SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895


# Effect of Moisture on Static and Fatigue Strength of Rubberwood/ Recycled Polypropylene Composites

Zaleha Mustafa[1,*], Tuan Muhammad Izuddin Nawi[1], Siti Hajar Sheikh Md Fadzullah[2], Mohd Nur Azmi Nordin[2], Thanate Ratanawilai[3]

[1] Faculty of Industrial and Manufacturing Technology and Engineering, Universiti Teknikal Malaysia Melaka, 76100, Melaka, Malaysia
[2] Faculty of Mechanical Technology and Engineering, Universiti Teknikal Malaysia Melaka, 76100, Melaka, Malaysia
[3] Department of Industrial and Manufacturing Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, 90112 Songkhla, Thailand

**ARTICLE INFO**

***Article history:***
Received 27 April 2024
Received in revised form 22 June 2024
Accepted 5 July 2024
Available online 30 July 2024

***Keywords:***
Fatigue strength; water ageing; moisture; hysteresis loop; recycled polypropylene; rubberwood polymer composite

**ABSTRACT**

While the field of plant fibre composites is experiencing rapid growth in research and development, there are still essential considerations that must be addressed before these materials can be adopted by industries for structural applications. One of the primary concerns revolves around their durability. This study aims to assess how moisture affects the static and fatigue behaviour of a rubberwood/recycled polypropylene composite. The specimens were exposed to a humid environment at 23 °C in water immersion for 30 days. Quasi-static and tension-tension fatigue tests were carried out. Results show that exposure to moisture has caused a significant decrease in their initial quasi-static strength and stiffness. The fatigue strength, on the other hand, has been enhanced. The fatigue strength coefficient decreases by more than half after ageing, suggesting a less pronounced decrease in maximum stress as the number of cycles increases. The fatigue hysteresis loop and evolution of the secant modulus of non-aged composite show more pronounced fatigue damage when compared to the aged composite.

## 1. Introduction

Research and advancements in plant fibre composites are experiencing rapid growth, especially in sectors like automotive and plastics industries, construction, and end-use industries due to their affordability, versatility in design, and favourable environmental characteristics [1-4]. Wood polymer composites (WPC) primarily consist of wood flour, frequently sourced from timber industry waste materials. Wood flours are blended with polymeric materials using a compounding process to create a robust and stable composite system that offers a promising alternative to traditional timber. The thermoplastic can be sourced from post-consumer products [5] as part of an effort to mitigate plastic waste in the environment. As interest in utilizing cellulosic fibre composites across a broad spectrum of applications grows, certain applications may subject these composites to cyclic or alternating loads

* *Corresponding author.*
*E-mail address: zaleha@utem.edu.my*

https://doi.org/10.37934/aram.122.1.5461

during their operational lifespan. Structural materials frequently encounter fatigue failures even before reaching their tensile strength [6-10]. The mechanical degradation of the materials under cyclic loading occurs cumulatively and differs from static loading. Thus, the application of WPC composites in structural materials presents significant challenges due to their fatigue reliability under varying load conditions.

Wood fibre as such rubberwood used in this study is a lignocellulosic material and thus can be also vulnerable to moisture absorption, particularly in humid environments or when immersed in water [11]. Moisture absorption can have a substantial influence on the performance of organic materials, resulting in changes in their chemical and physical attributes, which in turn can have an impact on their mechanical and thermal properties [12,13]. Although the impact of moisture has been thoroughly examined under static conditions [14-16], the information and understanding of its combined effects with moisture under dynamic loading onto WPC particularly rubberwood remains relatively limited. Therefore, considering factors like moisture in conjunction with fatigue loading is imperative to comprehensively assess and model the effects of service loads and conditions on prospective materials, ensuring the integrity of fatigue design for safety. In this study, we aim to explore how moisture affects the fatigue characteristics of rubberwood/recycled polypropylene composite to understand the complex behaviour of the materials.

## 2. Methodology

### *2.1 Composite Material and Specimen Preparation*

The materials used in this study are rubberwood / recycle PP (rPP) pellets with the optimised composition of rPP (50.3 wt.%), rubberwood flour (37.5%), calcium carbonate (7 wt.%), MAPP (3.9 wt.%), UV (0.2 wt.%), lubricant (1 wt.%). The manufacturing process of the pellet and specimens is fully detailed in our previous study [8,9]. The rubberwood/ recycled composite plate was cut into dumbbell-shaped for tensile test (ASTM D638).

### *2.2 Conditioning and Hydrothermal Ageing*

Prior to any test, the sample was pre-conditioned at 50% RH at a laboratory temperature of 23°C and labelled as unaged condition. A portion of the specimens was subsequently submerged in distilled water at room temperature(23°C) for a maximum duration of 30 days. The samples were intermittently removed and weighed using a precision electronic balance accurate to 0.01 g. Finally, it was oven-dried until their mass equilibrium was reached. The specimen then is conditioned again at 50% RH at 23 °C prior to the test, the sample is known as the water-aged state.

### *2.2 Mechanical Testing*

Servopulser Shimadzu fatigue machine (Japan) with a capacity of 20 kN load cell was used to assess the static and fatigue performance of the rubberwood-based composite for both untreated and water-exposed samples. For the determination of the ultimate tensile strength of both untreated and treated specimens, a quasi-static test was conducted at a rate of 2 mm/min. Subsequently, fatigue testing was conducted using a tension-tension stress control mode, ranging from 40% to 80% of the ultimate tensile strength of the composite material. During the fatigue tests, a stress ratio (R) of 0.1 and a frequency of 4 Hz were maintained. The tests were continued until fracture occurred or, in cases where failure did not transpire, run-outs were designated after 1.5 million loading cycles.

Five sets of samples are repeated for each test level. All test was performed in air at ambient temperature as described in our previous study [8].

## 3. Results

### *3.1 Quasi-Static Tensile Testing*

The quasi-static properties for unaged and water-aged composites. For the unaged, the mean value for the ultimate tensile strength (UTS), elastic modulus and strain at failure, respectively 26.33 MPa, 1.69 GPa ± 0.16 and 1.59 %, similar to those reported by Srivabut *et al.*, [5]. Exposure of the composite to moisture has induced a significant decrease in their initial ultimate tensile strength and stiffness approximately - 53% and 56% respectively as reported in our preliminary study [17]. The degradation in the rubberwood/recycled PP composites is possibly due to the plasticizing effect of water as well as damage due to ageing [10,13,17]. In terms of the strain observed at the point of failure, a noticeable 18% increase was observed in the water-aged specimen. This change is consistent with the notion that water has a plasticizing effect on the amorphous carbohydrates present in the rubberwood fibres [18].

### *3.2 Fatigue Testing*

The stress and number of cycle (S-N) curves, from the tensile-tensile fatigue tests for both unaged and water-aged composite, are shown in Figure 1. Results show a gradual reduction in fatigue strength as the number of fatigue cycles increases for both conditions. The relationship between fatigue strength and the number of cycles follows the logarithmic equation (Eq.1).

$$S_{max} = \alpha - \beta \ln (N) \qquad (1)$$

where N represent the number of cycles at failure, $S_{max}$ is the ultimate tensile stress, $\alpha$ is the ultimate strength for a single cycle and $\beta$ is the fatigue strength coefficient of the material.

The $\beta$ parameter for the unaged specimens is equal to 1.0. However, upon examination of the aged specimens, a noticeable decrease in maximum stress within the low-cycle range is apparent when compared to their unaged counterparts. To illustrate, after 1000 cycles, the maximum stress following ageing measures is approximately 9.6 MPa, a significant reduction from the 21.6 MPa observed before ageing. Additionally, it's noteworthy that at higher fatigue cycle counts, the aged specimens exhibit a notably prolonged fatigue life compared to the unaged specimens. At 60% UTS, the average fatigue life of the unaged and aged composite is 321,000 and 536,000 cycles. From these findings, we can conclude that hydrothermal ageing, while causing a decrease in static rigidity and strength, actually enhances fatigue resistance as shown by the reduced value of the $\beta$ parameter, which drops to 0.47. This phenomenon is likely attributed to improved damage tolerance resulting from fibre swelling and potentially led to improvement of the matrix/fibre interface [19].

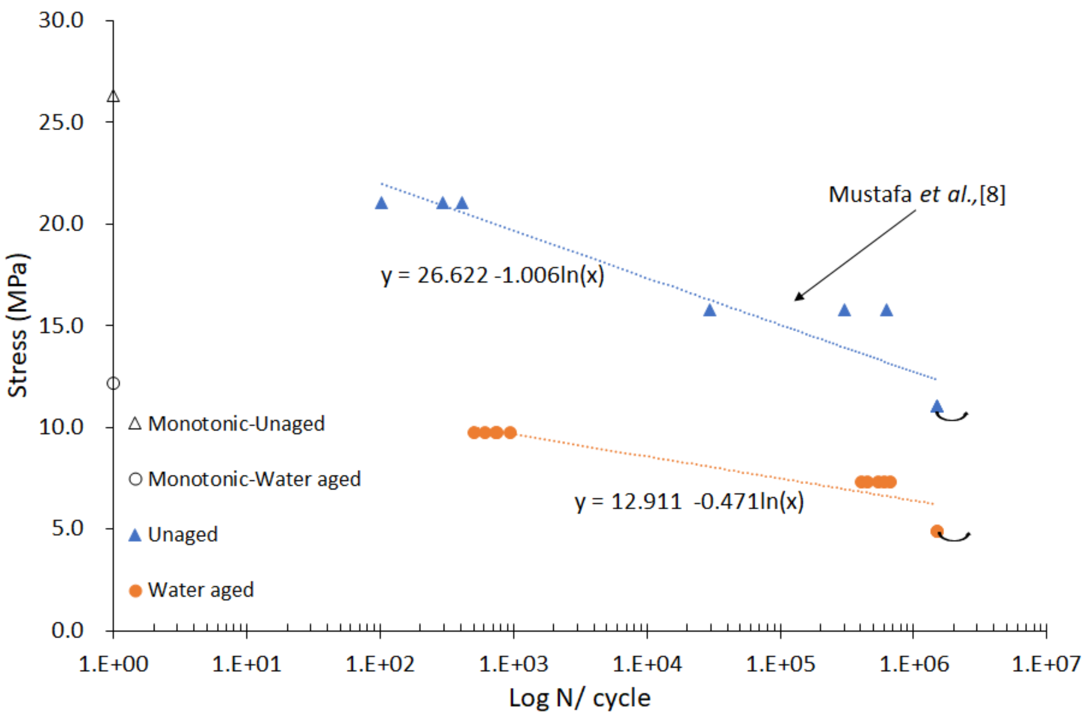


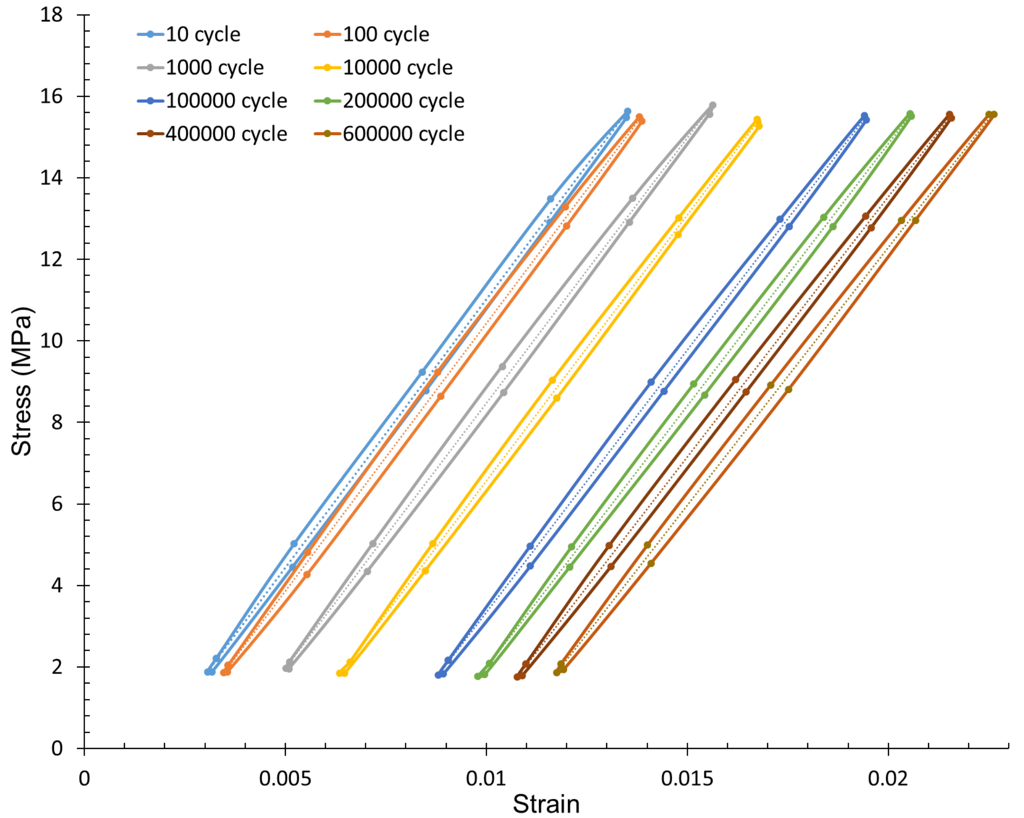

**Fig. 1.** S–N curves of the rubberwood /recycled PP composite collected before and after water ageing (arrows indicate run-out)

Figure 2 shows the hysteresis loop captured during the tension-tension fatigue test for both non-aged and water-aged rubberwood/recycled polypropylene (PP) composites. During cyclic loading, the material demonstrates a hysteresis loop resembling an ellipse. This phenomenon stems from both the viscoelastic properties of the polymer matrix and the friction occurring between surfaces that are debonded and delaminated.

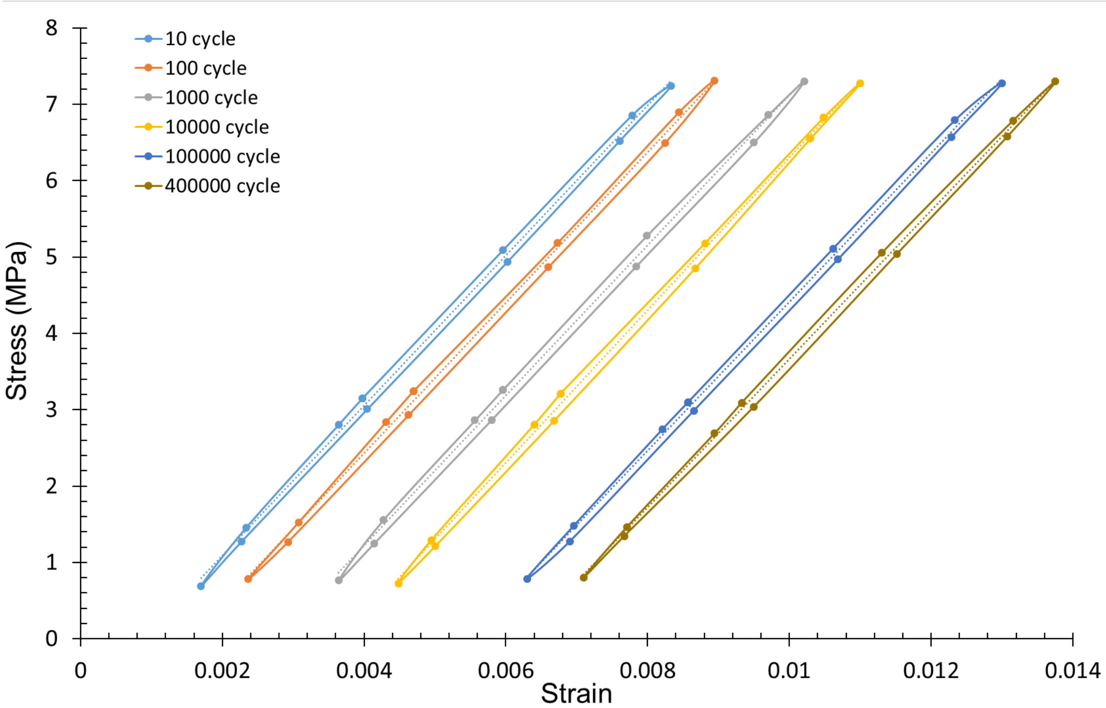
The slope of the load-displacement curve, measured from the highest peak to the lowest peak (known as the secant modulus, E), decreases as the material progresses from the initial first cycle (with the value E1) to cycle N (EN), indicating a reduction in stiffness, a phenomenon referred to as stiffness degradation. Additionally, the load-displacement curve may also shift due to the cyclic creep of the polymeric matrix.

Notably, it can be observed that, in both types of composites (non-aged and aged), the load-displacement curve shifts along the positive strain axis during the last cycle. As cyclic loading persists under fixed amplitude load control, the materials progressively become more compliant, leading to alterations in the amplitude of fatigue strains. This observation suggests significant creep has occurred.

In the case of non-aged wood-polymer composites (Figure 2a), the hysteresis loop is observed to become more open as the cycles progress. Conversely, for the aged composite (Figure 2b), the hysteresis loops of the first and last cycles appear almost identical, suggesting that very little volumetric damage occurred in the composite system before failure [6].




(a)




(b)

**Fig. 2.** Typical hysteresis loops before (a) and after (b) water ageing at different lifetime cycle fractions for a given dynamic stress (60% UTS)

The evaluation of composite stiffness under cyclic loading calculated from the hysteresis loop (Figure 2) is plotted in Figure 3. Stiffness degradation in composites serves as an indicator of the onset of crack propagation within the composite and a weakening of the bond between the fibres and the matrix. In theory, as the number of cyclic loading cycles increases, the density of cracks in the transverse direction tends to rise due to matrix splitting along the fibres. This damage hampers the effective transfer of load between the fibres, potentially leading to fibre failure before reaching the maximum stress observed in monotonic tensile tests, similar to those reported by Cadavid *et al*., [20]. Consequently, the resistance to fatigue and the secant modulus tends to decrease with increasing fatigue life cycles [21,22].

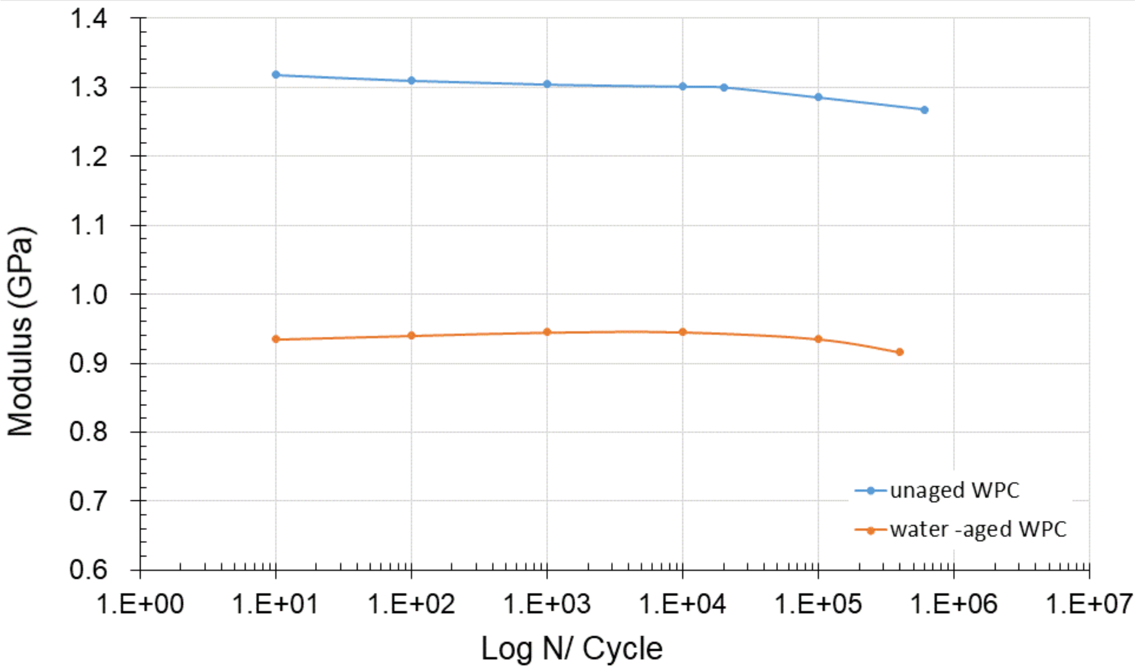



**Fig. 3.** The secant modulus with fatigue life cycle tests before (a) and after (b) water ageing for a given dynamic stress (60% UTS)

## 4. Conclusions

Comprehensive data regarding the mechanical behaviour, particularly the fatigue performance of wood polymer composite in ambient as well as influence by moisture is currently scarce. The objective of this study was to present fatigue data for rubberwood/ recycled PP both in ambient and water ageing. Exposure to moisture has caused a significant decrease in initial ultimate tensile strength and stiffness approximately - 53% and 56%. The composite also becomes more ductile, increasing strain at failure by 18%. However, the presence of moisture led to improvement in their fatigue resistance. The fatigue strength coefficient of the material is nearly halved following water aging, in comparison to unaged specimens. The fatigue hysteresis loop revealed that the non-aged composite exhibits a more expansive area, greater tensile creep, and more pronounced fatigue damage when compared to the aged composite. Thus, despite the high susceptibility of this composite to water, it demonstrates good resistance to ageing even under challenging conditions. However, it can be improved through the application of coatings that can prevent or mitigate water absorption when the material is submerged or exposed to liquid water. These research findings should be factored into the design of bio-based composite structures and when estimating their long-term durability and residual properties.

**Acknowledgement**
The authors acknowledge the financial support from the Universiti Teknikal Malaysia Melaka through a short-term grant (PJP/2023/TD/FKP/S01975) and the use of their laboratory and equipment.

## References

[1] Abdullah, Norihan, Khalina Abdan, Mohd Huzaifah Mohd Roslim, Mohd Nazren Radzuan, Lee Ching Hao, and Ayu Rafiqah Shafi. "Thermal Properties of Kenaf Fiber Reinforced Polyamide 6 Composites by Melt Processing." *Pertanika Journal of Science & Technology* 31, no. 5 (2023). https://doi.org/10.47836/pjst.31.5.16

[2] Al-Ghazali, Noor Abbas, Farah Nora Aznieta Abdul Aziz, Khalina Abdan, and Noor Azline Mohd Nasir. "Mechanical Properties of Natural Fibre Reinforced Geopolymer Composites: A Review." *Pertanika Journal of Science & Technology* 30, no. 3 (2022). https://doi.org/10.47836/pjst.30.3.16

[3] Mydin, Md Azree Othuman, Mohamad Sukeri Khalid, Roshartini Omar, Hadee Mohammed Najm, Shaker Mahmood Abdal Qaidi, and Paul Oluwaseun Awoyera. "Durability Properties of Lightweight Foamed Concrete Reinforced With 'Musa Acuminate'Fibre." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 29, no. 2 (2023): 145-158. https://doi.org/10.37934/araset.29.2.145158

[4] Roseli, Adyla Illyana, Nik Normunira Mat Hassan, Abdul Mutalib Leman, Najibah Abdul Latif, Yulfian Aminanda, Djoko Setyanto, Yuyun Tajunnisa, Yonrapach Areerob, Methawee Nukunudompanich, and Muhammad Farid Azmi. "Morphological, TGA, and FTIR on Rigid Polyurethane Composite Laminated with Untreated and Treated Bamboo Fiber Roof Insulation." *Journal of Advanced Research in Applied Mechanics* 117, no. 1 (2024): 91-106. https://doi.org/10.37934/araset.31.2.268280

[5] Srivabut, Chainarong, Thanate Ratanawilai, and Salim Hiziroglu. "Effect of nanoclay, talcum, and calcium carbonate as filler on properties of composites manufactured from recycled polypropylene and rubberwood fiber." *Construction and Building Materials* 162 (2018): 450-458. https://doi.org/10.1016/j.conbuildmat.2017.12.048

[6] Hacker, C. L., and M. P. Ansell. "Fatigue damage and hysteresis in wood-epoxy laminates." *Journal of materials science* 36 (2001): 609-621. https://doi.org/10.1023/A:1004812202540

[7] Haque, Md Minhaz-Ul, Koichi Goda, Shinji Ogoe, and Yuta Sunaga. "Fatigue analysis and fatigue reliability of polypropylene/wood flour composites." *Advanced Industrial and Engineering Polymer Research* 2, no. 3 (2019): 136-142. https://doi.org/10.1016/j.aiepr.2019.07.001

[8] Mustafa, Z., TM I. Nawi, S. H. S. M. Fadzullah, Z. Shamsudin, S. D. Malingam, and T. Ratanawilai. "Fatigue characteristic and Weibull analysis of sustainable rubberwood flour/recycled polypropylene composites." *International Journal of Automotive and Mechanical Engineering* 18, no. 4 (2021): 9179-9187. https://doi.org/10.15282/ijame.18.4.2021.03.0706

[9] Nordin, M. N. A., Z. Mustafa, T. Ratanawilai, and Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan. "EFFECT OF WATER AGEING ON FATIGUE DAMAGE OF RUBBERWOOD/RECYCLED POLYPROPYLENE COMPOSITES." In Proceeding of 23rd *ICCM International Conferences on Composite Materials*, Belfast (2023).

[10] Subeki, Nur, Achmad Fauzan Hery Soegiharto, Andi Firkriyanto, and Nadiaseptria Gidiazalia. "Crack Propagation Analysis of Fatigue Due to External Corrosion on the Construction of the Ferris Wheel in Alun-Alun Kota Batu." *Journal of Advanced Research in Applied Mechanics* 111, no. 1 (2023): 62-73. https://doi.org/10.37934/aram.111.1.6273

[11] Wang, Wei, Xiaomin Guo, Defang Zhao, Liu Liu, Ruiyun Zhang, and Jianyong Yu. "Water absorption and hygrothermal aging behavior of wood-polypropylene composites." *Polymers* 12, no. 4 (2020): 782. https://doi.org/10.3390/polym12040782

[12] Alaseel, Bassam Hamid, Mohamed Ansari Mohamed Nainar, Noor Afeefah Nordin, Zainudin Yahya, and Mohd Nazim Abdul Rahim. "Effect of Water Absorption on Flexural Properties of Kenaf/Glass Fibres Reinforced Unsaturated Polyester Hybrid Composites Rod." *Pertanika Journal of Science & Technology* 30, no. 1 (2022). https://doi.org/10.47836/pjst.30.1.22

[13] El Hawary, Omar, Luca Boccarusso, Martin P. Ansell, Massimo Durante, and Fulvio Pinto. "An overview of natural fiber composites for marine applications." *Journal of Marine Science and Engineering* 11, no. 5 (2023): 1076. https://doi.org/10.3390/jmse11051076

[14] Zulkafli, Norizzati, Sivakumar Dhar Malingam, Siti Hajar Sheikh Md Fadzullah, Zaleha Mustafa, Kamarul Ariffin Zakaria, and Sivaraos Subramonian. "Effect of water absorption on the mechanical properties of cross-ply hybrid pseudo-stem banana/glass fibre reinforced polypropylene composite." *Materials Research Express* 6, no. 9 (2019): 095326. https://doi.org/10.1088/2053-1591/ab3203

[15] de Seixas, G. B., H. F. M. de Queiroz, J. S. S. Neto, and M. D. Banea. "Effect of water on the mechanical and thermal properties of natural fibre reinforced hybrid composites." *Journal of Composite Materials* 57, no. 11 (2023): 1941-1958. https://doi.org/10.1177/00219983231166570

[16] Mustafa, Zaleha, Anira Shahidah Razali, Siti Hajar Sheikh Md Fadzullah, Sivakumar Dhar Malingam, Azlin Fazlina Osman, and Thanate Ratanawilai. "Mechanical and biodegradation properties of biodegradable unidirectional pineapple leaf fibre/polylactic acid composites." In *AIP Conference Proceedings*, vol. 2496, no. 1. AIP Publishing, 2022. https://doi.org/10.1063/5.0091422

[17] Mustafa, Zaleha, Tuan Muhammad Idzzuddin Nawi, Vaseetha Ravichandran, Toibah Abd Rahim, and Thanate Ratanawilai. "Rubberwood-Recycled Polypropylene Composites: Effect of Water Immersion on Tensile Properties." In *International Conference and Exhibition on Sustainable Energy and Advanced Materials*, pp. 167-170. Singapore: Springer Nature Singapore, 2021. https://doi.org/10.1007/978-981-19-3179-6_30

[18] Ebrahimnezhad-Khaljiri, Hossein. "Hygrothermal aging and their influence on mechanical properties of the bio-composites." In *Aging Effects on Natural Fiber-Reinforced Polymer Composites: Durability and Life Prediction*, pp. 115-136. Singapore: Springer Nature Singapore, 2022. https://doi.org/10.1007/978-981-16-8360-2_7

[19] Jeannin, Thomas, Michaël Berges, Xavier Gabrion, Romain Léger, Véronique Person, Stéphane Corn, Benoit Piezel, Patrick Ienny, Stéphane Fontaine, and Vincent Placet. "Influence of hydrothermal ageing on the fatigue behaviour of a unidirectional flax-epoxy laminate." *Composites Part B: Engineering* 174 (2019): 107056. https://doi.org/10.1016/j.compositesb.2019.107056

[20] Cadavid, M. Ospina, O. Al-Khudairi, H. Hadavinia, D. Goodwin, and G. H. Liaghat. "Experimental studies of stiffness degradation and dissipated energy in glass fibre reinforced polymer composite under fatigue loading." *Polymers and Polymer Composites* 25, no. 6 (2017): 435-446. https://doi.org/10.1177/096739111702500602

[21] Shah, Darshil U. "Damage in biocomposites: Stiffness evolution of aligned plant fibre composites during monotonic and cyclic fatigue loading." *Composites Part A: Applied Science and Manufacturing* 83 (2016): 160-168. https://doi.org/10.1016/j.compositesa.2015.09.008

[22] Jia, Yunlong, Bodo Fiedler, Wenkai Yang, Xinjian Feng, Jingwen Tang, Jian Liu, and Peigen Zhang. "Durability of plant fiber composites for structural application: A brief review." *Materials* 16, no. 11 (2023): 3962. https://doi.org/10.3390/ma16113962