The Effect of Immersion Weathering on the Tensile Properties of rHDPE Green Composite Material

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The effect of immersion weathering on the tensile properties of rHDPE green composite material

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Abstract: *The use of recycled high-density polyethylene (rHDPE) as a green composite material in construction has gained significant interest due to its potential to address environmental concerns and promote sustainable building practices. This approach supports the multiple SDGs (i.e. SDG 9, SDG 11, and SDG 13) by promoting sustainable development, reducing environmental impact, and supporting the transition towards a more circular and resource-efficient economy. This study investigates the mechanical properties of recycled HDPE composites, focusing on their suitability for various construction applications. The research evaluates the tensile strength of rHDPE composites through experimental testing and analysis. The samples were prepared by using both manual mixing and injection molding processes. Additionally, the study examines the effects of environmental factors, including moisture, and immersion exposure, on the performance of the rHDPE composites. The findings provide valuable insights into the mechanical behaviour and durability of rHDPE composites, informing material selection, design considerations, and sustainable construction practices.*

Keywords: Recycle HDPE; Bamboo Fibre; Natural Fibre Reinforcement Composite; Green Construction Materials

1. INTRODUCTION

Plastics have posed a significant threat to the environment in recent years because of the large quantities produced, which can cause significant harm to both the ecosystem and humanity. Plastic waste is projected to be generated in the amount of 350 million metric tonnes each year [1]. Malaysia has become the world's leading importer of plastic waste since 2017, reflecting trends in both worldwide production and use of single-use plastics [2]. In 2019, Malaysia produced 671,000 metric tonnes of plastic waste, as reported by the Ministry of Environment and Water [3]. Only 24% of the plastic waste was recycled. 76% of the remaining waste was either disposed of in landfills or thrown in open dumpsites. A large segment of that waste such as plastic particles dumped directly or indirectly in the ocean [4]. The Malaysian government has established a goal to eliminate all single-use plastics by 2030, aligning with the global Sustainable Development Goals (SDGs) that aim to promote sustainable consumption and production practices. Therefore, innovative solutions are urgently required to resolve this issue and transition to a more sustainable and circular economy.

This research effort is in line with several SDGs, with a particular focus on environmental sustainability, responsible consumption, and innovation [5]. The aim of SDG 9 (Industry, Innovation, and Infrastructure) by 2030 is to improve infrastructure and transform industries to ensure their sustainability. This will be achieved by enhancing resource-use efficiency and promoting the broad adoption of clean and environmentally friendly technology and industrial practices [5]. This research is significant as it enhances the awareness of the sustainability of composite materials and provides valuable insights for the development of eco-friendly solutions in the materials and construction sectors. The primary aim of SDG 14, also known as "Life below water," is to effectively mitigate and significantly reduce various types of marine pollution, including those that come from land-based activities, including marine debris and nutrient pollution, by the year 2025 [5]. This research aims to minimize the possible environmental effects of materials, namely by addressing the problem of marine pollution resulting from the degradation of composite materials, particularly plastic waste.

There is a growing need for innovative building materials that include enhanced mechanical qualities tailored to their intended application, cost-effectiveness, production capabilities, and sustainability. These materials are required to promote sustainable consumption and production trends [6,7]. Researchers and engineers are increasingly interested in natural fibre-reinforced polymeric materials as an alternative to traditional fibres [8,9,10,11,12]. Natural fiber-reinforced polymer composites have gained significant attention in recent years due to their potential to replace conventional synthetic fiber composites, offering environmental and economic benefits. A variety of advantages associated with natural fibres, such as degradability, environmental friendliness, biodegradability, exceptional stiffness to weight ratio, affordability, and lightweight, are the reasons for their wide use [9,11,12]. Bamboo fibre (BF) is a versatile and environmentally friendly organic material that has become more popular as a reinforcement in composite materials [8]. The environmentally friendly and biodegradable characteristics of these fibres have a beneficial effect on the environment. A composite material may be formed by combining bamboo fibre with recycled plastic, which can then be utilized as environmentally friendly construction materials. The composite material combines the advantages of both materials [13].

The introduction of high-strength materials (fibres) as reinforcement media can enhance the mechanical performance of plastics, which typically have inferior mechanical properties [14]. Several research have investigated enhancing the mechanical, physical, and thermal characteristics of plastics by using different types of natural fibres [14]. Previous work [15, 16, 17] has shown remarkable outcomes when combining different forms of polyethylene and natural fibre. Furthermore, an earlier study was carried out on the application of rHDPE composites strengthened by Zalacca Midrid fibre in an environment of tropical climate conditions [16]. [17] examined the durability of post-consumer plastics reinforced with wood twigs while exposed to the coastal weather conditions in Thailand. The study conducted by [18] highlights the potential of composites using Low-density polyethylene (LDPE) waste and pine wood waste emphasizing their environmental benefits and application possibilities in various industries. The study conducted by [19] examined the impact of several polymer types, specifically polypropylene (PP) and high-density polyethylene (HDPE), as well as different bamboo fibre percentage (10%, 30%, and 50%), on the physical, mechanical, and thermal characteristics of Melia dubia (hybrid) plywood. [20] used rice husk as a reinforcing material in recycled high-density polyethylene (rHDPE).

Bamboo fibers have been highlighted for their excellent mechanical properties and rapid growth rate. When combined with thermoplastic matrices, such as recycled HDPE, these fibers can produce composites with desirable mechanical performance while addressing environmental concerns related to plastic waste. Utilizing recycled plastics, specifically HDPE, in composite materials effectively addresses both environmental sustainability and material cost-efficiency [20]. Studies have demonstrated that recycled HDPE continues to maintain good mechanical properties for composite applications, however its performance can be improved by using natural fibres.

The tensile strength of natural fibre composites is influenced by several elements, including fiber type, matrix type, fiber-matrix adhesion, and processing conditions. Research has demonstrated that the introduction of bamboo fibres in composites leads to exhibit significant improvements in tensile strength when compared to composites from the pure polymer matrix. [22] observed a significant enhancement in the tensile strength of HDPE composites reinforced with bamboo fibres. They attributed this improvement to the effective transfer of stress from the matrix to the fibres. The mechanical properties of recycled HDPE (rHDPE) reinforced with bamboo fibre were examined by [13, 22]. The tensile strength of rHDPE material without any fibre loading was found to be 8.3 N/mm^2, which exceeds that of bamboo fibre with a 30% weight content. This was due to the lack of adhesive substances and the random orientation of bamboo fibres. Therefore, the objective of the present research is to examine the influence of water immersion on the physical and mechanical characteristics of rHDPE composites that are reinforced with bamboo fibres. The outcomes will provide valuable insights on the durability and effectiveness of these composites under moist conditions, enhancing their potential applications in various sectors.

2. MATERIALS AND METHODS

2.1 Materials

The composites are made through the mixture of recycled high-density polyethylene (rHDPE) plastic with the addition of bamboo fibres for reinforcement. The rHDPE pellets have a size range of 4 to 5 mm, as shown in Fig. 1. The bamboo fibre (Semantan) used is sourced from the local community's production in Kedah, Malaysia, as shown in Fig. 1. The bamboo fibre has a diameter ranging from 0.2 to 0.3 mm and has been prepared for size reduction. The bamboo fibre is reduced in size by using scissors until the fibre length of 4 to 6 mm.

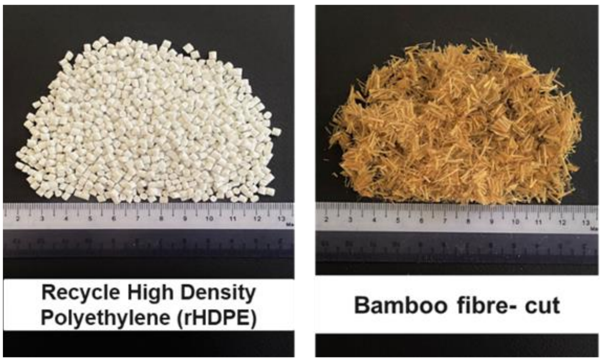

Fig. 1. rHDPE pellet (left) and bamboo fibre (right).

2.2 Preparation of Recycle HDPE and Bamboo Fibre Composite Specimen

The composites were made in accordance with the process described in Fig. 2, as part of the experimental design. The weight of the composites is determined by the combination of rHDPE plastic pellets and bamboo fibres, as indicated in Table 1. The rHDPE and BF were added to the beaker in accordance with their according weight percentages for dry mixing. The mixture is then placed into the injection machine and injected into the mould. The temperature control range in the melting box of the injection machine was 200ºC to 220ºC. The specimen was fabricated using a mould with dog bone shaped, following the guidelines of the American Society for Testing Materials (ASTM) standard, particularly ASTM D638-22 Standard Test Method. This specimen is used for testing mechanical properties.

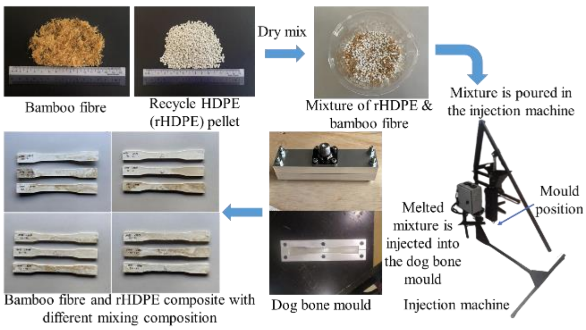

Fig. 2. rHDPE and bamboo fibre composite preparation.

Table 1. Composition of rHDPE and bamboo fibre composite

Composite rHDPE	Bamboo fibre (% wt)
Control	0
rHDPE/BF3	3
rHDPE/BF5	5
rHDPE/BF7	7

2.3 Water absorption test

The water absorption test was performed to investigate the weight increase of the material after immersion. The weight of composite specimen was measured before and after immersion in rainwater and acidic solution at room temperature. The weight changes were measured and recorded. Composite sampling was immersed in rainwater and acidic solution for 1 week and 4 weeks at room temperature. Eq. (1) was used to calculate water absorption. W_1 is the sample's initial weight, and W_2 is the sample's final weight after immersion.

$$\text{Water absorption } = \frac{W_2 - W_1}{W_1} x\ 100\% \qquad (1)$$

2.4 Tensile strength test

The tensile strength of the composites was determined using an Instron 5569A Universal Testing Machine, in accordance with the specifications provided in the ASTM D638-22 Standard Test Method. The dog-bone-shaped samples were produced using injection machine moulding. The specimens conducted tensile testing at a consistent strain rate of 10 mm/min under ambient conditions at a temperature of 25°C. The equation for calculating tensile strength, indicated as Eq. (2), and the equation for calculating Young's modulus, indicated as Eq. (3), were used in the calculation of tensile strength. σ represents the tensile strength (MPa), F denotes the load (N), A represents the cross-sectional area (mm^2), E denotes the Young's modulus, and ϵ represents the strain. The tensile strength and Young's modulus are calculated by averaging the measurements from five specimens.

$$\text{Tensile strength (MPa)}, \sigma = \frac{F}{A} \qquad (2)$$

$$\text{Young Modulus (MPa)}, E = \frac{\sigma}{\epsilon} \qquad (3)$$

3. RESULTS AND DISCUSSION

3.1 Water Absorption of Composites

The effect of the rHDPE and bamboo fibre reinforcement ratio on the water absorption of the composite after immersion with rainwater and acidic solution for 7 days and 28 days is illustrated in Fig.3 and Fig.4. This test measures the weight change of composite samples subjected to varying immersion times. It is apparent from the graph that the water absorption of each sample follows a similar pattern. The composite samples experience rapid water absorption and gain weight within 1 week to 4 weeks of immersion. The rHDPE composites with 7% of BF have the largest water absorption for immersion test in both rainwater and acidic with 3.5%. This observation is primarily linked to percentage BF's presence. In general, composites reinforced with natural fibres are susceptible to water absorption. This fragility is caused by the hydrophilic properties of natural fibres, which give composites a high-water absorption [23]. Using bamboo fibre as a reinforcement or filler can affect the water absorption capacity of composites due to the hydrophilic properties of bamboo fibre [23, 24].

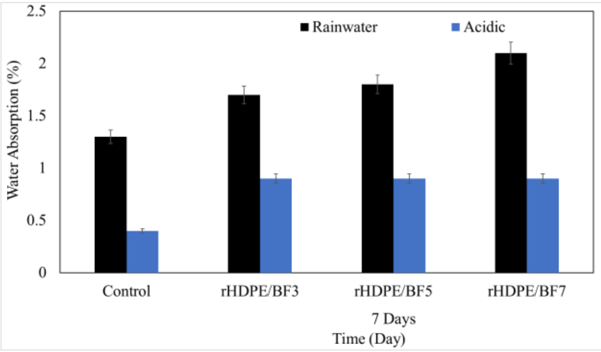

Fig. 3. Water absorption of rHDPE and BF composites after immersion with rainwater and acidic solution for 1 week.

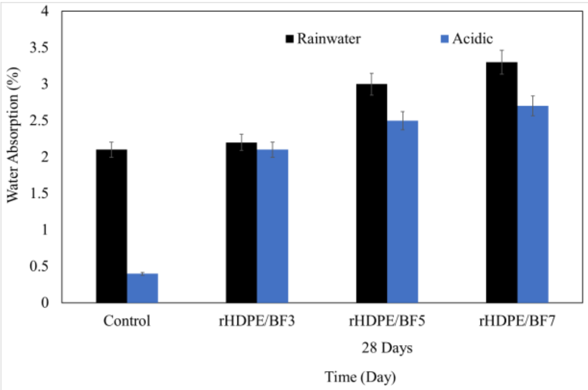

Fig. 4. Water absorption of rHDPE and BF composites after immersion with rainwater and acidic solution for 4 weeks.

Overall, the percentage of water absorption immersed in acidic shows lower than in rainwater in both 1 week and 4 weeks duration. Rainwater is generally considered to be a relatively neutral or slightly acidic solution with a pH close to 7. It may contain dissolved gases and impurities that can contribute to water absorption in the composite. The hydrophilic nature of natural fibres, such as bamboo fibre, can also increase the tendency for water absorption in the composite. As a result, rainwater can be readily absorbed by the composite, leading to swelling and potential changes in mechanical properties. Acidic solutions, on the other hand, can cause chemical degradation of the polymer matrix, which may result in some absorption of the acid solution [25]. However, acidic solutions are typically used in controlled laboratory environments or specific industrial applications. The concentration and type of acid used, as well as the exposure duration, will influence the extent of absorption and potential degradation of the composite.

The duration of the absorption experiment can also impact the rate. Immersion for 4 weeks shows higher water absorption than 1 week for both types of water. Initially, the absorption rate might be higher, but it can gradually decrease as the material reaches its saturation point [26]. The presence of water can weaken the interfacial adhesion between the matrix and reinforcement, causing a reduction in the composite's strength and stiffness.

3.2 Tensile strength of green composites material

Understanding the mechanical properties of the composite material would aid in identifying appropriate applications and determining the composites resistance. The stress-strain graph provides important information about the mechanical behaviour of a material. It helps determine the material's stiffness, ductility or brittleness. For rHDPE reinforced with bamboo fibre, the tensile strength and the shape of the stress-strain curve can be influenced by factors. In this research, the stress-strain curve varies because of percentage of fibre content and duration of waters immersion. Stress-strain graphs are instrumental in understanding how these materials respond to tensile loads. Fig. 5 and 6 shows the graph of stress-strain of rHDPE composites reinforced with 3% and 5% bamboo fibre immersion with rainwater and acidic solution.

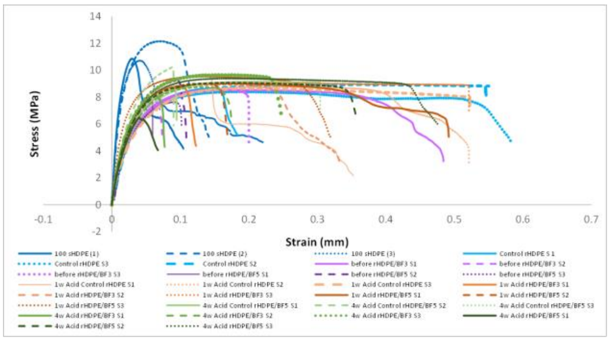

Fig. 5 Stress-strain graph of rHDPE and BF composite immersed with acidic solution.

The rHDPE/BF3 composite showed improved tensile strength compared to control rHDPE, with a stress-strain curve indicating enhanced stiffness. The impact of acidic and rainwater immersion was moderate, with a slight reduction in tensile strength. The rHDPE/BF5 composite exhibited the best balance of tensile strength and ductility. The tensile strength decreased after immersion, but the composite retained a significant portion of its mechanical integrity. Comparing the elastic regions of the stress-strain graphs reveals that immersion in rainwater or acidic solution after 1 week to 4 weeks has minimal effect on the elastic behaviour of the material. The initial linear portion of the graph, which represents Young's modulus, maintains a relatively constant slope. However, the yield point and subsequent region of plastic deformation may vary after immersion event. Immersion in rainwater or an acidic solution may alter the behaviour or strain hardening/softening characteristics of the material. The potential decrease in tensile strength after immersion is an important finding.

rHDPE displays lower tensile strength and elongation compared to standard HDPE due to impurities and degradation from previous use cycles. The curve shows a lower yield point and a shorter plastic deformation region, indicating reduced ductility. Aligning with research by [27], rHDPE exhibits reduced mechanical properties due to the presence of contaminants and prior degradation. Adding 3% and 5% bamboo fiber slightly enhances tensile strength and stiffness. The composite shows a higher initial modulus compared to control rHDPE. The curve displays an initial increase in stress with a shorter plastic region, indicating improved stiffness but reduced ductility. Similar to findings by [28], low fiber content composites show improved tensile strength but can exhibit reduced elongation due to limited fiber-matrix interaction [29].

The stress-strain analysis reveals that while rHDPE and BF composites show improved tensile strength compared to control rHDPE, their performance is influenced by fibre content and environmental exposure. Composites sample with 3% bamboo fiber content demonstrated the best balance between strength and durability. The degradation observed under acidic and rainwater immersion highlights the need for further research into surface treatments and fiber-matrix optimization to enhance the environmental resilience of these composites.

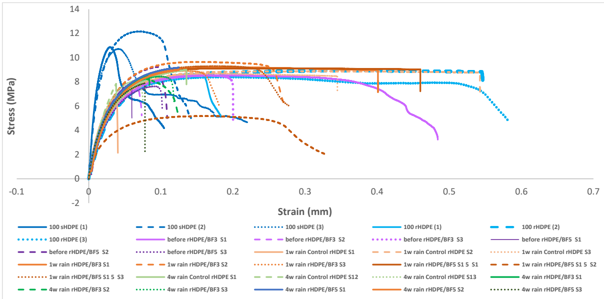

Fig. 6. Stress-strain graph of rHDPE and BF composite immersed with rainwater.

Standard HDPE and rHDPE generally exhibit good resistance to chemical and environmental degradation, but recycled materials show increased susceptibility due to inherent impurities and processing histories [30]. The addition of natural fibers, while improving initial mechanical properties, introduces variability and potential degradation pathways when exposed to environmental conditions [29]. The fiber-matrix interface is crucial for the composite's overall performance. Degradation of this interface due to water ingress or acidic conditions significantly impacts tensile strength [31]. Optimizing fiber content and improving fiber-matrix bonding through treatments can enhance durability and performance under adverse conditions [22].

Immersion in rainwater or an acidic solution can degrade the mechanical properties of a material, resulting in a lower tensile strength value. This indicates that the material has less ability to withstand tension before failure. Changes in the stress-strain behaviour observed after immersion in rainwater or acidic solution have significant implications for the application of recycled HDPE composites reinforced with bamboo fibre in environments exposed to these immersion conditions. The decreased tensile strength and potential alterations in failure mode suggest that the mechanical performance of the material may be compromised, affecting its suitability for certain applications.

The tensile strength represents the maximum stress the material can withstand before failure. Immersion in rainwater or acidic solution may result in a decrease in tensile strength due to the potential degradation of the material's mechanical properties. The tensile strength of a material is influenced by a variety of factors, including the composition and structure conditions. In the case of high-density polyethylene (HDPE) reinforced with different percentages of bamboo fibre, the addition of bamboo fibre can affect the material's performance.

Fig. 7 and Fig. 8 represent the variation of tensile strength with percentage of bamboo fibre composition before and after immersion in rainwater and acidic solution in 1 week and 4 weeks. The tensile strength of controlled samples with rHDPE and 3% BF shows the highest strength with 15.5 MPa. After 1 week immersion with rainwater and acidic, the tensile strength of composites not showing much different compared to the controlled sample. After 4 weeks immersion with rainwater, the tensile strength of rHDPE with 3% of BF shows the minimal reduction to 13.8 MPa. The similar pattern of reduction in tensile strength shows at rHDPE with 5% of BF and rHDPE with 7% of BF with 10.9 MPa and 10.3 MPa. After 4 weeks immersion with acidic, the tensile strength of rHDPE with 3% of BF shows the minimal reduction to 13.4 MPa. The similar pattern of reduction in tensile strength shows at rHDPE with 5% of BF and rHDPE with 7% of BF with 9.5 MPa and 9.2 MPa.

The tensile strength of rHDPE and BF composite increases with increasing fibre volume fraction up to a weight composition of 3%, after which it decreases below the previously observed trend. This is because tensile properties are dependent on fibre orientation and fibre/matrix interfacial adhesion [13, 22]. With an increase in fibre weight fraction, agglomeration is more likely to occur [22]. This significantly reduces the fibre/matrix interfacial adhesion and the matrix-to-BF tension transfer efficiency. Similar findings have been published in prior research [24, 32]. The absence of adhesive substances and the use of random bamboo fibre directions could all be factors in this rHDPE/bamboo composite's low tensile strength [13].

Exposure to acidic solution is prone to produce significant reduction in tensile strength compared to exposure to rainwater. Rainwater, usually indicating a slightly acidic or neutral pH, is less corrosive in comparison to highly concentrated acidic solutions. Although precipitation can contribute to the absorption of water and potential swelling of the composite, the influence on tensile strength is likely to be insignificant [34]. On the other hand, exposure to acidic environments can cause chemical degradation of the polymer matrix, which may result in a decrease in mechanical strength and other properties [32].

Rainwater immersion resulted in less severe degradation compared to acidic water but still caused a reduction in tensile strength, particularly in composites with higher bamboo fiber content. The cyclic wetting and drying in rainwater conditions can lead to swelling and shrinkage, exacerbating micro-cracks and interface degradation, consistent with findings by [35]. Acidic water immersion caused degradation and potential leaching of components, more so in composites with higher bamboo fiber content. The presence of acids can accelerate the degradation of the fiber-matrix interface, reducing tensile strength and altering the stress-strain behavior, as discussed by [36].

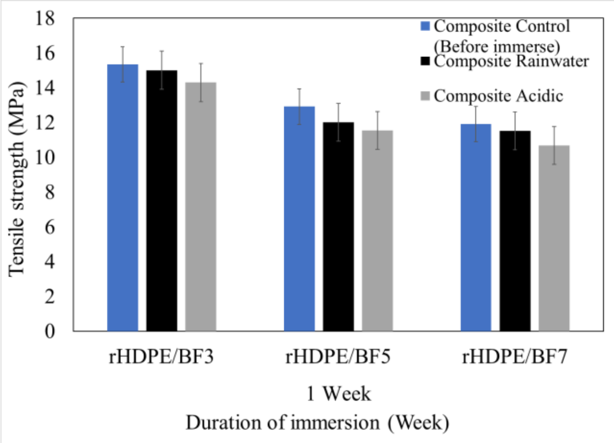

Fig. 7. Tensile strength of rHDPE and BF composites after immersion with rainwater and acidic solution for 1 weeks.

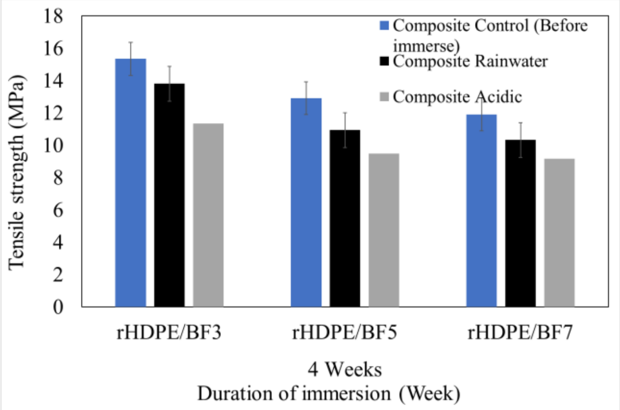

Fig. 8. Tensile strength of rHDPE and BF composites after immersion with rainwater and acidic solution for 4 weeks.

In general, it is expected that for composites with a higher weight fraction of reinforcement immersed in water, the relative extent of reduction in tensile characteristics will be greater than for dry samples. This could be because excessive amounts of water cause the fibres to swell, filling the spaces between the fibre and the polymer matrix and finally resulting in a deterioration in the mechanical properties of the composites [25]. The tensile strength and young modulus of were determined and are shown in Table 2. The composition of both the recycled HDPE matrix and the bamboo fibres influences the composite's Young's modulus. Young modulus shows an increasing trend with larger fractions of fibre in the rHDPE matrix. The reinforcing effect of bamboo fibres increases the stiffness of the composite. It indicates that more bamboo fibre tends to lead the composite to be stiffer and more brittle [13].

Table 2. Tensile strength and young modulus of rHPDE and bamboo fibre composite

Composite	Tensile strength (MPa)	Young Modulus (MPa)
Standard HDPE	19.6	340
Control rHDPE	12.3	297
rHDPE/BF3	15.3	352
rHDPE/BF5	12.9	377
rHDPE/BF7	11.9	390

4. CONCLUSIONS

The mechanical properties and water absorption behaviour of rHDPE composites reinforced with bamboo fibres have been investigated. The water absorption test revealed that the weight obtained by all composites increases with immersion time up to 4 weeks, after which they gain weight rather slowly. The tensile strength of rHDPE and BF composite have significantly affected after immersion weathering condition especially with acidic solution compared to rainwater after 4 weeks duration. Very minimal change on tensile strength of rHDPE and BF composite after immersion weathering condition with acidic solution and rainwater after 1 week duration. Bamboo fibre improves the tensile strength of composites. The greatest improvement was observed at 3% of BF. As BF percentage increased, these properties tend to be decreased, likely due to fibre agglomeration at higher loading ratios. However, when compared to the control sample, these properties exhibit significant improvement. The findings of this investigation indicate the importance of considering immersion effects when utilizing bamboo-reinforced recycled HDPE composites in environments exposed to rainwater or acidic solutions.

5. ACKNOWLEDGMENT

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