PROGRESS IN ENGINEERING APPLICATION AND TECHNOLOGY
e-ISSN: 2773-5303

PEAT

Vol. 7 No. 1 (2026) 549-557
https://publisher.uthm.edu.my/periodicals/index.php/peat

Natural Weathering Effects on Mechanical and Thermal Properties of Bamboo Cotton Textile Waste Reinforced Recycled Polypropylene Composites for Construction Applications

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DOI: https://doi.org/10.30880/peat.2026.07.01.063

Article Info

Received: 12 January 2026
Accepted: 20 February 2026
Available online: 25 May 2026

Keywords

Bamboo cotton textile waste, recycled polypropylene, reinforced composite, natural weathering, mechanical properties, thermal properties

Abstract

The increasing generation of plastic and textile waste has become a serious environmental issue and has encouraged the development of more sustainable materials. In this study, bamboo cotton textile waste (BCTW) was used as a natural reinforcement in recycled polypropylene (rPP) composites to study the effects of natural weathering on mechanical and thermal properties. The composites were prepared with different BCTW loadings using an internal mixing and compression moulding process, with maleic anhydride grafted polypropylene (MAPP) added as compatibilizer. Natural weathering exposure carried out under outdoor conditions. Prior to weathering, the BCTW were characterized using Fourier Transform Infrared Spectroscopy (FTIR) and Field emission scanning electron microscopy (FESEM) followed by composites testing using differential scanning calorimetric (DSC) to evaluate the initial chemical, morphological and thermal properties. The effects of natural weathering were analyzed based on changes observed in tensile and thermogravimetric (TGA) results. The results show that the addition of BCTW increased the stiffness of the composites while tensile strength showed better performance at moderate fiber contents. Thermal analysis indicated a slight reduction in thermal stability after weathering exposure. Among all formulations, the composite with 15 wt% BCTW shows the most balanced overall performance after weathering. Overall, the findings suggest that bamboo cotton textile waste reinforced recycled polypropylene composites have good potential as sustainable materials for outdoor applications.

1. Introduction

The rapid increase in plastic and textile waste has become a major environmental concern worldwide. Polypropylene (PP) is one of the most commonly used thermoplastic polymers because of its low cost, lightweight nature and good mechanical properties [1]. However, a large amounts of PP waste are generated every year and improper disposal can cause long-term environmental problems. At the same time, textile waste especially from blended fabrics such as bamboo cotton has increased significantly due to fast fashion and limited recycling options [2]. Most of this waste ends up in landfills or is incinerated which leads to resource wastage and environmental pollution.

One possible solution to this problem is the development of polymer composites using recycled polypropylene (rPP) reinforced with natural fibers or textile waste. Bamboo cotton textile waste (BCTW) contains a high amount of cellulose which allows it to act as a reinforcing material in polymer composites [3]. The reinforcement of BCTW into rPP not only helps to improve material stiffness but also reduces the use of virgin polymers and promotes sustainable material development. Compared to single natural fibers, textile waste has a more complex structure due to its woven or knitted form, surface treatments and yarn arrangement which can affect fiber-matrix interaction and overall composite performance [4].

Despite these advantages, bamboo and cotton fibers are naturally hydrophilic which causes them to absorb moisture easily. This can lead to swelling and weak interfacial bonding when combined with hydrophobic polymer matrices such as polypropylene [5]. These issues become more serious when the composites are used in outdoor environments. Natural weathering exposes materials to ultraviolet (UV) radiation, humidity, rainfall and temperature changes. In polypropylene-based composites, UV exposure can cause photo-oxidation and chain scission while moisture absorption of the textile fibers can weaken the fiber-matrix interface and reduce mechanical strength over time [6].

To improve compatibility between the natural fibers and the polymer matrix, maleic anhydride grafted polypropylene (MAPP) is commonly used as a compatibilizer. The anhydride groups in MAPP can react with the hydroxyl groups on the fiber surface can lead to better interfacial adhesion and stress transfer [7,8]. Many studies have shown that the use of MAAPP improves the mechanical properties of natural fiber reinforced PP composites [9]. However, there are limited studies focusing on bamboo cotton textile waste reinforced recycled PP composites especially under natural weathering conditions.

Most existing studies focus on virgin PP or single natural fibers and use accelerated aging methods rather than real outdoor exposure. As a result, the combined effects of recycled PP, textile waste reinforcement, compatibilizer and natural weathering are still not well understood. Therefore, this study aims to investigate the effects of natural weathering on the mechanical and thermal properties of bamboo cotton textile waste reinforced recycled polypropylene composites. The findings from this study are expected to provide useful information on the durability and potential application of these sustainable composites for outdoor use.

2. Methodology

The methodology section provides a detailed description of the study.

2.1 Materials and Chemicals

Recycled polypropylene (rPP) was used as the polymer matrix in this study while bamboo cotton textile waste (BCTW) was used as the reinforcing material. Maleic anhydride grafted polypropylene (MAPP) was added as a compatibilizer to improve the interfacial bonding between the hydrophilic textile fibers and the hydrophobic rPP matrix. Sodium hydroxide (NaOH) was used for fiber surface treatment. All materials were used as received unless stated otherwise.

2.2 Preparation of Bamboo Cotton Textile Waste

The bamboo cotton textile waste was first cleaned to remove dust and surface impurities then dried in an oven to remove moisture. The dried textile waste was cut into small pieces to ensure better dispersion during mixing. An alkaline treatment was carried out by soaking the textile waste in a 5% sodium hydroxide (NaOH) solution for a 3 hours to remove surface impurities such as waxes and hemicellulose. After treatment, the fibers were thoroughly washed with distilled water until neutral pH was achieved and then dried again before composite fabrication.

2.3 Composite Formulation

Composite compositions and designation of materials in this study is shown in Table 1. The addition of bamboo cotton textile waste fibers is in the range of 5 – 25 wt% of BCTW/MAPP/rPP.

Table 1 *Designation of BCTW-rPP composites with MAPP*

Sample	Designation (%)	rPP (wt%)	BCTW (wt%)	MAPP (wt%)
rPP/BCTW Fiber 5	H/BC/5	90	5	5
rPP/BCTW Fiber 10	H/BC/10	85	10	5
rPP/BCTW Fiber 15	H/BC/15	80	15	5
rPP/BCTW Fiber 20	H/BC/20	75	20	5
rPP/BCTW Fiber 25	H/BC/25	70	25	5

2.4 Composite Fabrication

The rPP, treated BCTW and MAPP were melt-mixed using an internal mixer at 180 °C temperature and 60 rpm rotational speed. Different fiber loadings of 5, 10, 15, 20 and 25 wt% were prepared to study the effect of reinforcement content. After mixing, the compounded materials were crushed into smaller granules and compression moulded into flat sheets using a compression moulding machine at 190 °C. Standard test specimens were then cut from the moulded sheets using a laser cutting machine.

2.5 Natural Weathering Exposure

Natural weathering exposure was conducted by placing the composite specimens outdoors under real environmental conditions at Pagoh student residential college . The samples were exposed for a fixed duration of 10 days during which they were subjected to natural sunlight, humidity, rainfall and temperature fluctuations. This exposure was intended to simulate real outdoor service conditions and evaluate the durability of the composites. Table 2 shows the samples composites use for the weathering exposure.

Table 2 *Designation of controlled and weathered BCTW-rPP composites with MAPP*

Conditions	Composites	Designation (%)
Controlled	rPP/BCTW	H/BC/5
		H/BC/15
		H/BC/20
Weathered	rPP/BCTW	H/BC/5
		H/BC/15
		H/BC/20

2.6 Characterization and Thermal Analysis Before Weathering

Fourier transform infrared spectroscopy (FTIR) was conducted on unweather treated BCTW to identify the functional groups present and evaluate fiber in the range of 4000-500 cm^{-1} with a resolution of 4 cm^{-1}. Field emission scanning electron microscopy (FESEM) was used to observe the surface morphology and dispersion of treated BCTW. Differential scanning calorimetry (DSC) analysis was carried out using a heating rate of 10 °C min^{-1} under a nitrogen atmosphere and were heated from 30 °C to 200 °C to determine the thermal transition behavior including melting temperature and degree of crystallinity before weathering exposure.

2.7 Mechanical Testing

Tensile testing was carried out using a universal testing machine (UTM) according to ASTM D638. The tests were performed at room temperature using a crosshead speed of 10 mm min^{-1}. Tensile test were conducted for both unweather and weathered samples.

2.8 Thermal Stability Analysis

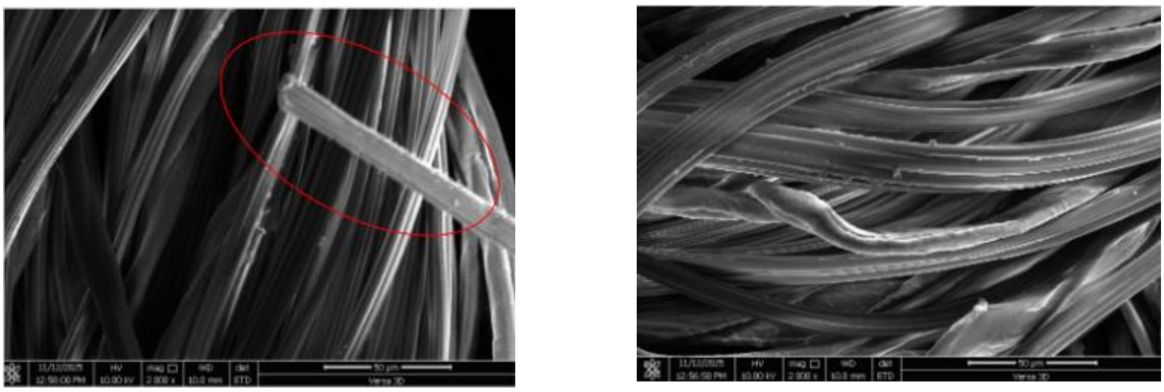
Thermogravimetric analysis (TGA) was conducted on both unweather and weathered composites to assess changes to evaluate changes in thermal stability due to natural weathering. The samples were heated from 30 °C to 600 °C at a heating rate of 10 °C min^{-1}.

3. Results and Discussion

This chapter discussed the results of testing described earlier in Chapter 2.

3.1 Characterization of Bamboo Cotton Textile Waste (BCTW) Fibers

The surface morphology of BCTW fibers is significantly affected by alkali treatment. FESEM images at Fig. 1 show that untreated fibers exhibit a smooth and compact surface due to the presence of non-cellulosic components such as lignin, hemicellulose and wax whereas alkali-treated fibers display a rough and irregular surface with exposed microfibrils and fiber bundle separation. Similar observations have been reported by [10]. The removal of non-cellulosic components during alkali treatment increases surface roughness and effective surface area which improves the mechanical interlocking and stress transfer at the fiber-matrix interface. However, bubble-like features observed on treated fibers suggest possible residual NaOH due to insufficient rinsing which may lead to surface damage or fiber embrittlement if not properly controlled. Therefore, controlled alkali treatment effectively improves the interfacial bonding potential and dispersion of BCTW fibers in polymer composites while excessive treatment or poor washing may negatively affect composite performance.



(a) **(b)**

Fig. 1 *(a) untreated BCTW fiber, (b) treated BCTW fiber*

3.2 Chemical Composition and Functional Groups of Bamboo Cotton Textile Waste

Fourier Transform Infrared (FTIR) spectroscopy was used to identify the chemical functional groups present in the fibers. It confirms that alkali treatment significantly modifies the surface chemistry of BCTW fibers. The FTIR spectra at Fig. 2 show a broad O-H stretching band at 3330-3400 cm^{-1} in both untreated and treated fibers with reduced intensity after NaOH treatment along with decreased C-H stretching peaks at 2850-2920 cm^{-1} with a significantly diminished C=O peak at ~1730 cm^{-1}, reduced lignin-related aromatic peaks at 1500-1600 cm^{-1} and sharper cellulose-related C-O and C-O-C peaks at 1000-1200 cm^{-1}. The reduction in O-H intensity shows that partial removal of hemicellulose and surface-bound moisture, lowering fiber hydrophilicity and improve the compatibility with hydrophobic polymer matrices while the decrease in C-H and carbonyl peaks confirms the removal of surface waxes hemicellulose. The partial lignin removal exposes cellulose microfibrils to enhance the fiber-matrix adhesion without compromising structural rigidity and the sharpening of cellulose peaks suggest increased crystallinity due to elimination of amorphous components [10]. Therefore, alkali treatment effectively optimizes the chemical structure of BCTW fibers by reducing hydrophilicity, increasing surface cleanliness and crystallinity and improve the interfacial bonding potential and durability in polymer composite applications.

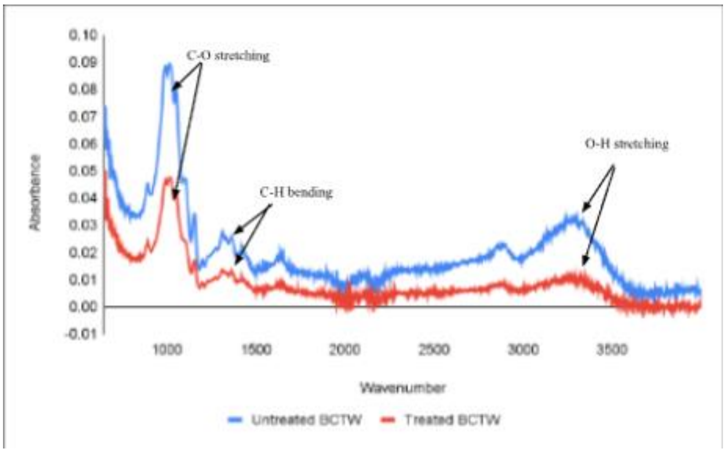


Fig 2 *FTIR analysis of untreated and treated BCTW*

3.3 Thermal Transitions

The samples undergo differential scanning calorimetry (DSC) analysis only before weathering test to measure the heat flow into or out of a sample versus temperature/time to detect physical/chemical changes like melting, curing or glass transitions, revealing material properties such as crystallinity, stability and purity.

Table 3 *DSC data of unweathered rPP and BCTW-rPP composites*

Sample	Melting point, T_m (℃)	Heat of Fusion (J/g)	Degree of Crystallinity (%)
rPP	121.88	57.35	46.1
rPP/BCTW/5	122.17	65.13	31.2
rPP/BCTW/15	122.14	59.19	28.3
rPP/BCTW/25	122.03	36.52	17.5

DSC analysis in Table 3 indicates that the addition of BCTW fibers and MAPP influence the crystallization behaviour of rPP without completely altering its melting characteristics. Neat rPP exhibits a melting temperature of 121.88 °C while rPP/MAPP/BCTW composites show only a slight increase to 122.03-122.17 °C alongside changes in heat of fusion (ΔHf) and degree of crystallinity as summarize in Table 3. The minimal change in melting temperature confirms that the crystalline structure and crystal type of polypropylene remain stable after fiber and with MAPP compatibilizer primarily improves the fiber-matrix adhesion rather than altering PP crystallinity. At low to moderate BCTW contents (5-15 wt%), ΔHf and crystallinity increase due to improved dispersion and improves compatibility and the heterogeneous nucleation effect of natural fibers facilitated by MAPP [11,12]. In contrast, a higher fiber loading (25 wt%), ΔHf and crystallinity decrease as excessive fibers restrict polymer chain mobility and disrupt chain regularity by limiting crystal growth despite the presence of MAPP [13].

3.4 Environmental Weathering Conditions During Exposure Period

Table 4 *Weathering conditions data for 10 days*

Days	Day / Night	Temperature (°C)	Humidity (%)	Remarks
Day 1	Day	31.11	70	Cloudy
	Night	25	94	Clear
Day 3	Day	31.11	66	Clear
	Night	25	94	Clear
Day 5	Day	31.11	70	cloudy
	Night	25	94	Clear
Day 7	Day	28.89	74	Rainy
	Night	25	94	Clear
Day 10	Day	28.89	74	Rainy
	Night	25	94	Clear

Table 4 shows the weather conditions during the weathering exposure period at selected intervals (Day 1, 3, 5, 7 and 10) with both day and night cycles. During the daytime, temperatures ranged between 28.89°C and 31.11 °C with relative humidity values between 66% and 74%. The daytime weather varied from cloudy to rainy where it may influence moisture absorption and surface degradation of the samples.

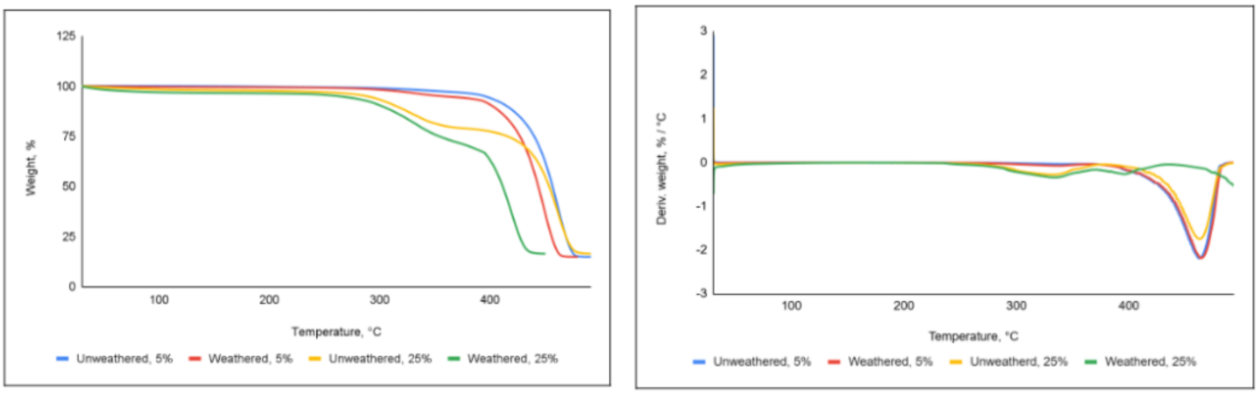
At night, the temperature remained constant at 25°C with consistently humid nighttime environment can introduce moisture diffusion and accelerate weathering-related effects especially for hydrophilic materials. Overall, the combination of temperature variation, high humidity and alternating weather conditions provides realistic outdoor weathering conditions that can significantly affect the mechanical and thermal properties of the composites.

3.5 Thermal Properties of Bamboo Cotton Reinforced Composites

Thermogravimetric analysis (TGA) demonstrate that fiber loading and weathering can influence the thermal stability of rPP/MAPP/BCTW composites.

TG curves as shown in Fig. 3(a), all composites exhibit a similar degradation trend with minimal weight loss at lower temperatures followed by rapid degradation at higher temperatures, consistent with polypropylene-based natural fiber composites [11]. The unweather 5 wt% BCTW composite shows good thermal stability with negligible weight loss until approximately 350 °C where the rPP matrix dominates thermal behaviour and that effective fiber-matrix bonding with MAPP delays the degradation onset [10]. In contrast, the unweather 25 wt% BCTW composite begins degrading at lower temperatures due to the higher proportion of thermally unstable lignocellulosic components such as hemicellulose and cellulose and possible fibre agglomeration that reduces the effectiveness of MAPP [11,14]. After 10 days of weathering, both composites exhibit earlier degradation as a result of photo-oxidative chain scission of the rPP matrix and interfacial weakening caused by UV exposure and oxygen [15]. The weathered 25 wt% BCTW composite shows the greatest reduction in thermal stability due to increase moisture absorption, fiber degradation and interfacial microcrack formation which effect the heat penetration during TGA [13]. Therefore, lower BCTW loading combined with MAPP compatibilizer results in more effective interfacial stability and thermal resistance.

Next, DTG analysis reveals that fiber loading and weathering can affect the thermal degradation behaviour of the composites. As shown in Fig. 3(b), all samples shows a dominant degradation peak at higher temperatures associated with rPP matrix decomposition with noticeable variations in peak position and width depending on BCTW content and weathering condition (Sanjay et al., 2018). The unweather 5 wt% BCTW composite shows a sharp and narrow DTG peak at a higher temperature where it show more uniform degradation and higher thermal resistance due to improved fiber-matrix interaction with MAPP compatibilizer [10,16]. In contrast, the unweather 25 wt% BCTW composite shows a broader DTG peak at a slightly lower temperature, reflecting overlapping degradation. After weathering, both composites show a shift of the main DTG peak toward lower temperatures. Therefore, lower BCTW loading results in higher peak degradation temperatures and more controlled thermal degradation while higher fiber content increases thermal instability and broadens the degradation range consistent with previous findings [16].



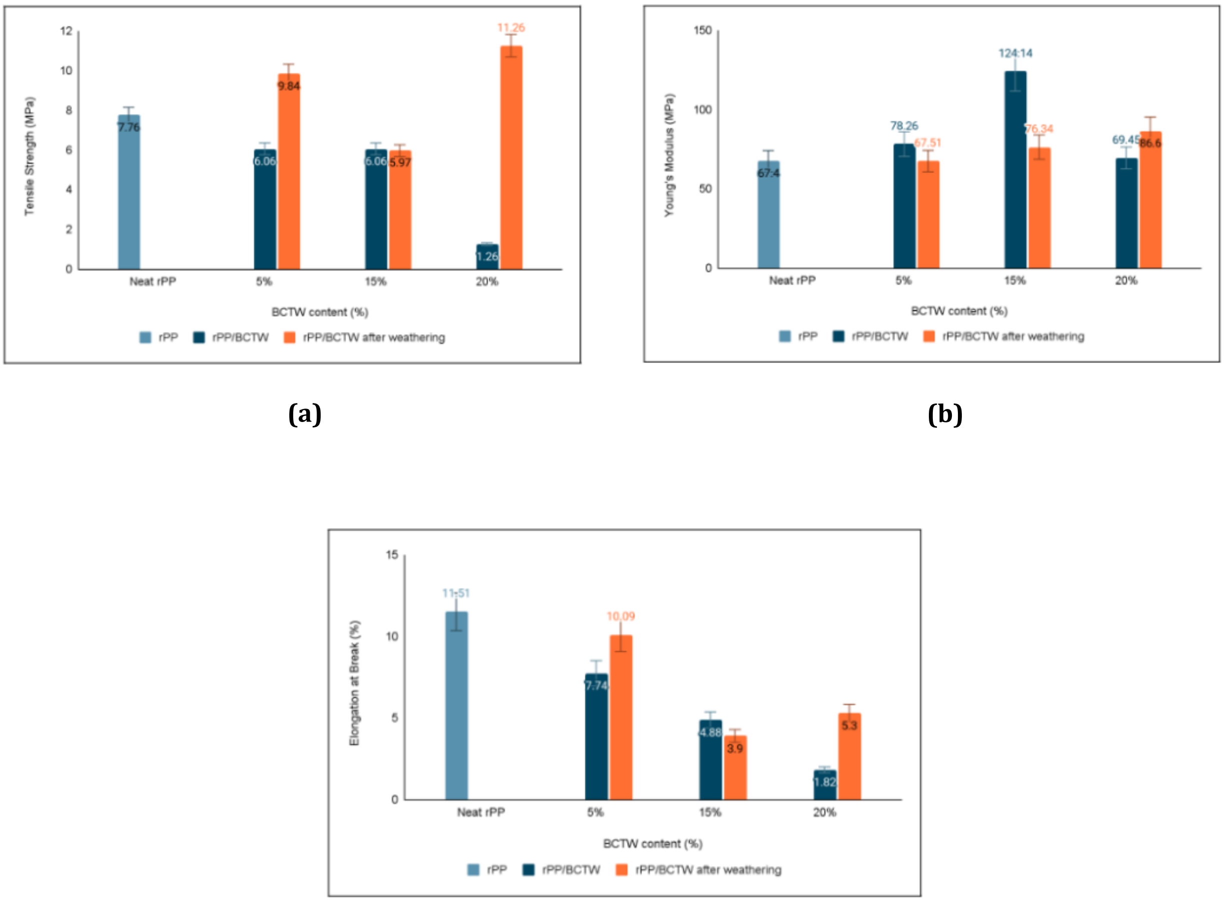
(a) **(b)**

Fig. 3 *(a) TG curve, (b) DTG curve of BCTW-rPP composites before and after weathering*

3.6 Mechanical Properties of Bamboo Cotton Textile Waste Reinforced Recycled Polypropylene (BCTW-rPP)

Tensile properties of bamboo cotton textile waste reinforced recycled PP composites which are tensile strength, Young's Modulus and elongation at break can be influenced by fiber content, weathering and the presence of MAPP compatibilizer.

As shown in Fig. 4, neat rPP exhibits a tensile strength of 7.76 MPa, Young's modulus of 67.4 MPa and elongation at break of 11.51%. incorporation of BCTW increases stiffness with Young's modulus reaching 124.14 MPa at 20 wt% fiber loading before weathering while tensile strength and elongation vary with fiber content where 5 wt% BCTW shows tensile strength of 6.06 MPa and elongation of 7.74%, 15 wt% BCTW exhibits stable tensile strength of 6.05 MPa and moderate ductility which 4.88% and 20 wt% BCTW shows very low initial tensile strength of 1.26 MPa and elongation of 1.82%. the improved stiffness and tensile performance at low to moderate fiber loading are associated to the rigid, cellulose-rich bamboo-cotton fibers restricting polymer chain mobility and improve the stress transfer with MAPP further promoting fiber-matrix adhesion [5,17]. At high fiber loadings, fiber agglomeration and poor dispersion reduce reinforcement efficiency, causing low tensile strength and ductility despite compatibilization [18]. Weathering generally reduces Young's modulus due to UV and moisture-induced fiber swelling, interfacial debonding and microcracks [19] but can increase tensile strength at low and high fiber contents by helps in structural rearrangement and improving interfacial. Overall, the 15 wt% BCTW composite achieves the best balance of strength, stiffness and ductility where the composite can maintain stable performance before and after weathering that makes it the most suitable choice for construction board applications [5].



(a) **(b)**

(c)

Fig 4 *(a) tensile strength, (b) Young's modulus, (c) Elongation at break of BCTW-rPP composites before and after weathering*

4. Conclusion

This study successfully investigated the effect of natural weathering on the mechanical and thermal properties of bamboo cotton textile waste (BCTW) reinforced recycled polypropylene (rPP) composites. The composites were produced using different BCTW fiber loadings with Maleic Anhydride-grafted Polypropylene (MAPP) added as compatibilizer to improve the fiber-matrix interaction. The performance of the composites was analyzed before and after exposure to natural outdoor weathering. Overall, the research objectives were achieved through systematic composite fabrication, material characteristics, weathering exposure and the performance evaluation.

The results show that NaOH treatment effectively changes the bamboo-cotton fibers by removing surface impurities and increasing the surface roughness as confirmed by FESEM and FTIR analysis. This surface modification improved the interfacial bonding between the hydrophilic fibers and the hydrophobic rPP matrix with presence of MAPP. From both mechanical and thermal analyses, a fiber loading of 15 wt% was found to be the most suitable composition as it shows the best balance between tensile strength, stiffness and thermal stability before and after weathering. In conclusion, the findings state that bamboo cotton textile waste has strong potential as a sustainable reinforcement for recycled polypropylene with the formulation containing 15 wt% BCTW and MAPP show the most practical and durable performance for non-structural and semi-structural outdoor applications.

Acknowledgement

I would like to express my sincere gratitude to my project supervisor, Dr. Mazatusziha binti Ahmad for her continuous guidance, support and advice throughout the completion of this project. Their patience, encouragement and constructive feedback greatly helped me in understanding the research work and improving the quality of this study. I also want to thank the Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia for its support to accomplish this project.

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