properties and expand its practical application [6–8].

Poly (butylene adipate-co-terephthalate) (PBAT) is eco-friendly polymers which totally biodegraded with the assist of naturally occurring enzymes in a few weeks. It has the same properties as low density polyethylene (LDPE), but with superior mechanical properties. Its excellent physical properties give high flexibility when blended with other biodegradable resins. As a result, PBAT is an excellent candidate for toughening polymers such as poly (lactic acid) and PHBV [9].

Inorganic-organic nanocomposite materials with functional organic compounds immobilized into a layered inorganic matrix have a potential to offer scientific and technological advantages since the organized two-dimensional arrays of organic species between the interlayers can result in novel functions that are different from the typical functions of the individual organic species [10–17].

An electrostatic layer-by-layer assembly technique that employs inorganic nanocomposites as building blocks is a possible means of forming a well-ordered multilayered architecture containing the arrays because the nanocomposites have ultimate two-dimensional anisotropy with nanoscale thickness and microscale length in the plane of sheet [18]. It is known that some smectite clay minerals like montmorillonite, metal phosphates, and layered oxides can be exfoliated into negatively charged nanosheets [19]. In contrast, positively charged nanosheets are a minority among exfoliated nanosheets. Recently, the exfoliation of layered double hydroxides (LDHs) has been studied as a method of preparing such positively charged nanosheets [20]. LDH nanosheets have high potential for being used as building blocks to integrate negatively charged organic molecules into restricted arrays, due to their high stability and compatibility with many functional molecules [21–24].

Layered double hydroxide (LDH) is one of the attractive choices as nanofiller which have significantly improved the physicochemical properties of polymer matrix. In contrast to either neat polymer or the conventional composites, polymer nanocomposites are characterized by improved mechanical, thermal, and barrier properties, reduced gas permeability, and flame retardancy [25–28]. Improvement in properties of the nanocomposites is related to their unique phase morphology that maximizes the interfacial interaction between the well-dispersed nanometer size domains and the matrices. LDH has received world-wide attention because they are useful to be incorporated in many applications, such as catalysis, stabilizer, flame retardant materials, medical materials, adsorbents, ion exchangers, and in environmental chemistry [29].

In this research, our aims are to investigate the influences of stearate-Zn₃Al LDH nanolayers on the tensile properties and morphology of PHB/PBAT blends.

2. Experimental Section

2.1. Materials. Poly [(r)-3-hydroxybutyric acid] was purchased from Sigma-aldrich, Germany, in powder form.

Poly (butylenes adipate-co-terephthalate), PBAT, trade name ECOFLEX, F BX 7011, was supplied by BASF Plastic Technologies, USA. Zinc nitrate (Zn (NO₃)₂·6H₂O) was supplied by Bendosen Laboratory Chemicals, Norway. Aluminium nitrate (Al(NO₃)₃·9H₂O) was supplied by Hmbg Chemicals, Germany. All the chemicals were used as received without further purification process.

2.2. Synthesis of Zn₃Al LDH. The Zn₃Al LDH was synthesized via coprecipitation by adding dropwise a solution of NaOH (1M) into a 250 mL solution of 22.30 g Zn (NO₃)₂·6H₂O and 9.38 g Al (NO₃)₃·9H₂O with the mole ratio of 3 : 1 until pH 7 was obtained. The solution was stirred vigorously under nitrogen atmosphere in order to minimize any contamination of carbonate from the air. At 100 rpm and 70°C, the resulting suspension was shaken for 16 hours. The slurry was filtered and washed several times with deionized water. The Zn₃Al LDH was obtained after being dried at 60°C for 24 hours.

2.3. Preparation of Stearate-Zn₃Al LDH. The stearate-Zn₃Al LDH was prepared by replacing nitrate ions in the LDH layers with stearate ions using the following method. One gram of dry Zn₃Al LDH was dispersed into 1L of 0.003 M sodium stearate solution. The solution was stirred for 24 hours and aged at 70°C in water bath. The slurry was filtered and washed several times with deionized water and dried at 60°C. The dried sample was ground and sieved into particles which were less than 100 micrometer. This chemical modification method already reported by Costantino et al. [30].

2.4. Preparation of PHB/PBAT/Stearate-Zn₃Al LDH Nanocomposites. The nanocomposites of PHB/PBAT blend and stearate-Zn₃Al LDH were prepared by a solution casting method. The blend composition was kept constant (PHB 90 wt% + PBAT 30 wt%) whereas the stearate-Zn₃Al LDH content was varied between 0 wt% and 5 wt%. Desired amount of stearate-Zn₃Al LDH and blend were measured and transferred into 50 mL of choloform. Both mixtures were stirred for 1h, mixed, and stirred for another 1h. The mixture was casted in a petri dish and left in fume cupboard for few days to obtain the sample sheets.

2.5. Characterization Techniques. X-ray diffraction (XRD) measurement for LDHs and nanocomposites were carried out by using Shimadzu XRD 6000 diffractometer at 30 kV and 30 mA with Cu-Kα radiation of the wavelength of 1.5405 nm in 2θ range from 2 to 30°. Fourier-transform infrared (FTIR) spectra of the materials were recorded using a Perkin Elmer Spectrum 1000 series Spectrophotometer equipped with attenuated total reflectance (ATR). The infrared spectra of the samples were recorded in the range of frequency of 400–4,000 cm⁻¹. Scanning electron microscopy (SEM) images were obtained using a Philips XL30 ESEM scanning electron microscope operated at 20 kV. The samples were coated with gold by a Bio-Rad coating system before viewing. Tensile tests were carried out by a Universal Testing Machine, Instron 4302, according to ASTM D638-5. The samples were cut into

dumbbell shape and the average of thickness and width were measured. The average of at least 5 measurements of tensile test was used in calculation.

3. Results and Discussion

3.1. Characterization of Zn_3Al LDH and Stearate- Zn_3Al LDH.

Figure 1 illustrates the XRD patterns for the pristine and stearate- Zn_3Al LDH in the range of 2θ from 2 to 30° . Both LDHs were crystalline in nature with definite and distinct of layered structure. By using Bragg's equation, $n\lambda = 2d \times \sin \theta$, the first diffraction peak from both pristine and stearate- Zn_3Al LDH was used to calculate the basal spacing (d). The clay interlayer spacing was increased from 8.77 Å in pristine LDH (corresponding 2θ value of $\langle 003 \rangle$ peak is 10.08°) to 24.94 Å in stearate- Zn_3Al LDH ($2\theta = 3.54^\circ$) after the modification of pristine LDH with stearate ions. The increase of the basal spacing indicates that the stearate anions were intercalated into the interlayers of LDH successfully [25].

FTIR spectra of the pristine Zn_3Al LDH and stearate- Zn_3Al LDH are exposed in Figure 2. The broad absorption peak observed was at around 3398 cm^{-1} in pristine LDH for O–H stretching of both hydroxide layers and interlayer water molecules [26]. An intense peak observed at 1340 cm^{-1} is due to the asymmetric and symmetric vibration of the nitrate anions in Figure 2(a) [27]. At about 1639 cm^{-1} , the interlayer water of stretching vibration (H–OH) can be obtained. The lattice vibration bands of the M–O and O–M–O (M = Mg or Al) bonding are present at below 800 cm^{-1} region.

At the same time, the stearate- Zn_3Al LDH spectrum (Figure 2(b)) shows the peak at around 2850 and 2917 cm^{-1} which exhibits the C–H stretching vibration due to appearance of the $-\text{CH}_3$ and $-\text{CH}_2$ group in the chain of stearate anions [29]. Carboxylate asymmetric and symmetric stretching is represented by two intense absorption peaks at 1546 cm^{-1} and 1409 cm^{-1} , respectively [31]. It can be concluded that spectrum of the stearate- Zn_3Al LDH and pristine Zn_3Al LDH contains many similar major peaks. Surface morphology of the pristine Zn_3Al LDH and modified stearate- Zn_3Al LDH particles are shown in Figure 3. As shown in Figure 3, the clay is received as porous particles in the existence of the organic anions [26].

3.2. Characterization of PHB/PBAT/Stearate- Zn_3Al LDH.

XRD patterns for pure PHB, pure PBAT, PHB/PBAT blend, and PHB/PBAT/LDH nanocomposites are shown in Figure 4. The peaks obtained in the diffraction patterns of the pure films of PHB and PBAT also appeared in PHB/PBAT blends. The diffraction pattern of polymer blend displayed distinct peaks (2θ) at 13.18° , 16.48° , 19.76° , 21.96° , 25.36° , and 26.90° , which correspond to the (020), (110), (101), (111), (121), and (002) reflections of the orthorhombic crystalline lattice, respectively. The diffraction peaks remain practically unchanged in PHB/PBAT nanocomposites diffractograms can be observed. This observation suggested that the polymer blend crystalline lattice is not modified appreciably in the existence of LDH [32].

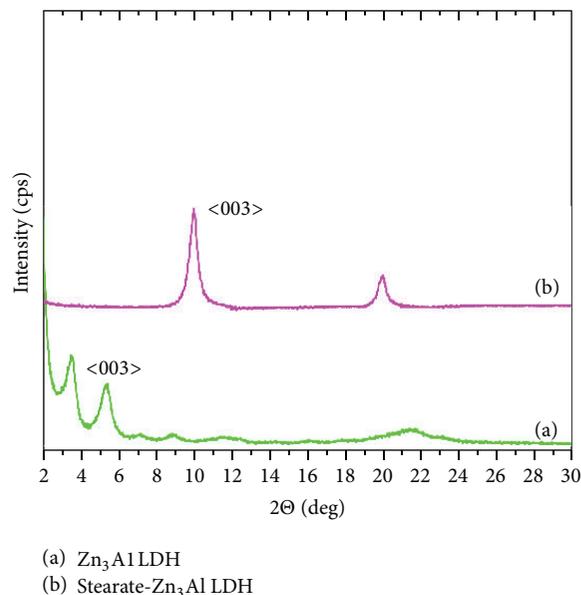


FIGURE 1: XRD pattern of (a) pristine Zn_3Al LDH and (b) stearate- Zn_3Al LDH.

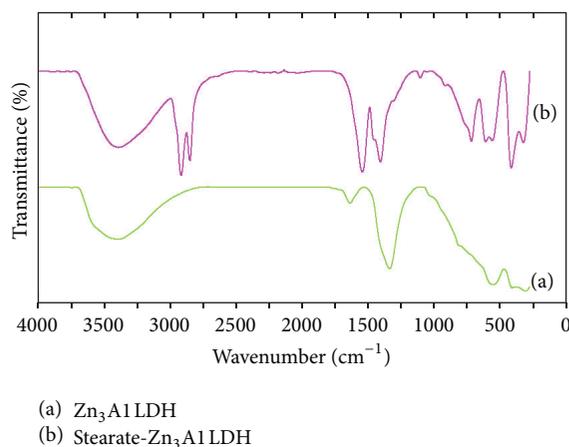


FIGURE 2: FTIR spectra for (a) pristine Zn_3Al LDH and (b) stearate- Zn_3Al LDH.

The presence of the diffraction peak in the PHB/PBAT/LDH nanocomposites with 1.0, 2.0, 3.0, 4.0, or 5.0 wt% of the LDH indicated that the stearate- Zn_3Al LDH layers were completely intercalated in the blend matrix. The interlayer spacings for 1.0, 2.0, 3.0, 4.0, or 5.0 wt% of the LDH in polymer blend were 41.25 Å, 43.70 Å, 40.87 Å, and 40.49 Å, respectively.

The FTIR spectra of PHB, PBAT, PHB/PBAT blend, and PHB/PBAT/stearate- Zn_3Al LDH nanocomposites are shown in Figure 5. The C=O stretching bands of PHB are located at 1719 cm^{-1} , with shoulders at about 1740 cm^{-1} , which are representative of PHB crystalline and amorphous

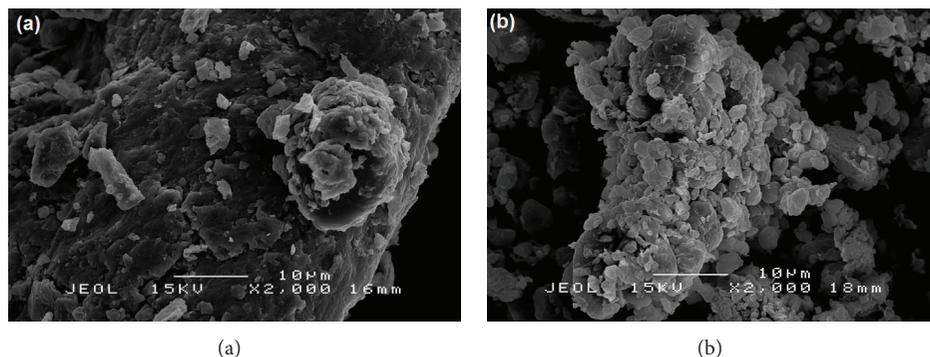


FIGURE 3: Scanning electron micrographs of (a) pristine Zn_3Al LDH and (b) stearate- Zn_3Al LDH.

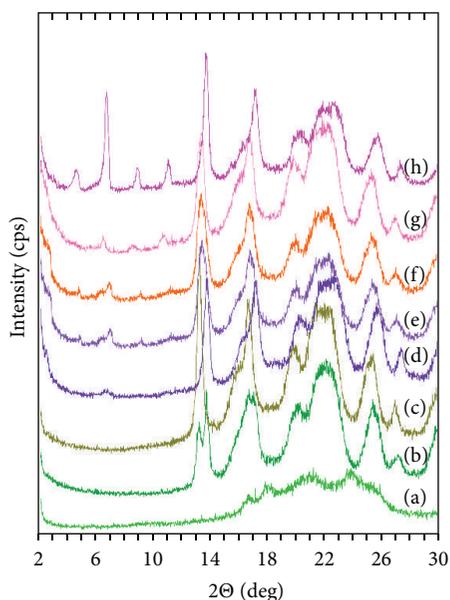


FIGURE 4: XRD pattern for (a) pure PBAT, (b) pure PHB, (c) PHB/PBAT blend, and nanocomposites of 1.0, 2.0, 3.0, 4.0, and 5 wt% of stearate- Zn_3Al LDH (d-h).

zone. Meanwhile, the major peak observed was at 1712 cm^{-1} for C=O stretching and 1475 cm^{-1} for aromatic C=C stretching in PBAT chains. The spectra of PHB/PBAT blend and PHB/PBAT/stearate- Zn_3Al LDH are consistent with the combination of PHB and PBAT. No major peak shifting and no new peak formation in the blend and nanocomposites spectra indicate that there is no strong interaction among PHB, PBAT, and stearate- Zn_3Al LDH.

The tensile properties of PHB, PHB/PBAT blend, and PHB/PBAT/LDH nanocomposites were shown in Figures 6 and 7. The tensile strength of neat PHB was 25.54 MPa and decreased to 23.10 MPa with the addition of 10 wt% of PBAT. The tensile strength decreased again as the PBAT contents increase up to 50 wt%. This observation was shown

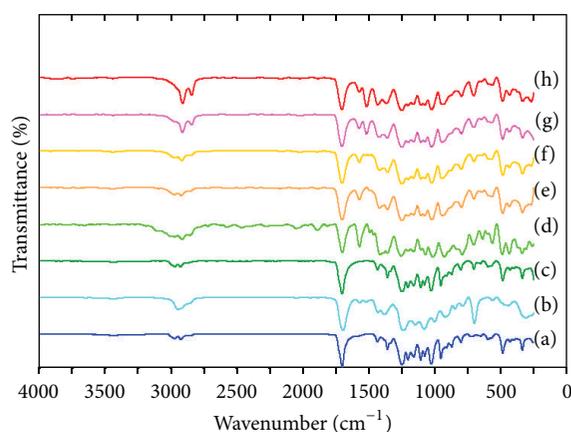


FIGURE 5: FTIR spectra for (a) pure PHB, (b) pure PBAT, (c) PHB/PBAT blend, and nanocomposites of PHB/PBAT with 1.0, 2.0, 3.0, 4.0, and 5 wt% of stearate- Zn_3Al LDH (d-h).

in Figure 6(a). The effect of the amount of PBAT on tensile modulus and elongation at break for PHB/PBAT composites were shown in Figures 6(b)-6(c), respectively. The tensile modulus and elongation at break increased with the loading of 10 wt% of PBAT content as compared to neat PHB. However, they were decreased thereafter as shown in Figures 6(b)-6(c). It was indicated that PBAT is able to enhance the elasticity of PHB. However, incorporation of more than 20 wt% PBAT content deteriorates the properties of the final products. As a result, PHB/PBAT blend with 90/10 ratio was chosen as the best ratio among others.

Figure 7(a) shows that addition of 1 wt% of stearate- Zn_3Al LDH into PHB/PBAT blend decreased the tensile strength to 19.62 MPa. Further increase in the stearate- Zn_3Al LDH decreased the tensile strength too as compared to that blend. The tensile strength for 2.0, 3.0, 4.0, and 5.0 wt% of the LDH in polymer blend was 18.17, 18.13, 18.70, and 19.60 MPa, respectively. It may be due to the extended aggregation of LDH layer into the blend matrix [31]. Figure 7(b) shows

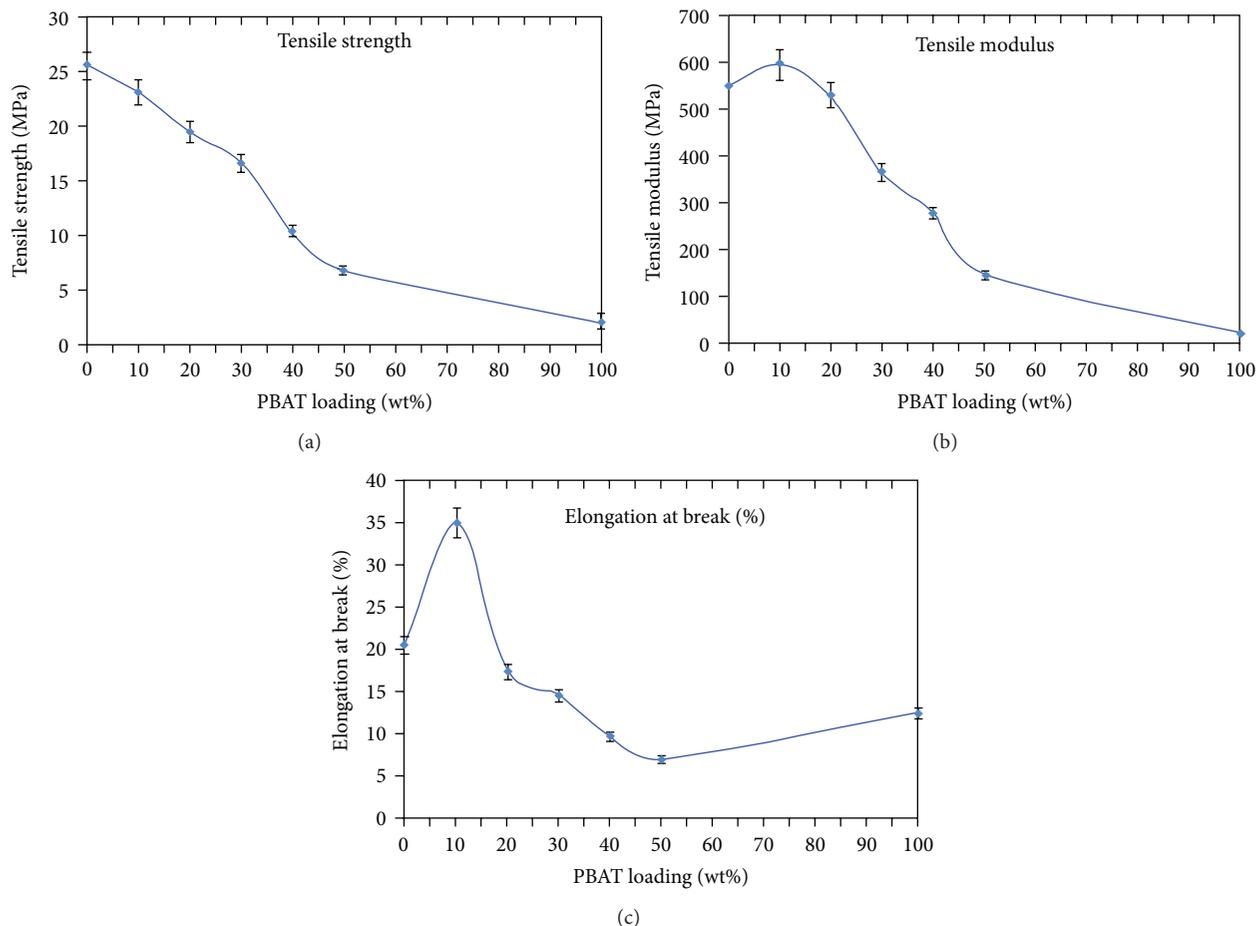


FIGURE 6: Tensile strength, tensile modulus, and elongation at break for PHB/PBAT blends (a–c).

that tensile modulus for nanocomposites also decreased as compared to the blend.

Adding 2.0 wt% LDH into the polymer blend increased the elongation at break from 35.03% up to 54.58%, with an improvement of 56% compared to that of the unfilled PHB/PBAT blend in Figure 7(c). The significant increase in the flexibility of the nanocomposites may be due to the presence of the long chain hydrocarbon parts of stearate anions in the modified LDH that act as a plasticizer. The elongations at break for 1.0, 3.0, 4.0, and 5.0 wt% nanocomposites were 38.55, 25.15, 10.10, and 9.53%, respectively. Decreasing trend of elongation at break can be observed after further addition of 3.0 to 5.0 wt% of LDH. It may be due to the presence of large agglomerates which make the nanocomposites more brittle, decrease of elongation at break consequently.

Figure 8 shows SEM micrographs obtained from the tensile fracture surfaces of PHB/PBAT blend and its nanocomposites containing 2.0 wt% of stearate- Zn_3Al LDH. The image of the fractured surface of the PHB/PBAT blend sample (Figure 8(a)) shows a relatively compact solid surface indicating that the sample is brittle while the images of the 2.0 wt% nanocomposites (Figure 8(b)) show the rough and stretched surfaces which support the reduction of the rigidity of the samples.

The dispersion of stearate- Zn_3Al LDH in the composites was observed by TEM as shown in Figure 9 which presented PHB/PBAT nanocomposites with 2.0 wt% loading of stearate- Zn_3Al LDH. The dark parts of the micrograph were the stearate- Zn_3Al LDH while PHB/PBAT matrix was represented by the clear parts. The TEM images of 2.0 wt% of LDH/PHB/PBAT nanocomposites confirmed that the intercalated silicate layers that were well distributed can be observed in PHB/PBAT as suggested by XRD diffractogram. The figures clearly show that the stack consists of several silicates layers, which indicated the formation of intercalated nanocomposites. The result supported by basal reflection in XRD diffractogram which confirmed the intercalated type of nanocomposites was formed. The TEM image revealed that the LDH layers are in intercalated but not well-ordered structure form and dominantly distributed in the PHB/PBAT matrix.

4. Conclusions

Stearate- Zn_3Al LDH was successfully prepared via ion exchange reaction. The presence of alkyl group in FTIR spectrum indicated that the stearate anions were

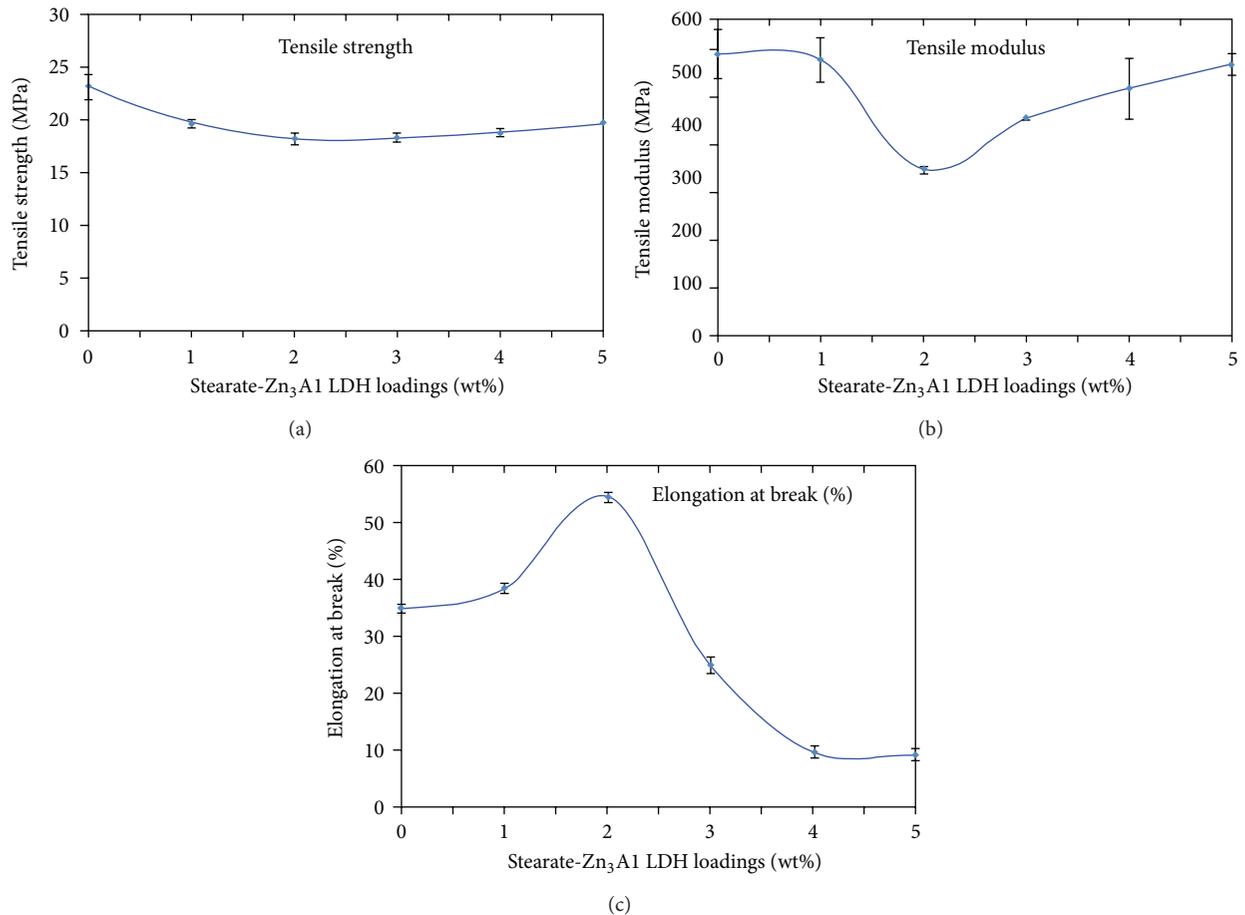


FIGURE 7: Tensile strength, tensile modulus, and elongation at break of PHB/PBAT blends with different stearate-Zn₃Al LDH content (a–c).

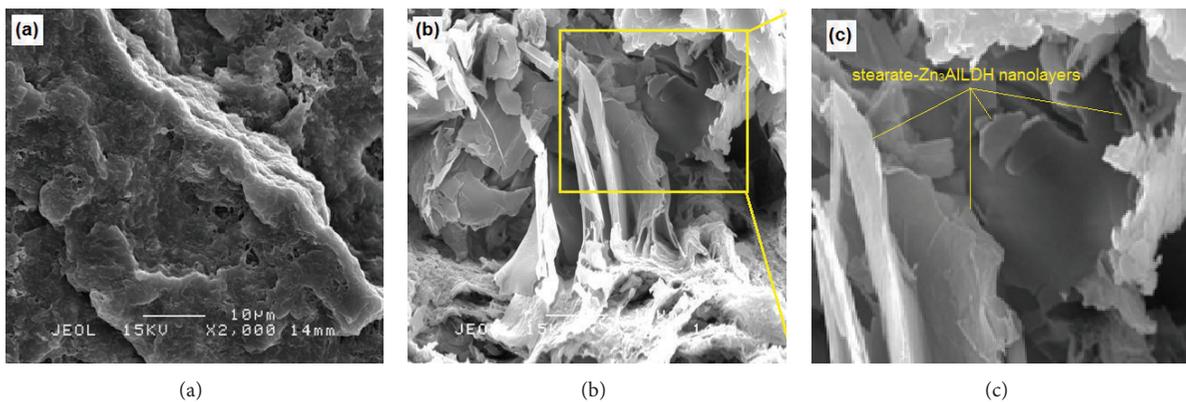


FIGURE 8: Scanning electron micrograph of (a) PHB/PBAT blend and (b, c) 2.0 wt% nanocomposites with low and high resolutions.

successfully intercalated into pristine LDH. The X-ray diffraction (XRD) patterns showed that the basal spacing of stearate-Zn₃Al LDH was higher than that of the pristine LDH. PHB/PBAT nanocomposites were successfully prepared with modified stearate-Zn₃Al LDH through solution casting method. The XRD and TEM showed that the PHB/PBAT/stearate-Zn₃Al LDH formed intercalated

structure as the modified stearate-Zn₃Al LDH content increased thus facilitating better compatibility of PHB/PBAT between the galleries of LDH. Mechanical analyses of nanocomposites showed that adding 2.0 wt% SLDH into the polymer blend increases the elongation at break from 35.03% up to 54.58%, with an improvement of 56% compared to that of the neat PHB/PBAT blend.

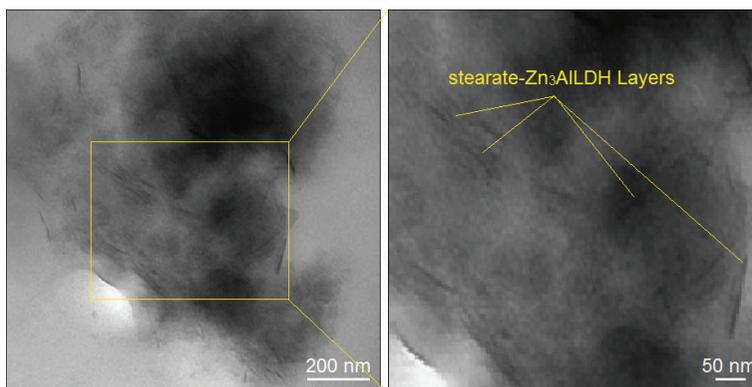


FIGURE 9: TEM micrographs of PHB/PBAT/2.0 wt% stearate-Zn₃Al LDH.

Conflict of Interests

The authors declare that there is no conflict of interests.

Acknowledgments

The authors would like to acknowledge the financial support from the Universiti Putra Malaysia (UPM) (RUGS Project no. 9199840). The authors are also grateful to the staff of the Department of Chemistry UPM and the Institute of Bioscience UPM for the technical assistance.

References

- [1] W. S. Ahn, S. J. Park, and S. Y. Lee, "Production of poly(3-hydroxybutyrate) by fed-batch culture of recombinant escherichia coli with a highly concentrated whey solution," *Applied and Environmental Microbiology*, vol. 66, no. 8, pp. 3624–3627, 2000.
- [2] S. Godbole, S. Gote, M. Latkar, and T. Chakrabarti, "Preparation and characterization of biodegradable poly-3-hydroxybutyrate-starch blend films," *Bioresource Technology*, vol. 86, no. 1, pp. 33–37, 2003.
- [3] L. H. Innocentini-Mei, J. R. Bartoli, and R. C. Baltieri, "Mechanical and thermal properties of poly(3-hydroxybutyrate) blends with starch and starch derivatives," *Macromolecular Symposia*, vol. 197, pp. 77–87, 2003.
- [4] F. Gassner and A. J. Owen, "Physical properties of poly(β -hydroxybutyrate)-poly(ϵ -caprolactone) blends," *Polymer*, vol. 35, no. 10, pp. 2233–2236, 1994.
- [5] D. Lovera, L. Márquez, V. Balsamo, A. Taddei, C. Castelli, and A. J. Müller, "Crystallization, morphology, and enzymatic degradation of polyhydroxybutyrate/polycaprolactone (PHB/PCL) blends," *Macromolecular Chemistry and Physics*, vol. 208, no. 9, pp. 924–937, 2007.
- [6] K. Fukushima, C. Abbate, D. Tabuani, M. Gennari, and G. Camino, "Biodegradation of poly(lactic acid) and its nanocomposites," *Polymer Degradation and Stability*, vol. 94, no. 10, pp. 1646–1655, 2009.
- [7] A. El-Hadi, R. Schnabel, E. Straube, G. Muller, and M. Riemschneider, "Effect of melt processing on crystallization behavior and rheology of poly(3-hydroxybutyrate) (PHB) and its blends," *Macromolecular Materials and Engineering*, vol. 287, pp. 363–372, 2002.
- [8] M. Eili, K. Shameli, N. A. Ibrahim, and W. M. Z. Wan Yunus, "Degradability enhancement of poly(lactic acid) by stearate-Zn₃Al LDH nanolayers," *International Journal of Molecular Sciences*, vol. 13, pp. 7938–7951, 2012.
- [9] M. Yamaguchi and K. Arakawa, "Control of structure and mechanical properties for binary blends of poly(3-hydroxybutyrate) and cellulose derivative," *Journal of Applied Polymer Science*, vol. 103, no. 5, pp. 3447–3452, 2007.
- [10] M. B. Ahmad, K. Shameli, W. M. Z. W. Yunus, N. A. Ibrahim, and M. Darroudi, "Synthesis and characterization of Silver/Clay/Starch bionanocomposites by green method," *Australian Journal of Basic and Applied Sciences*, vol. 4, no. 7, pp. 2158–2165, 2010.
- [11] M. B. Ahmad, K. Shameli, M. Darroudi, W. M. Z. W. Yunus, and N. A. Ibrahim, "Synthesis and characterization of silver/clay nanocomposites by chemical reduction method," *American Journal of Applied Sciences*, vol. 6, no. 11, pp. 1909–1914, 2009.
- [12] M. B. Ahmad, M. Y. Tay, K. Shameli, M. Z. Hussein, and J. J. Lim, "Green synthesis and characterization of silver/chitosan/polyethylene glycol nanocomposites without any reducing agent," *International Journal of Molecular Sciences*, vol. 12, no. 8, pp. 4872–4884, 2011.
- [13] K. Shameli, M. B. Ahmad, S. D. Jazayeri, P. Shabanzadeh, P. Sangpour, and H. Jahangirian, "Investigation of antibacterial properties silver nanoparticles prepared via green method," *Chemistry Central Journal*, vol. 6, no. 1, pp. 1–10, 2012.
- [14] K. Shameli, M. B. Ahmad, E. A. Jaffar Al-Mulla, N. A. Ibrahim, and P. Shabanzadeh, "Green biosynthesis of silver nanoparticles using *Callicarpa maingayi* stem bark extraction," *Molecules*, vol. 17, no. 7, pp. 8506–8517, 2012.
- [15] K. Shameli, M. B. Ahmad, S. D. Jazayeri, and P. Shabanzadeh, "Synthesis and characterization of polyethylene glycol mediated silver nanoparticles by the green method," *International Journal of Molecular Sciences*, vol. 13, no. 6, pp. 6639–6650, 2012.
- [16] K. Shameli, M. B. Ahmad, A. Zamanian et al., "Green biosynthesis of silver nanoparticles using *Curcuma longa* tuber powder," *International Journal of Nanomedicine*, vol. 7, pp. 5603–5610, 2012.
- [17] M. B. Ahmad, J. J. Lim, K. Shameli, N. A. Ibrahim, and M. Y. Tay, "Synthesis of silver nanoparticles in chitosan, gelatin and chitosan/gelatin bionanocomposites by a chemical reducing agent and their characterization," *Molecules*, vol. 16, no. 9, pp. 7237–7248, 2011.

- [18] S. Srivastava and N. A. Kotov, "Composite Layer-by-Layer (LBL) assembly with inorganic nanoparticles and nanowires," *Accounts of Chemical Research*, vol. 41, no. 12, pp. 1831–1841, 2008.
- [19] S. J. Ahmadi, Y. D. Huang, and W. Li, "Synthetic routes, properties and future applications of polymer-layered silicate nanocomposites," *Journal of Materials Science*, vol. 39, no. 6, pp. 1919–1925, 2004.
- [20] T. Hibino and W. Jones, "New approach to the delamination of layered double hydroxides," *Journal of Materials Chemistry*, vol. 11, no. 5, pp. 1321–1323, 2001.
- [21] S. H. Cypes, W. M. Saltzman, and E. P. Giannelis, "Organosilicate-polymer drug delivery systems: controlled release and enhanced mechanical properties," *Journal of Controlled Release*, vol. 90, no. 2, pp. 163–169, 2003.
- [22] J. Zhu, F. M. Uhl, A. B. Morgan, and C. A. Wilkie, "Studies on the mechanism by which the formation of nanocomposites enhances thermal stability," *Chemistry of Materials*, vol. 13, no. 12, pp. 4649–4654, 2001.
- [23] V. Bugatti, U. Costantino, G. Gorrasi, M. Nocchetti, L. Tammaro, and V. Vittoria, "Nano-hybrids incorporation into poly(ϵ -caprolactone) for multifunctional applications: mechanical and barrier properties," *European Polymer Journal*, vol. 46, no. 3, pp. 418–427, 2010.
- [24] A. Szépe, A. Szabó, N. Tóth, P. Anna, and G. Marosi, "Role of montmorillonite in flame retardancy of ethylene-vinyl acetate copolymer," *Polymer Degradation and Stability*, vol. 91, no. 3, pp. 593–599, 2006.
- [25] F. R. Costa, A. Leuteritz, U. Wagenknecht, D. Jehnichen, L. Häußler, and G. Heinrich, "Intercalation of Mg-Al layered double hydroxide by anionic surfactants: preparation and characterization," *Applied Clay Science*, vol. 38, no. 3–4, pp. 153–164, 2008.
- [26] E. Mahboobeh, W. M. Z. W. Yunus, Z. Hussein, M. Ahmad, and N. A. Ibrahim, "Flexibility improvement of poly(lactic acid) by stearate-modified layered double hydroxide," *Journal of Applied Polymer Science*, vol. 118, no. 2, pp. 1077–1083, 2010.
- [27] Y. Ding, Z. Gui, J. Zhu, Y. Hu, and Z. Wang, "Exfoliated poly(methyl methacrylate)/MgFe-layered double hydroxide nanocomposites with small inorganic loading and enhanced properties," *Materials Research Bulletin*, vol. 43, no. 12, pp. 3212–3220, 2008.
- [28] F. Leroux and J. Besse, "Polymer interleaved layered double hydroxide: a new emerging class of nanocomposites," *Chemistry of Materials*, vol. 13, no. 10, pp. 3507–3515, 2001.
- [29] J. Liu, G. Chen, and J. Yang, "Preparation and characterization of poly(vinyl chloride)/layered double hydroxide nanocomposites with enhanced thermal stability," *Polymer*, vol. 49, no. 18, pp. 3923–3927, 2008.
- [30] U. Costantino, F. Marmottini, M. Nocchetti, and R. Vivani, "New synthetic routes to hydrotalcite-like compounds—characterisation and properties of the obtained materials," *European Journal of Inorganic Chemistry*, no. 10, pp. 1439–1446, 1998.
- [31] H.-B. Hsueh and C.-Y. Chen, "Preparation and properties of LDHs/polyimide nanocomposites," *Polymer*, vol. 44, no. 4, pp. 1151–1161, 2003.
- [32] R. M. Da Silva Moreira Thiré, L. C. Arruda, and L. S. Barreto, "Morphology and thermal properties of poly(3-hydroxybutyrate-co-3-hydroxyvalerate)/attapulgite nanocomposites," *Materials Research*, vol. 14, no. 3, pp. 340–344, 2011.



Hindawi

Submit your manuscripts at
<http://www.hindawi.com>

