INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 2 (2024) 278-287
https://publisher.uthm.edu.my/ojs/index.php/ijie

Mechanical Characteristics of Biocomposites Based on Rice Husk Reinforced Recycled Polypropylene

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DOI: https://doi.org/10.30880/ijie.2024.16.02.029

Article Info

Received: 3 April 2024
Accepted: 11 June 2024
Available online: 3 August 2024

Keywords

Rice husk, recycled polypropylene, biocomposites, natural fiber composites, waste recycling, sustainable development goals (SDGs)

Abstract

This work aims to investigate the influence of the combination ~~of~~ between agriculture waste, rice husk (RH) and domestic plastic waste, recycled polypropylene (RPP) in producing environmentally friendly materials. In the current investigation, four distinct compounds were selected to identify the most effective combination for achieving the highest result of mechanical properties outcomes. Samples were created with variable RH concentrations (10%, 20%, 30%, and 40% by weight). The results showed that RH-RPP with 20% of RH had the highest mechanical properties. Scanning electron microscopy (SEM) images prove the enhanced mechanical characteristics. In addition, the water absorption and thickness swelling analysis show that RH-RPP composites with 20% RH concentration produce competitive results of 1.14% and 2.06%, respectively. Therefore, the finding from the present study summarized that the combination of RH and RPP with 20% of RH percentage had a great potential in producing competitive eco-friendly material for engineering applications especially for packaging materials. In addition, it is expected to provide an alternative for the management of crop waste and domestic plastic waste. Thus, able to contribute to the environmental sustainability and resource efficiency which towards sustainable development goals (SDGs), thereby contributing to sustainable development goals especially in line with the SDG 12, responsible consumption, and production. Therefore, able to contribute to environmental sustainability and resource efficiency towards sustainable development goals (SDG), especially SDG 12 which is responsible consumption and production.

1. Introduction

In an era where environmental sustainability and resource efficiency are paramount concerns towards sustainable development goals (SDGs), the development of innovative materials plays a pivotal role in addressing these challenges. One such innovation is using crop residue and domestic plastic waste to become sustainable eco-friendly materials. In Malaysia there are 1.3 billion tonnes of agricultural waste and 9 billion tonnes of plastic waste was produced annually [1–3]. This phenomenon was driving the major issue in waste disposal management [4–6]. Therefore, the development of bio composite material represents a harmonious blend of nature and industry, harnessing the strength of agricultural waste and recycled plastics to create a versatile, eco-friendly material with a wide range of applications [7–9].

Polypropylene (PP) is a versatile polymer with many applications across different industries. Its combination of physical properties and cost-effectiveness makes it a popular choice for manufacturers and consumers. This phenomenon causes PP to be one of the primary materials in plastic waste production in Malaysia. Therefore, the utilization of recycled polypropylene (RPP) as a matrix in composite materials is seen to have tremendous potential. Moreover, the previous study presents that the molding temperature of PP between 160°C and 170°C is compatible with a fiber degradation temperature of approximately 200°C [10–13].

On the other hand, rice husk (RH), an agricultural by-product abundantly generated in the rice milling process, has long been considered a waste material [14–16]. Therefore, using rice husks from an environmental perspective helps reduce waste, decrease greenhouse gas emissions, promote clean energy production, and support sustainable agricultural practices. Furthermore, the combination of waste RH and waste recycling of PP as bio composites seen to have high potential to become alternative to conventional polymer for engineering application such as automotive component and packaging material. Other than that, the combination also seemingly capable of contributing to reducing the carbon footprint and conserving valuable resources towards sustainable development goals [17].

However, one common drawback of natural fiber composites in engineering application especially for outdoor application is their moisture absorption behaviour, which affects the dimensional stability and mechanical properties of composites. This factor is other consideration for RH selection as a reinforcement agent in this study. It is due to RH contains a high percentage of silica, which is believed to have good water resistance properties [14–16]. Previous study show that the utilization of RH as a reinforcement agent in polymer composites able to increase the mechanical properties and lower the water absorption compared with other filler like wheat husk and wood fiber [2]. In addition, the combination of RH and high density polyethylene (HDPE) able to produced 15.8 MPa with 40% as an optimum RH percentage [18].

Therefore, the primary objective of this study is to investigate the effect of RH percentage on the mechanical properties and water absorption performance of RH-RPP composites. In addition, the study aimed to determine the optimal RH concentration for maximizing the mechanical properties and water absorption characteristics of RH-RPP composites. The findings of this study are expected to unravel the potential of this composite material of RH-RPP in contributing to a more sustainable and circular economy, where waste is transformed into a valuable resource, and the preservation of the environment goes hand in hand with technological innovation.

2. Materials and Method

2.1 Material

The Rice husk utilized in this study was purchased from Pemalang, Indonesia. The RH was in particle size of 100 microns. Meanwhile, the recycled polypropylene was purchased from CKY Recycle Plastic Sdn. Bhd. Which based in Nilai, Negeri Sembilan, Malaysia. Fig. 1 shows the 100-micron size of RH and RPP used in this research.

2.2 Sample Fabrication

First, the RH is sieved using an industrial seiving machine to ensure that the RH used is 100 microns in size. Then, the RH and RPP were oven-dried at 80°C for 3 hours. Previous studies have determined that the optimal drying temperature for natural fiber is 80°C for 3 hours [19–21]. Fig. 2 below shows the process flow in this research starting from material preparation, manufacturing and fabrication process of composite samples, mechanical testing and morphology analysis.

(a) **(b)**

Fig. 1 *The physical condition of material used in current research (a) 100 micron in size of RH; (b) RPP*

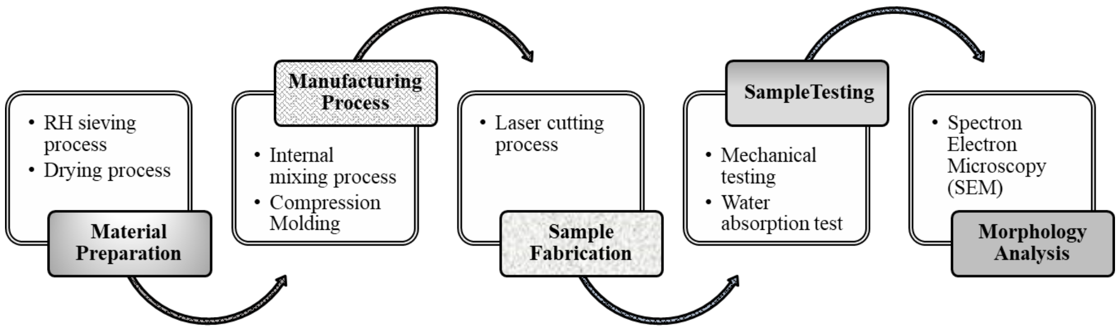

Fig. 2 *The process flow in current research*

The subsequent process is the RH and RPP mixing with a variable fiber and matrix percentage. The specific mixing composition in sample preparation is presented in Table 1. In the mixing procedure, the Brabender Plastograph EC internal mixing apparatus was preheated to a temperature of 180°C and adjusted to a processing speed of 40 revolutions per minute (rpm). Prior to the insertion of the RH, a RPP was heated at the specified temperature and allowed to reach a stable state. The composites were mixed for a total of 20 minutes. Then, RH-RPP compounds were cut into pallets.

The subsequent step was fabricating a composite plate through compression molding, creating a plate with dimensions of 180 mm × 180 mm × 6 mm. The mold temperature was set to 180°C, and a constant pressure of 6.0 MPa was applied during a preheating phase lasting 5 minutes, followed by a subsequent press phase lasting 10 minutes. Following this, a cooling period of 10 minutes was seen under identical pressure conditions [22]. After that, the tensile, flexural, and water absorption samples were laser-cut using a Thye Hong laser cutting equipment in accordance with ASTM D638, ASTM D790, and ASTM D570, respectively.

Table 1 *Detail mixing proportions in sample fabrication*

Sample	RH (wt %)	RPP (wt %)
RH10	10	90
RH20	20	80
RH30	30	70
RH40	40	60

2.3 Mechanical Testing

The tensile and flexural tests were conducted using a 5kN Shimadzu AGS-J universal testing machine following ASTM D638 and ASTM D790. A crosshead speed for tensile and flexural tests was set at 1 mm/min and 1.28 mm/min, respectively [23–25]. Five samples of each sample type were tested for failure. In addition, the tensile and flexural modulus were determined using the Chord modulus, E, where the modulus value was computed between 0.1% and 0.5% strain value.

2.4 Fracture Morphology

The surfaces of the tensile samples were visually inspected using a JEOL JSM-6380LA scanning electron microscope (SEM). The study aimed to evaluate the impact of RH inclusion on the bonding between the fiber-matrix interface by comparing and examining the surface morphology of composites with different percentages of RH.

2.5 Water Absorption Test

The water absorption test is a commonly used method to determine the amount of water that a material can absorb. In this study, the water absorption and thickness swelling analysis was conducted according to ASTM D570. Five samples for each configuration were selected and immersed in distilled water for 25 hours for water absorption analysis and 28 days for thickness swelling behavior characterization [26]. Fig. 3 shows the samples under the water absorption test.

Fig. 3 *The water absorption test for RH-RPP composites samples*

Then, the data of water absorption was measured and calculated according to a specific duration based on the following equation:

$$Water\ Absorption\ (\%) = \left(\frac{W_t - W_b}{W_b}\right) \times 100 \quad (1)$$

Where, W_t is a sample weight after a particular immersion duration and W_b is an initial sample weight before the immersion process. Meanwhile, the thickness swelling behavior was measured and calculated according to the following equation:

$$Thickness\ swelling\ (\%) = \left(\frac{T_t - T_b}{T_b}\right) \times 100 \quad (2)$$

Where, T_t is thickness after a certain immersion duration and T_b is an initial thickness before the immersion process.

3. Results and Discussion

3.1 Influence of RH Percentage on Mechanical Properties

Fig. 4 depicts the relationship between tensile and flexural properties with different percentages of RH. It's worth noting that there is a 44% increment in the tensile strength of the RH-RPP composite when the RH percentage increases from 10% to 20%. Similar results were observed for flexural strength. Fig. 4 shows an increase of 57% in flexural strength with RH utilization up to 20% concentration. Previous studies stated that the increase in fiber concentration acting as reinforcement is directly related to the enhancement of the mechanical properties of the natural fiber composites [27].

However, from the experimental perspective, the increase over the optimum value always deteriorates the mechanical properties of natural fiber, as shown in Fig. 4. The 5% and 11% decrease in both tensile and flexural strength occurred when the RH percentage was further increased from 20% to 30%. In addition, the sample with

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40% RH presents a lower value with 8.27 MPa for tensile strength and 17.15 MPa for flexural strength. The findings of this study are consistent with most previous studies where the mechanical properties value decreased when the fiber percentage was over the optimum value. The primary factor of this occurrence is that the reduction in the matrices at higher fiber content caused the interfacial adhesion between fiber and matrix to weaken. This phenomenon led to low mechanical properties as a result of composites [13, 21, 28]. This phenomenon is similar with the previous finding from Zhang et. al, where the RH-HDPE produced optimum tensile strength at 40% of RH composition. The further increase of RH content up to 70% was decrease the tensile strength of the composites [18].

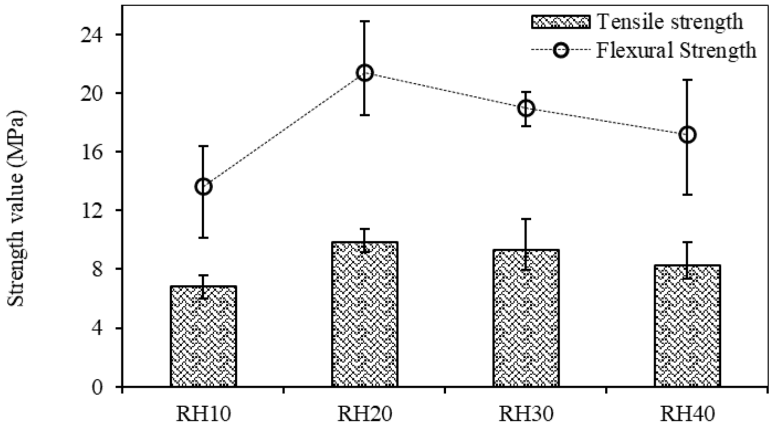

Fig. 4 *Effect of tensile and flexural properties on different RH percentages*

Therefore, the present study summarized that 20% RH is preferable for an optimum percentage of RH-reinforced RPP composites. In addition, Fig. 5 compares the tensile and flexural strength results of the present study with selected conventional polymers that have been used in current engineering applications, especially in automotive engineering, which were low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS), polyvinyl chloride (PVC), polybutylene terephthalate (PBT), polycarbonate (PC) and nylon 6.6. The RH-RPP composites present the lowest tensile strength value compared to the selected conventional polymers. However, the flexural strength result shows a competitive value, which is higher than LDPE and almost similar to HDPE flexural strength.

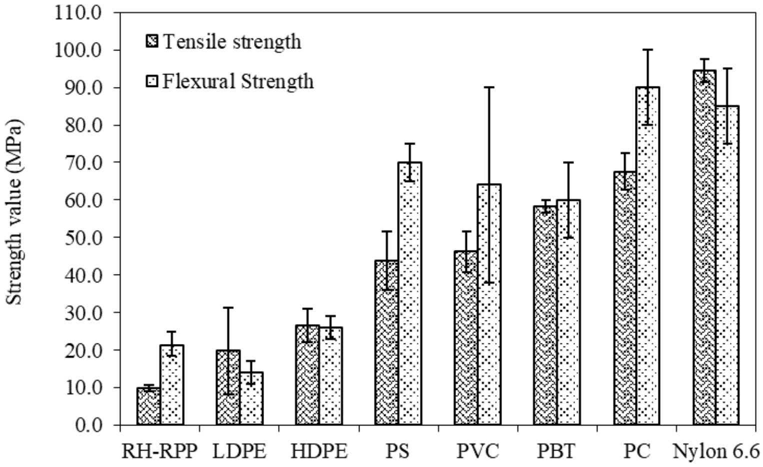

Fig. 5 *Comparison of tensile and flexural strength between RH-RPP composites with conventional polymer [29–31]*

The present finding showed that RH-RPP composites have tremendous potential as an alternative to conventional polymers in engineering applications. However, the further improvement in the manufacturing process of the composite in the future is expected able to improve this condition. According to the previous study, the optimal parameter combination between temperature, pressure and mixing duration during the mixing process of filler like RH and matrix like RPP is one of the factors that able in producing better interfacial adhesion [19, 20]. Thus, it is expected to enhance the tensile and flexural strength to make it more feasible to become an alternative to conventional polymer for engineering applications, especially in the automotive and packaging industries.

3.2 Morphology Analysis on Tensile Fracture Sample

The scanning electron microscopy (SEM) pictures in Fig. 6 illustrate the comparison of the interface bonding between RH and RPP under 100X magnification for the RH10, RH20, RH30, and RH40 samples. Fig. 6a and 6b show that the interfacial bonding between the RH fiber and the RPP matrix in the RH10 and RH20 samples is good, as evidenced by the gap between fiber and matrix. This behavior could be explained by the excellent adherence of the fiber surfaces to the RPP matrix. As a result, samples with 20% RH show the highest tensile and flexural strength compared to other samples. This finding indicates that the RH20 sample significantly improves interfacial adhesion where the stress is suspected to be well transferred from matrix to fiber. The anticipated outcome of this study is predicted to be a significant contributing factor in yielding improved mechanical properties for RH20 samples. However, RH10 presented the lower tensile and flexural strength expected due to the low concentration of the RH as a reinforcement agent.

Meanwhile, the SEM image on the RH30 and RH40 samples shows the apparent fiber pull-out phenomenon with the big gap between fiber and matrix for both samples. This finding explains why the mechanical properties results of the RH30 and RH40 samples produce lower mechanical properties than RH20. In higher fiber concentrations, the reduction in the matrices percentages causes the interfacial adhesion to weaken. Thus produce low mechanical properties of the composites[13]. Therefore, the finding deduces that the interfacial bonding and mechanical properties of RH-reinforced RPP composites with 20% of RH composition are markedly better than other RH and RPP sample combinations. According to the previous study, the interfacial adhesion between RH and RPP can be further improve by application of coupling agent such as maleic anhydride polypropylene (MAPP) [31].

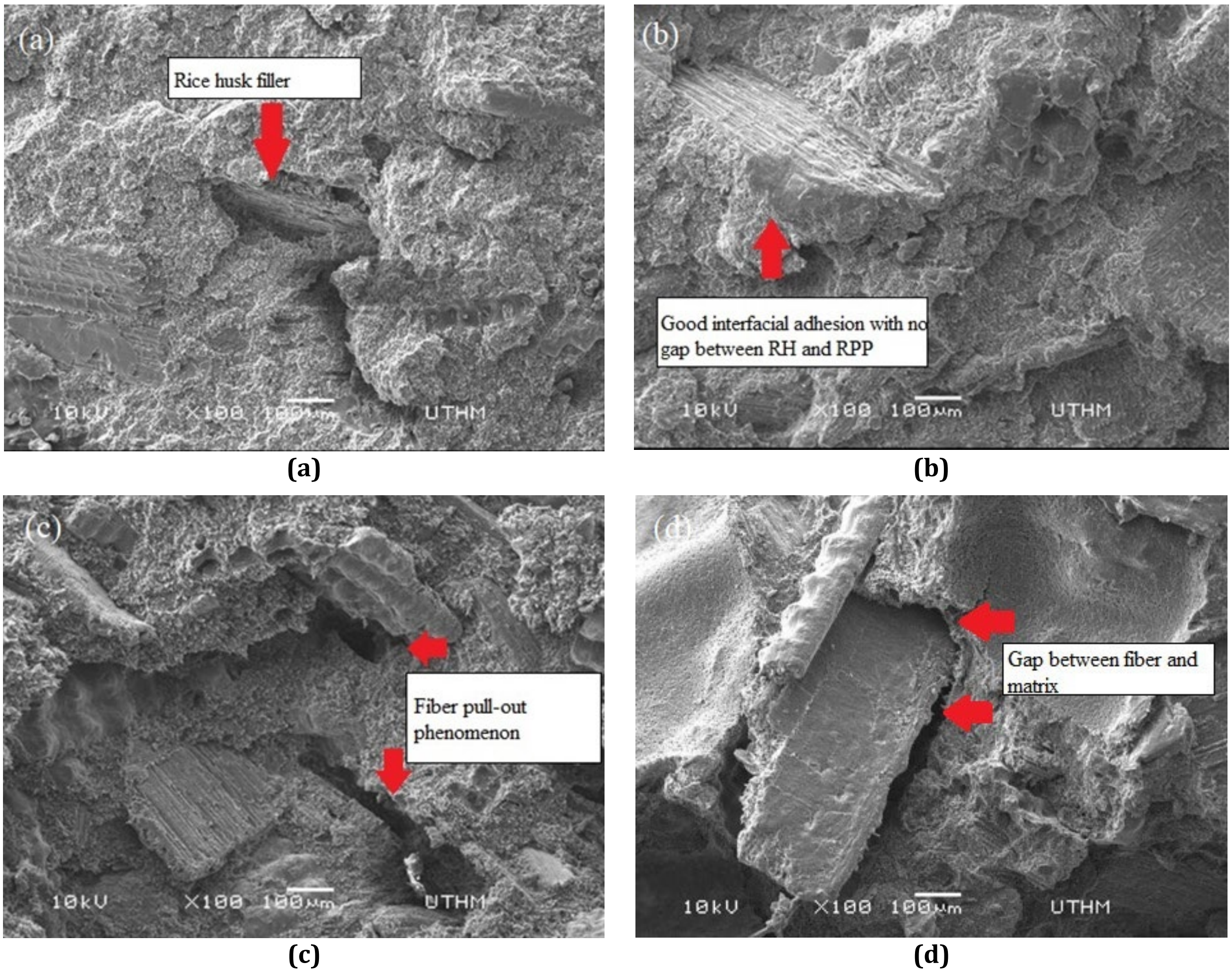

Fig. 6 *SEM image of RH-RPP composites subjected to different RH percentages (a) RH10; (b) RH20; (c) RH30; (d)RH40*

3.3 Influence of RH Percentage on Water Absorption Performance

Fig. 7 shows the plotted percentage of water absorption over the immersion time. The rate of water absorption varied and depended on the duration of immerses. As observed in Fig. 7, the water uptake reaches equilibrium after 24 hours. By comparing the samples, the water absorption value is the lowest for sample RH10%, which is 0.63%. Meanwhile, the highest water absorption value, 2.28%, was produced by the sample RH40, which contained 40% of RH. On the other hand, samples RH20 and RH30 show water absorption rates of 1.14% and 1.24%, respectively. The present study shows tremendous water absorption performance for RH-RPP composites. Most conventional polymers in engineering applications have less than 1.40% water absorption [32, 33]. Therefore, the RH-RPP sample up to 30% of RH concentration shows competitive results. In addition, the present study also indicates that the fiber concentration is a significant factor linked to the variations in water absorption. The higher content of cellulose and hemicellulose in the RH means the percentage of hydroxyl (-OH) and acetyl (C_2H_3O) group is higher, which is the principal contributor to moisture absorption [27, 34–36].

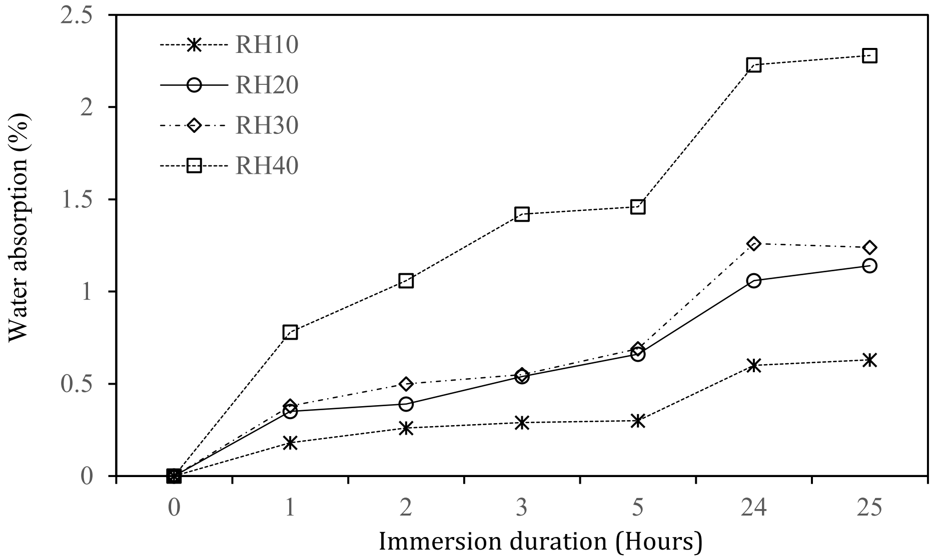

Fig. 7 *Comparison of water absorption rate between RH10, RH20, RH30 and RH40*

The results of the thickness swelling are presented in Fig. 8. According to Fig. 8, the thickness swelling of the composite sample abruptly in the first seven days and then gradually slows when reaching the 14 days of immersion and reaches equilibrium between the second and third week. Sample of RH10 and RH20 show almost similar thickness swelling values, which is approximately 2%. Meanwhile, RH30 and RH40 samples indicate 2.6% and 4.5% of thickness swelling values, respectively. As a result, the thickness swelling is more dominant on the composite sample containing 40% of RH. Similar to the water absorption result, the thickness swelling varies on the fiber percentage, whereas the sample with higher fiber percentage produces a more increased thickness swelling value. In addition, higher thickness swelling can be linked to the softening effect caused by water molecules that reduce the rigidity of the cellulose structure where the composite samples expand in the vertical and horizontal direction [36, 37].

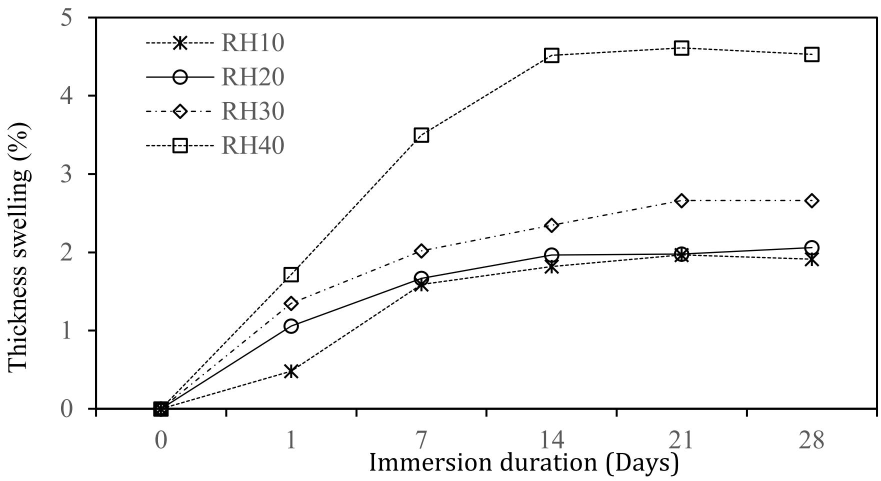

Fig. 8 *Comparison of thickness swelling result between RH10, RH20, RH30 and RH40*

4. Conclusion

Incorporating RH into RPP is an initiative to create a versatile, eco-friendly material for a wide range of applications, especially in engineering applications. The influences of different RH percentage on mechanical properties and water absorption characteristic of RH-RPP composites was studied. Mechanical properties results indicated that 20% of RH combination is an optimum composition in generating maximum value of tensile and flexural strength compared with other combinations which is 9.80 MPa and 21.36 MPa, respectively. In addition, the scanning electron microscopy (SEM) images of the fracture tensile samples reveal a high degree of interfacial adhesion between the fibers and matrix for the sample of RH20, as well as an effective transmission of stress from the matrix to the fibers. Furthermore, the results obtained from the water absorption analysis also show that RH-RPP composites, especially with 20%, produce competitive water absorption behavior and thickness swelling characteristics. The maximum water absorption and thickness swelling for the RH20 sample were 1.14% and 2.06%, respectively, competitive with current conventional polymers. Therefore, the finding from the present study summarized that the combination of waste RH and RPP had great potential in producing competitive, eco-friendly material for engineering applications. In addition, the compatibility of RH and RPP combination is expected to provide an alternative for RH residue and PP waste management issue. Thus, able to contribute to the environmental sustainability and resource efficiency which towards sustainable development goals (SDGs).

Acknowledgement

Communication of this research is made possible through monetary assistance by INTI International University, Universiti Tun Hussein Onn Malaysia and the UTHM Publisher's Office via Publication Fund E15216.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Tezara Cionita, Jamiluddin Jaafar;* ***data collection:*** *Syed Mohd Amri Syed Abdul Karim, Mohamad Fadhlin Zulkiflee. Muhammad Izuddin Shamsuddin;* ***analysis and interpretation of results:*** *Jamiluddin Jaafar, Ramli Junid, Deni Fajar Fitriyana, Al Ichlas Imran, Mohammad Hazim Mohamad Hamdan;* ***draft manuscript preparation:*** *Tezara Cionita, Jamiluddin Jaafar, Januar Parlaungan Siregar. All authors reviewed the results and approved the final version of the manuscript.*

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