Penerbit Akademia Baru

Malaysian Journal on Composites Science and Manufacturing

Journal homepage:

https://akademiabaru.com/submit/index.php/mjcsm

ISSN: 2716-6945

A Study of Fracture Toughness Towards Polypropylene Nanoclay Nanocomposites with Different Bamboo Fiber Loading

Mohd Hilmi Othman[1,*], Mohd Ariff Sulor[1], Saliza Azlina Osman[1], Mohd Azhar Harimon[2], Al Emran Ismail[2], Eliza M. Yusup[2], Nuzaimah Mustafa[3], Rokbi Mansour[4], Eko Pujiyanto[5]

[1] Department of Manufacturing Engineering, Faculty of Mechanical and Manufacturing Engineering, University Tun Hussein Onn Malaysia, Parit Raja, 86400 Batu Pahat, Johor, Malaysia

[2] Department of Mechanical Engineering, Faculty of Mechanical and Manufacturing Engineering, University Tun Hussein Onn Malaysia, Parit Raja, 86400 Batu Pahat, Johor, Malaysia

[3] Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia

[4] Department of Mechanical Engineering, University Mohamed Boudiaf of M'sila, 28000, Algeria

[5] Department of Industrial Engineering, Engineering Faculty, University of Sebelas Maret Jln. Ir. Sutami No. 36 A, Surakarta, 57126, Indonesia

ARTICLE INFO

Article history:
Received 17 December 2024
Received in revised form 12 March 2025
Accepted 17 March 2025
Available online 30 March 2025

Keywords:

ABSTRACT

The development of sustainable, high-performance materials is crucial to meet the demands for eco-friendly and durable composites in various industries. Polypropylene nanoclay composites reinforced with natural fibres, such as bamboo, offer a promising alternative due to their improved mechanical properties and environmental benefits. However, the fracture toughness of these polypropylene nanoclay composites with varying bamboo fibre loadings remains insufficiently studied, particularly in terms of how different fibre concentrations impact the material's resistance to crack propagation and overall mechanical integrity under stress. Therefore, this paper was published to elucidate the findings of fracture toughness analysis of polypropylene nanoclay bamboo fibre nanocomposite that consist of 0 wt.%, 3 wt.% and 6 wt.% of bamboo fibre loadings. This research aims to systematically investigate how different bamboo fibre loadings affect the fracture toughness of polypropylene nanoclay nanocomposites. The study will assess the composite's behaviour under fracture and determine the optimal fibre loading for maximizing fracture toughness while maintaining lightweight and eco-friendly characteristics. The sample was moulded by an injection moulding procedure, with compounded samples of polypropylene, bamboo fibre, polypropylene-graft-maleic anhydride (compatibilizer), and nano clay. The optimal injection moulding temperature for the sample was determined using Differential Scanning Calorimetry and Thermogravimetric Analysis. The Mode 1 plane strain fracture toughness was evaluated using the Linear Elastic Fracture Mechanics approach in accordance with ASTM D5045. As for the results, the composite with 6 wt.% bamboo fibre has the highest value of the average fracture toughness with 62.9743 $MPa.m^{1/2}$, as compared with sample of 3 wt.% bamboo fibre, which is 59.6709 $MPa.m^{1/2}$. Meanwhile, the sample without the presence of bamboo fibre has lowest average

* *Corresponding author.*
E-mail address: hilmi@uthm.edu.my

https://doi.org/10.37934/mjcsm.16.1.140149

Fracture toughness; three-point bending test; bamboo fiber; polypropylene; nanoclay

fracture toughness at 43.260 MPa.m$^{1/2}$. In conclusion, the bamboo fibre has proven its potential to be a promising reinforcing agent, and it can be used in any suitable applications, such as automotive components, building materials and packaging solutions.

1. Introduction

Natural fiber such as bamboo fibers, have attracted a lot of interest in the replacement of synthetic fibers because of their low density, vast availability, low cost, and biodegradability. The reason bamboo fibers were selected in the present study is that among the numerous types of renewable natural fibers, bamboo has the fastest rate of growth [1]. The bamboo's cellulose fibers are aligned down to its length, giving it maximum tensile strength, flexural strength, and rigidity in that direction [2]. Bamboo fiber reinforced plastics have mechanical qualities that are equivalent to other regularly used composites like glass fiber reinforced plastics [3]. It was found that bamboo fiber reinforced epoxy composite had a higher tensile strength than jute fiber reinforced epoxy composite in a study that was carried out relatively recently [4]. This material can be employed in areas where carbon fiber and glass fiber-based composites were used [5], because this composite has higher tensile, flexural, hardness, and impact strength than epoxy [6].

The incompatibility of natural fibers with polymer matrices and their low resistance to moisture, on the other hand are often what restrict the potential of natural fibers in the manufacturing of these composites; furthermore, these limitations represent a big concern [7]. However, considering potential applications compared to synthetic fiber composites, such as glass and carbon, it was found that the natural fibers can replace synthetic fibers in existing applications. Direct comparisons between structural characteristics of synthetic fiber (glass and carbon) and natural fiber (flax, jute and hemp) composite structural members have been made experimentally for thin-walled channel sections in compression. It has been shown that natural fiber structural laminates are generally structurally equivalent to their glass fiber counterparts in equivalent fiber mass applications, with regards to compression strength and stiffness [8].

To enhance the properties of these natural fiber composites, the use of polypropylene-graft-maleic anhydride (PPgMA) is a suitable coupling agent and compatibilizer for natural reinforced composites. The maximum weightage concentration of compatibilizing agent needed to improve the composite polymer is more than 10 wt.%, while there is no improvement obtained for the PPgMA when the concentration is higher than 25 wt.% [9]. Adding reinforcement materials like carbon fibers with maleic anhydride improves the strength of polypropylene. The previous work aimed to study the effect of adding maleic anhydride and carbon fibers on the mechanical properties of polypropylene enhanced by presenting carbon fibers. Carbon fibers added at different ratios (0, 2, 4, 6, and 8) % and 1% of maleic anhydride were added to pure polypropylene. It was observed that increasing the carbon fiber content enhanced the tensile strength, modulus of elasticity, and hardness of polypropylene while the elongation decreased, but it enhanced after maleic anhydride addition [10].

The addition of nanoclay in a composite system also had been signified. Research discovered that nanoclay can be well dispersed in epoxy resin composites, and it was possible to strengthen and change the mechanical properties of fiber reinforced polymer [11]. The addition of nanoclay to epoxy, for instance, in amounts less than 10% by weight has provenly improved the mechanical properties such as tensile strength and tensile modulus [12]. Based on a review, with proper preparation and the right formulation, the results of using nanoclay show that several advantages have been obtained, such as improved mechanical properties, and produced a significant increase in thermal stability, as well as self-extinguishing characteristics for flammability, such that the flammability of pristine polymers are significantly reduced after nanocomposite formation with layered silicate [13].

Natural fiber nanocomposite overall properties have improved because of fiber selection, extraction, treatment, and interfacial engineering, as well as composites processing [14]. On top of that, bamboo fiber is one of the most used natural fibers and has significant potential as a reinforcing fiber in polymer composites. Even though bamboo is abundant in most tropical regions, it has not been used to its full potential as a reinforcing agent. Incorporating a comparative analysis of polypropylene nanoclay nanocomposites with different bamboo fiber loadings, alongside other natural and synthetic fibers, would offer valuable insights into the performance advantages and limitations of bamboo fiber. Therefore, this study analyzed the fracture of bamboo fiber suitability as the reinforcing agent.

Furthermore, ss the load applied to the specimen is increased, the crack grows. The resistance to the fracture may be characterized by the stress intensity called fracture toughness. Due to the growing demand for it across a variety of applications, fracture toughness of bio composites is predicted to play a crucial role in the future. When mechanical loading is applied, natural fiber-reinforced epoxy-based composites are typically prone to brittle fracture. A line that runs from one place to another appears at the point of a fissure in a substance. The crack tip has a significant stress concentration. Thus, crack tip analysis is useful for obtaining displacement and stress field. The stress intensity factor (K_{IC}), which is created by combining the two variables into one, simplifies the issue. The fracture toughness values are useful for engineering structures like oil and gas pipelines, nuclear pressure vessels and piping, petrochemical structures, aircraft, ships, and automotive structures in performance evaluation, material characterization, and quality assurance [15].

Despite the promising potential of polypropylene nanoclay composites reinforced with natural fibers, such as bamboo, limited studies have focused specifically on the impact of bamboo fiber loading on the fracture toughness of these composites. While there has been significant research on enhancing mechanical properties like tensile and flexural strength through nanoclay and natural fiber integration, there remains a gap in understanding how varying bamboo fiber content influences the composite's resistance to fracture. Furthermore, the synergistic effects between nanoclay dispersion and bamboo fiber loading on fracture mechanisms are not well understood, especially regarding optimal fiber-matrix adhesion and crack propagation resistance. This gap in the literature highlights the need for a comprehensive study that assesses different bamboo fiber loadings within PP-nanoclay composites, analyzing how these variations affect fracture toughness and identifying the ideal composition for maximum durability. Addressing this gap can advance applications in industries requiring materials with both lightweight and high fracture toughness properties, such as automotive and construction [16-18].

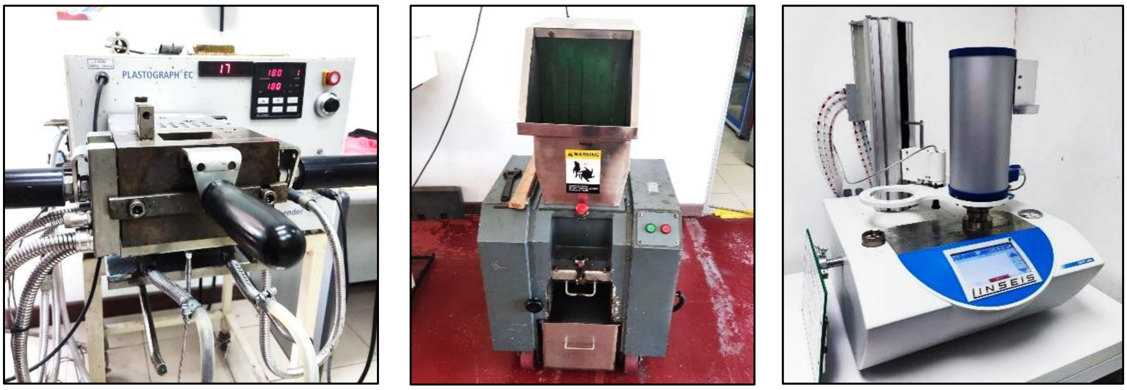
Therefore, this paper was published to elucidate the findings of fracture toughness analysis of polypropylene nanoclay bamboo fiber nanocomposite that consists of 0 wt.%, 3 wt.% and 6 wt.% of bamboo fiber loadings. This research aims to systematically investigate how different bamboo fiber loadings affect the fracture toughness of polypropylene nanoclay nanocomposites. The study will assess the composite’s behavior under fracture and determine the optimal fiber loading for maximizing fracture toughness while maintaining lightweight and eco-friendly characteristics.

2. Methodology

This study began with the mixing processes consisting of polypropylene, bamboo fiber, polypropylene-graft-maleic anhydride, and nano clay by utilizing the Brabender Plastograph as shown in Figure 1(a). This apparatus is located at Polymer and Ceramic Laboratory of Universiti Tun

Hussein Onn Malaysia (UTHM). The formulation used to form all three samples was stated in Table 1. After the compound is mixed, the feedstock is crushed into small pellets using Plastic Granulator SLM 50FY as shown in Figure 1(b). Thermogravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC) are used to determine the optimal temperature for the injection molding process in Figure 1(c), using Linseis Simultaneous Thermal Analyzer (STA) PT 1600. The optimum temperature which is at 170°C is used during the injection molding process by using the Nissei NP7F injection molding machine as shown in Figure 2.

Subsequently, all samples for the PPNCGS were heated to 300°C for TGA and DSC analysis. Melt temperature is set to 170°C, packing pressure is set to 40%, screw speed is set to 30%, and filling time of 3 seconds are the selected as the processing condition for injection molding. Based on previous studies, these four major factors of injection molding processing condition were identified effecting shrinkage, warpage and quality testing of the specimen product through experimental and simulation process [19-23]. Based on the results of Thermogravimetric analysis (TGA) analysis the optimum temperature for the composites to melt for 0 wt.%, 3wt.% and 6 wt.% are 167.2°C, 165.7°C and 164.8°C respectively. So, the recommended range of temperature for the injection molding process is between 170°C to 190°C [24].



(a) (b) (c)

Fig. 1. (a) Brabender mixer (b) Plastic granulator 50FY (c) Linseis STA PT 1600

Table 1
Material formulation for polypropylene nanoclay bamboo fibre nanocomposite

Formulation	0% wt.	3% wt.	6% wt.
Polypropylene	84	81	78
PPgMA	15	15	15
Nanoclay	1	1	1
Bamboo fibre	0	3	6

Fig. 2. Nissei NP7F injection moulding

The sample produced is run to a fracture toughness test using the Universal Testing Machine according to the ASTM D5045 - three-point bending test [25]. ASTM D5045 uses a specific formula to calculate the fracture toughness of a material based on the results of a three-point bend test. The test generally uses single-edge notched bend (SENB) specimens. These geometries are specifically designed to promote a state of plane strain, essential for valid toughness measurements. The parameters for fracture toughness testing are velocity, 2.500 mm/min, breadth, 4 mm, length, 78 mm and width, 10 mm. The formula used to calculate the fracture toughness of the material is known as the "plane-strain fracture toughness," and it is represented by the symbol K_{Ic} [26,27]. The formula for calculating the plane-strain fracture toughness is as the following:

$$K_{Ic} = \frac{3SP}{2tW^2}\sqrt{\pi \mathrm{a}} \cdot F_1(\alpha),\ \alpha = \frac{\mathrm{a}}{W} \quad (1)$$

$$F_1(\alpha) = \frac{1.99 - \alpha(1-\alpha)\left(2.15 - 3.93\alpha + 2.7\alpha^2\right)}{(1+2\alpha)(1-\alpha)^{\frac{3}{2}}} \quad (2)$$

where K_{Ic} is strain fracture toughness in MPa.$m^{1/2,}$ S is supported length in cm, P is applied load in kN, t is specimen thickness, W is specimen width in cm, a is crack length and F_1 (α) is calibration factor determined form ASTM D5045.

3. Results

Fracture toughness is a critical property in material science that measures a material's resistance to crack propagation under applied stress. This analysis is vital for understanding the durability, safety, and performance of materials used in various applications, such as aerospace, automotive, and construction. The fracture toughness of composites, particularly those reinforced with natural fibres like bamboo, jute, and flax, is influenced by factors such as fibre-matrix bonding, fibre orientation, and processing techniques. The results of this study consist of the analysis of fracture toughness and the discussion about the application and recommendation related to this study. This aims to evaluate fracture toughness, comparing it across materials to optimize engineering applications.

3.1 Analysis of Fracture Toughness

The parameter that has been use in this experiment are all same for all the sample. Based on the setting, several results were obtained such as maximum force, maximum stress maximum strain, break force, break stress and break strain. Table 2 shows the measurement of the Single Edge Notch Bending (SENB) specimen. Based on the results in Table 2 shows that the average maximum force for sample 0, 3 and 6 wt.% is 113.719 N, 160.6095 N and 169.50 N respectively. The fracture toughness was calculated according to the Eqs. (1) and (2) that provide from the ASTM D5045 standard specific in three-point bending test experiment. The value of fracture toughness is increasing when the number of weightages of bamboo fibre increase in the sample with the maximum fracture toughness, K_{Ic}, 64.1496 MPa.m$^{1/2}$ for 6 wt.% bamboo fibre sample in the test 3. The value of fracture toughness is influence by the maximum force (P) that were applied to the specimen as shown in the Eq. (1). The lowest maximum stress during the fracture test experiment is shown in the sample 0 wt.% with 41.2396 N/mm^2. Other than that, the value of maximum displacement was increase when the value of maximum force increase. According to the results of fracture toughness, K_{Ic} obtained from the Table 2, it was found that the lowest value of fracture toughness, K_{Ic} was obtained from trial test number 2 for the mixture of 0 wt.% bamboo fiber and the highest value of fracture toughness, K_{Ic} was obtained from trial test 3 for the mixture of 6 wt.% bamboo fiber.

Table 2
Results data based on three point bending test fracture toughness

Sample (bamboo fiber wt.%)	Test	Max force (N)	Max stress (N/m^2)	Max strain (%)	Break force (N)	Break stress. (N/mm^2)	Break strain (%)	Fracture toughness, $\boldsymbol{K_{Ic}}$ (MPa.m$^{1/2}$)	Average fracture toughness, $\boldsymbol{K_{Ic}}$ (MPa.m$^{1/2}$)
0 wt.%	1	116.438	17.466	8.816	102.719	15.41	8.876	43.2600	42.2498
	2	111.00	16.65	6.656	99.313	14.90	6.735	41.2396	
	3	113.719	17.058	7.736	101.016	15.15	7.806	42.2498	
3 wt.%	1	161.313	24.197	10.86	50.156	7.52	14.389	59.9323	59.6709
	2	159.906	23.986	11.03	50.00	7.50	17.801	59.4096	
	3	160.610	24.092	10.94	50.078	7.51	16.095	59.6709	
6 wt.%	1	167.219	25.083	12.98	50.031	7.51	26.321	62.1266	62.9743
	2	168.626	25.294	13.06	50.109	7.53	29.734	62.6493	
	3	172.657	25.898	15.14	53.438	7.62	31.875	64.1469	

The findings shown that the value of fracture toughness, K_{Ic}, will rise if additional bamboo fibre is included in the mix. This condition had satisfied the agreement with the findings from Khan *et al.,* [23] which states that the bamboo fibre reinforced epoxy composite with a fibre length of 25mm has a higher fracture toughness, K_{Ic}value, than the composites with a shorter fibre length. This research also concurred that the fracture behaviour of bamboo fibre-reinforced epoxy composites was influenced by the interfacial bonding between the bamboo fibres and the epoxy matrix. It was also suggested that a proper surface treatment of bamboo fibres and optimizing fibre content significantly influence fracture behaviour [23].

In studying the fracture toughness, tensile strength, and impact resistance of bamboo fibre composites compared to jute, flax, and synthetic fibres like glass and carbon, bamboo fibre composites demonstrate considerable strength with sustainability advantages, yet typically lower performance than glass and carbon fibres in high-stress applications. Natural fibres such as jute and flax have competitive environmental benefits but may lack the durability seen in synthetic options.

Glass and carbon fibres, however, excel in mechanical performance, especially in structural applications, making them challenging to replace where high toughness and strength are needed [28]. As for further assessment, flax fiber composites show fracture toughness values around 2-5 $MPa·m^{1/2}$, jute composites are generally lower, while synthetic glass fibers can exceed 20 $MPa·m^{1/2}$. Bamboo fibers, by their inherent flexibility and strength, with the value of fracture toughness falls between the value of flax and synthetic glass fibers, providing a balance of sustainability and toughness for various engineering applications [8].

The study of fracture toughness in polypropylene nanoclay composites with varying bamboo fiber loadings reveals valuable insights into the role of natural fiber reinforcement in composite materials. Findings indicate that increased bamboo fiber loading enhances fracture toughness, aligning with prior literature that highlights natural fibers' reinforcing properties. For instance, studies by Pickering *et al.,* [29] and Jawaid *et al.,* [30] confirm that natural fibers like bamboo improve toughness through their high cellulose content, which contributes to improved energy absorption during fracture events. Moreover, comparisons to synthetic fiber-reinforced composites, such as glass or carbon fibers, reveal bamboo's benefits in both fracture toughness and environmental sustainability, addressing the demand for eco-friendly composite materials in industrial applications. These results deepen the understanding of how bamboo can serve as a feasible alternative in composites requiring structural durability without sacrificing cost or sustainability.

Further, the correlation between bamboo loading and composite toughness highlights potential pathways for optimizing polypropylene-based composites for various applications, extending existing knowledge on fiber-matrix interactions within hybrid composites. This study's findings could encourage further examination of bamboo fibers' interfacial bonding with polypropylene nanoclay and how different loading percentages affect mechanical performance, contributing to advancements in sustainable composite manufacturing [30].

3.2 Application and Recommendation

The adaptable qualities of natural fibre reinforced polymer composite including polypropylene nanoclay bamboo fibre make them perfect for usage in a wide range of application, from everyday items to more sophisticated and specialized end use [31]. Natural fibre polymer composite is actually already being offered for a variety used, including those in packaging, automotive, medical product, aerospace, sports, road pavement and other industries [32-35]. Polypropylene nanoclay baboo fibre with high fracture toughness is suitable for applications where structural integrity and durability are essential. It can be used in various structural components such as automotive parts, aerospace component and construction material. Fracture toughness is important for consumer goods that may experience impacts or stresses during use. This advanced material can be employed in the production of household appliances, furniture and other consumer products that require enhanced impact resistance and longevity [36].

4. Conclusions

From the ASTM D5045 experiment it is found that the sample with bamboo fibre has better fracture toughness compared to sample without the bamboo fibre. Thus, this proves the potential of bamboo fibre in enhancing the fracture toughness of a composites which is aligned to the objective which is to incorporate environmentally friendly biodegradable Nano clay-bamboo fibres in polymer composites to prove the potential of natural fibres. From the trials, the fracture toughness of nano clay-bamboo fibre is also evaluated, which is a considerably high especially for the 3 wt.% and 6 wt.%.

The result of 6% is found to be higher than 3 wt.% bamboo fibre. The experiment can be further improved for next research. Despite of good fracture toughness obtained, there are necessary improvement required which is to improve the accuracy of data by increasing number of samples for the fracture toughness test and the range of weight percentage of bamboo fibre in the sample should be wider. In conclusion, the bamboo fibre has proven its potential to be a promising reinforcing agent, and it can be used in any suitable applications, such as automotive components, building materials and packaging solutions.

Acknowledgement
This research was supported by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS/2021/TK0/UTHM/02/17) under VOT K371. We would also like to express our gratitude for Universiti Tun Hussein Onn Malaysia (UTHM) for providing both support and motivation.

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