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Recycled Household Plastic and Oil Palm Filler Reinforced Epoxy Composite for Lightweight Construction Applications

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ABSTRACT

Polypropylene is extensively used in aerospace, automotive and construction applications due to its versatile properties. This project aims to reduce plastic and oil palm waste and promote the development of strong, sustainable and eco-friendly construction materials. The objective of this project is to develop a sustainable yet high-performance construction material by incorporating polypropylene particles, oil palm empty fruit bunch (OPEFB) fibres and oil palm shell (OPS) particles into epoxy composites through the hand lay-up method. The composite specimens undergo ASTM D638 tensile test to determine the tensile properties. The addition of PP particles in varying weights shows decrease in tensile strength, likely due to poor dispersion and compatibility with the epoxy matrix. Incorporating 3 wt% OPEFB fibres with fibre length from 2mm to 4mm improves tensile strength by 2.32% and 23.36% respectively at higher PP particle loadings which are 15 wt% and 25 wt%. Adding 1 wt% and 3 wt% OPS particles improves the tensile strength by 2.96% and 4.68% respectively, in composites with 10 wt% PP particles and 3 wt% OPEFB fibres. The tensile performance may be improved by treating PP particles with compatibilizers such as silane or maleic anhydride grafted polypropylene.

Keywords: Polypropylene, oil palm, epoxy composite, tensile properties, construction material.

1 INTRODUCTION

Polymer matrix composite (PMC) is a type of composite material made by combining a polymer matrix with reinforcement. PMCs are widely used in various applications including construction, aerospace, automotive, and energy fields (Guo, Ruan, Shi, Yang, & Gu, 2020). Polypropylene (PP) is a thermoplastic polymer that is widely used in various applications due to its versatile properties. It is commonly found in everyday items such as packaging materials, household goods, and automotive parts. Oil palm is a valuable commercial crop primarily cultivated to produce palm oil which is widely used in food processing, biofuels, pharmaceuticals, and others. Malaysia is the second largest producer of palm oil in the world; hence there are abundant oil palm fibres that can be used in composite material instead of being directly disposed of.

The PP is immiscible with epoxy so the interfacial adhesion between untreated PP particles and epoxy is poor (Singh, Nanda, & Mehta, 2017). The hydrophilic natural oil palm filler including oil palm empty fruit bunch (OPEFB) and oil palm shell (OPS) are incompatible with the hydrophobic polymer including epoxy. Surface modification such as alkali treatment on the natural filler is required to modify the filler surfaces to improve the interfacial bonding between fillers and matrix. The research study on using recycled household PP or PP particles as the reinforcing phase in the composite is limited. This limitation is significant as it underscores the need to explore the potential benefits and applications of such materials in composite manufacturing. This research project aims to study the influence of different filler types such as PP particles, OPEFB fibres and OPS particles on the tensile properties of composites.

2 EXPERIMENTAL DETAILS

2.1 Research Activities Progress

This research project took place in the Geo-Mechanics Lab of Curtin University Malaysia from March to October 2023. E-1101 epoxy and H-191 hardener from Pan Asel Chemicals (M) Sdn Bhd were used in this project. The PPs

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were collected from household plastic. The OPEFB and OPS were provided by Sarawak Oil Palms Berhad in Miri, Sarawak.

2.2 Materials Preparation

The polypropylene (PP) was washed with tap water and detergent to remove physical contaminants and rinsed with distilled water. The PP was wiped dry and dried with a hair dryer until completely dry. The PP were cut manually with scissors into smaller pieces, blended into particles with a blender and sieved through 1 mm sieve. The collected OPEFB and OPS were washed with tap water to remove contaminants and dried at 105°C for 24 hours in the Memmertz oven to reduce moisture content. The OPEFB and OPS were then soaked in 5% sodium hydroxide solution for 24 hours for alkaline treatment. The OPEFB and OPS were washed with tap water, soaked in distilled water for 1 hour, washed again to remove the sodium hydroxide, and dried in oven at 105°C for 12 hours. The OPEFB fibres were cut with scissors to obtain fibre length between 2mm to 4mm and sieved through a 500µm sieve to ensure the fibres were sufficiently short. The OPS were crushed with blender and the crushed OPS were sieved to obtain fine particle size which is below 300 µm. The OPEFB fibres and OPS particles were stored in airtight plastic containers separately to avoid contact with atmospheric moisture.

2.3 Composite Specimens Preparation

The ratio of epoxy to hardener is 2:1. In the first stage of composite preparation, PP particles with weight percentage of 0 wt%, 5 wt%, 10 wt%, 15 wt%, 20 wt% and 25 wt% were used as reinforcement of the composites. Their tensile strengths were determined through the ASTM D638-22 tensile test. In the second stage, composite specimens with the same weight percentages of PP particle were reinforced with 3 wt% OPEFB fibres. The composite specimens were subjected to tensile test again to determine the effect of OPEFB fibres on the tensile strength when different weight percentages of PP particles were applied. In the third stage, selected PP particle contents (0 wt%, 5 wt%, 10 wt%, and 15 wt%) with higher tensile strength and OPS particles (1 wt%, 2 wt%, and 3 wt%) were applied to fabricate composite specimens. Tensile tests were then conducted on the specimens to determine the optimal weightage of OPS particles for the composites. The methodology of this research project is shown in Figure 1.

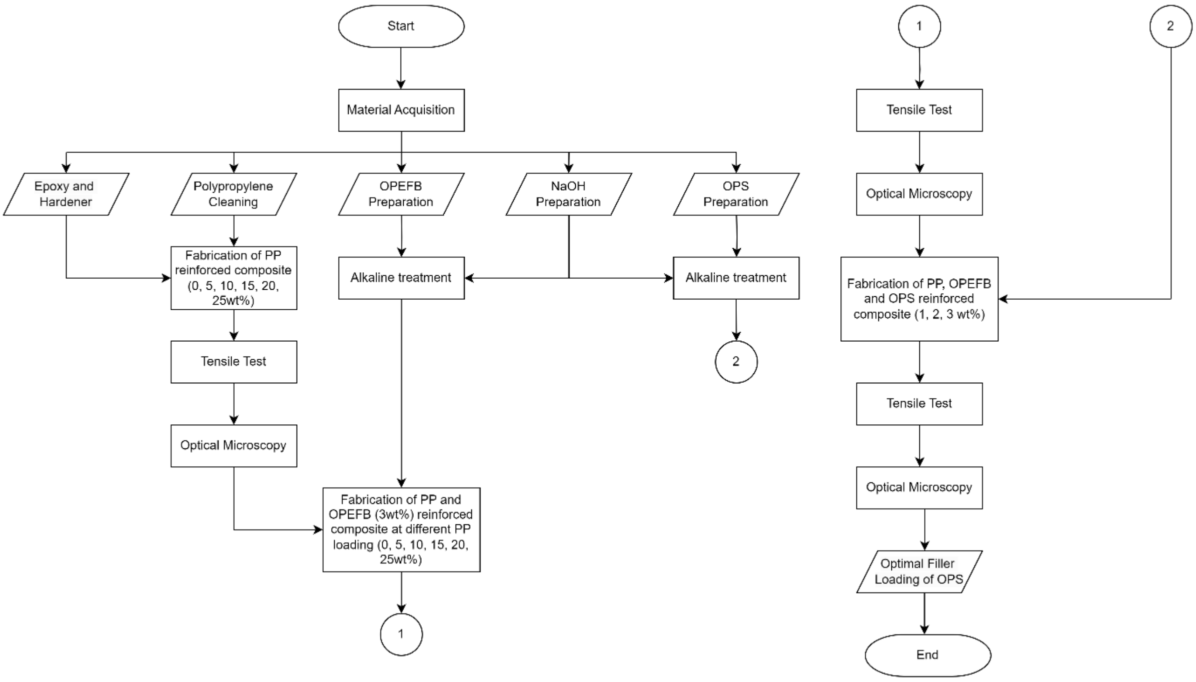


Figure 1: Methodology flowchart.

The epoxy and hardener were poured into disposable cups and weighed using an electronic balance to obtain a total mass of about 45g. The required amounts of PP particles, OPEFB fibres and OPS particles were weighed, added into the disposable cup with epoxy and hardener, and stirred gently by using a popsicle stick in anticlockwise direction for 2 minutes. The disposable cup with the mixture was put in vacuum chamber for 10 minutes to reduce the amount of air bubbles in the mixture. The mixture was stirred again by using a popsicle stick in anticlockwise direction for 1 minute. The mixture was poured into the mould and left in the laboratory at room temperature for 24 hours. The mould with the mixture was then placed in laboratory oven at 100°C for 1 hour for the post-curing process. The composite specimens were removed from the moulds and placed on table. Then, the moulds were placed on the specimens for 2 hours to minimize potential deformation of the specimens. 4 specimens were fabricated for each combination of the reinforcement weightage.

2.4 ASTM D638-22 Tensile Test

The fabricated specimens will undergo tensile test by using Lloyd LR Plus Universal Testing Machine. The tensile test will be based on ASTM D638-22 testing standard as it is used to determine the tensile properties of polymer composites which are tensile strength, tensile modulus, elongation and Poisson's ratio (Raj, Michailovich, Subramanian, Sathiamoorthyi, & Kandasamy, 2021). The specimen thickness is about 3.2mm. The shape of the specimen is similar to a dumbbell as shown in Figure 2. Among 5 types of specimens, the type I specimen is chosen to be used in this project and the specimen dimensions are shown in Table 1. The speed of testing for the specimens is 5 mm/min.

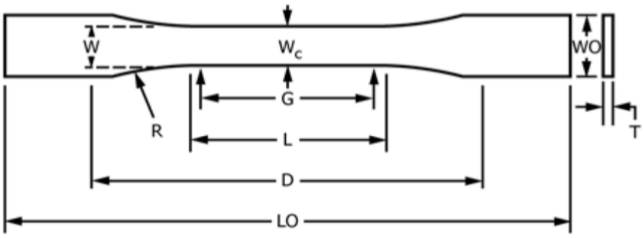


Figure 2: Specimen of ASTM D638-22. From "D638 Standard Test Method for Tensile Properties of Plastics," by American Society for Testing and Materials, 2022, p. 5. Copyright 2022 by ASTM.

Table 1: Dimensions of type I specimen

Dimensions	Value (mm)
Thickness, T	3.2
Width of narrow section, W	13
Length of narrow section, L	57
Width overall, WO	19
Length overall, LO	165
Gage length, G	50
Distance between grips, D	115
Radius of fillet, R	76

Adapted from: "D638 Standard Test Method for Tensile Properties of Plastics," by American Society for Testing and Materials, 2022, p. 5. Copyright 2022 by ASTM.

2.5 Optical Microscopy

The fractured surfaces of composite specimens chosen for optical microscopy were sawed with handsaw, resulting in specimens with thickness of approximately 5 mm. The fractured surfaces of the sawn specimens were then subjected to optical microscopy using Olympus BX53M Microscope.

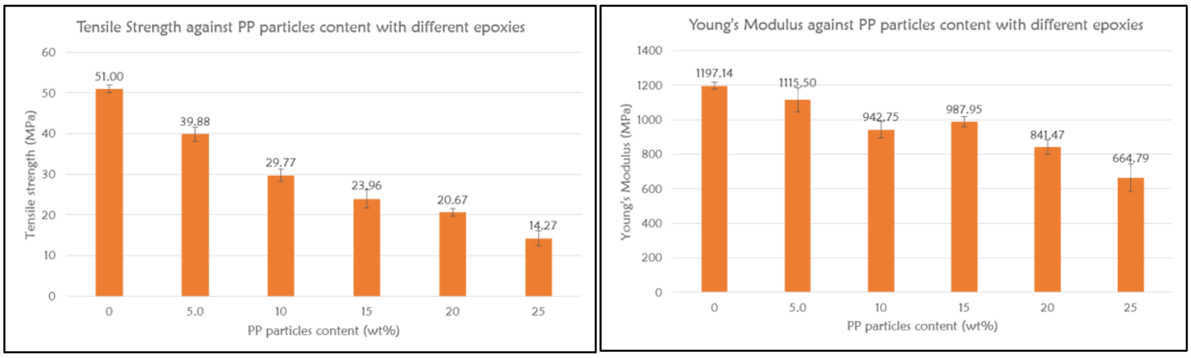
3 RESULTS AND DISCUSSIONS

3.1 PP Particle Reinforced Epoxy Composite

The tensile strength and Young's Modulus of the neat epoxy specimen are 51 MPa and 1197.14 MPa as shown in Figure 3 (a) and (b). The inclusion of the untreated PP particles caused the decrease in the tensile strength and Young's Modulus until they reached 14.27 MPa and 664.79 MPa, respectively. As the PP particle content increases, the tensile strength and Young's modulus decrease. According to the research of Singh et al. (2017), the inclusion of untreated PP fibres diminished the tensile, flexural and impact strength due to the incompatibility of PP fibres with epoxy and other components. The compatibility can be improved by silanisation treatment or maleic anhydride grafting. For instance, the functional groups of maleic anhydrides grafted PP react and act as the chemical link with the epoxy group of the epoxy resin. As per the research of Li, Wen, Liu, & Tang (2014), it was observed that ester bond and new carboxyl group were formed from the reaction between the hydroxyl group of epoxy and anhydride group of MAPP. With the inclusion of MAPP and epoxy, the tensile strength and Young's modulus of the composites (PP/MAPP/epoxy/short carbon fibre) were improved by 273% and 239% respectively.

The lower density of PP compared to epoxy causes the PP particles to float in the epoxy resin after stirring and degassing processes. Despite stirring it again, the PP particles still tend to float when the mixtures were poured into the moulds. This uneven dispersion of PP particles causes poor load distribution between the epoxy matrix and PP particles, which is detrimental to the tensile properties of the composite. During the blending of PP particles, electrostatic charges might be generated on the PP particles, causing them to adhere to the blender wall or agglomerate. Agglomeration causes stress concentrations and impedes the load transfer in the composite.

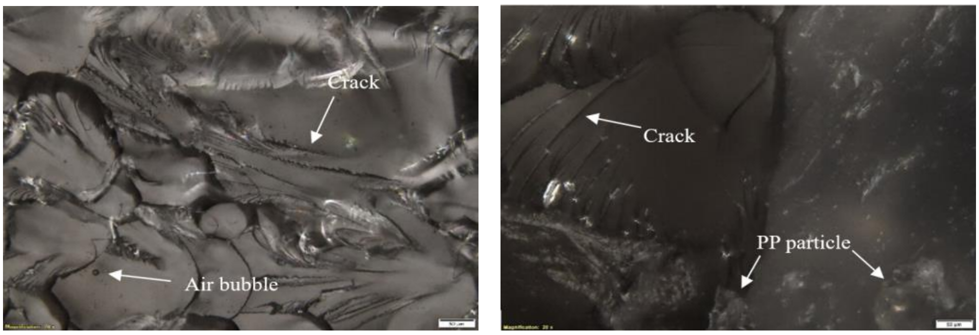
The blended PP particles which were sieved through a 1 mm sieve, mostly exceed 700 µm due to equipment limitations. Larger particles are prone to critical flaws which lead to crack initiation and propagation. Smaller particle sizes enhance composite mechanical properties by increasing the surface area between the matrix and particles and improving load transfer efficiency (Fu, Feng, Lauke, & Mai, 2008). The immiscibility between PP and epoxy results in poor interfacial adhesion and mechanical properties. Air bubbles in epoxy act as local stress concentrations and promote crack growth. Recycled household PP may contain impurities such as polyethylene, propane, methane, and water.



(a) (b)

Figure 3: (a) Tensile strength (b) Young's Modulus of composite against PP particle content.

The epoxy composite specimens with PP particle content of 0 wt% and 5 wt% were chosen for optical microscopy as they have higher tensile strength and a considerable amount of PP particles. Both Figure 4 (a) and (b) indicate crack propagation on the fractured surface. The cross-linked polymer chain structure in the cured epoxy improved the strength but also increased its brittleness so it is poor to resist crack initiation and propagation. Air bubbles were observed in neat epoxy specimens and serve as local stress concentrations and cause premature failure. Despite degassing, the air bubbles might still enter the mixtures during the second stirring process. Figure 4 (b) shows that the PP particles appear to be irregularly shaped and have rough surfaces. The interfacial bonding between PP particles and epoxy matrix is poor due to the incompatibility of PP and epoxy which can be improved by treating PP particles with maleic anhydride grafted polypropylene (MAPP) or silane (Alo, Otunniyi, Pienaar, & Sadiku, 2021).



(a) (b)

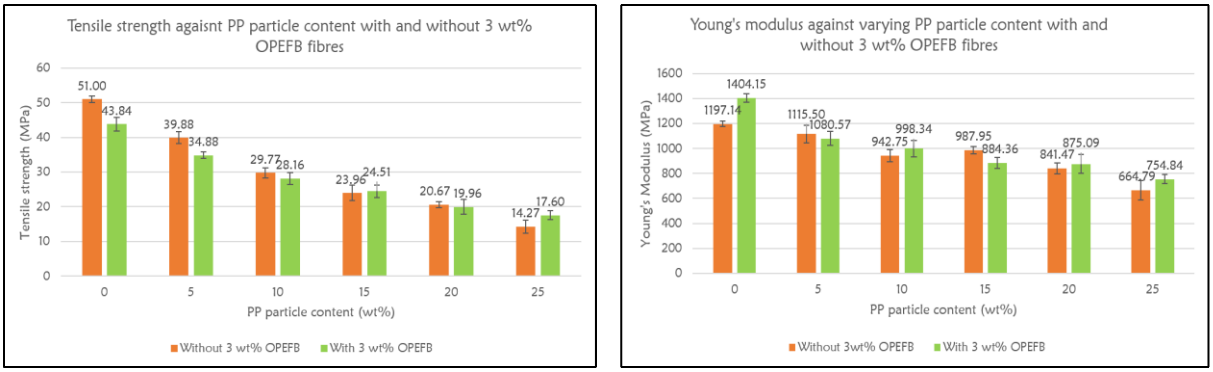
Figure 4: Optical microscopy of specimens with (a) 0 wt% PP particles (b) 5 wt% PP particles.

3.2 PP Particle and OPEFB Fibre Reinforced Epoxy Composite

3 wt% OPEFB fibres were added into composite specimens containing PP particle content ranging from 0 wt% to 25 wt% to determine their effect on tensile properties, while maintaining consistent contents of PP particle and epoxy from the previous stage. Incorporating 3 wt% OPEFB fibre into the composites still leads to decreasing tensile strength as PP particle content increases. However, the difference in tensile strengths between composites with and without OPEFB fibre decreases with increasing PP particle content. At 15 wt% PP particle content, the composites with 3 wt% OPEFB fibre showed higher tensile strengths than those without. Specifically, at 15 wt% PP particle content, tensile strength improved from 23.96 MPa to 24.51 MPa with an improvement of 2.32. At 25 wt% PP particle content, tensile strength improved from 14.27 MPa to 17.60 MPa with an improvement of 23.36%.

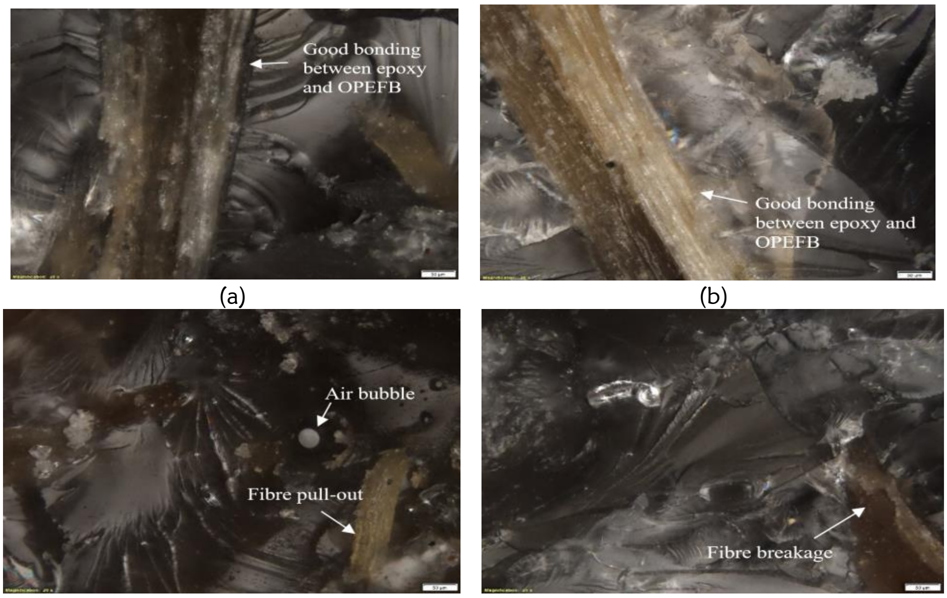
The reduced differences in tensile strength between composite specimens with and without OPEFB fibre suggest that the inclusion of 3 wt% OPEFB improved tensile strength, especially at PP particle contents of 15 wt% and 25 wt%. The results are in line with the research done by Putra et al. (2019), which stated that the rough and porous surfaces of alkaline-treated OPEFB fibres form strong mechanical locking with the matrix and improve tensile performance. The mechanical locking generated at the interface between OPEFB fibre and epoxy matrix during epoxy curing provides excellent resistance to the debonding of OPEFB fibres from the interface. From another investigation done by Puttaswamygowda, Sharma, Ullal, & Shettar (2024), the increase in strength is mainly caused by the betterment of the surface of the fibres after treatment that removes the dirt and lignin content present on the surface of the fibre. This will eventually cause the surface of the fibre to be rougher which in turn enhances the interfacial bonding ability between the fibre and the matrix. The randomly oriented OPEFB fibres provide better strength and Young's modulus under multidirectional loads, reducing cracking and impact due to random fibre orientation. Longitudinally aligned fibres improve tensile properties as the fibres are aligned in the direction of load and allow effective load transfer between fibres and matrix (Shinoj, Visvanathan, Panigrahi, & Kochubabu, 2011). Therefore, aligning fibre orientation to the tensile load direction improve composite tensile strength and Young's modulus.

The composite specimens with PP particle content of 0 wt%, 5 wt%, 10 wt% and 15 wt%, along with 3 wt% OPEFB fibres were chosen to undergo optical microscopy. In Figure 6, good interfacial bonding between OPEFB fibres and epoxy matrix was observed. The alkaline treatment made the OPEFB fibre's surface rough and remove impurities such as hemicellulose, lignin and waxes. Without the impurities, more fibre surfaces can be exposed to the interface for mechanical locking, improving the mechanical properties of composite (Mohammed et al., 2022). In Figure 6 (c), air bubbles were observed, and they are the most common source of void. The voids prevent the interfacial bonding between fibres and matrix, thus, weakening the tensile strength and Young's modulus of the composite (Ismail, Mohd Radzuan, Sulong, Muhamad, & Che Haron, 2021). The fibre pull-out shown in Figure 6(c) indicates a poor interfacial adhesion between the fibres and matrix as the load applied was not transferred to the fibres effectively. The fibre breakage shown in Figure 6 (d) depicts that the OPEFB fibres contribute to the load-carrying capacity of the composite as the load applied was transferred to the fibre, causing the fibre to break.



(a) (b)

Figure 5: (a) Tensile strength (b) Young's Modulus with varying PP particle with & without 3 wt% OPEFB fibres



(a) (b)

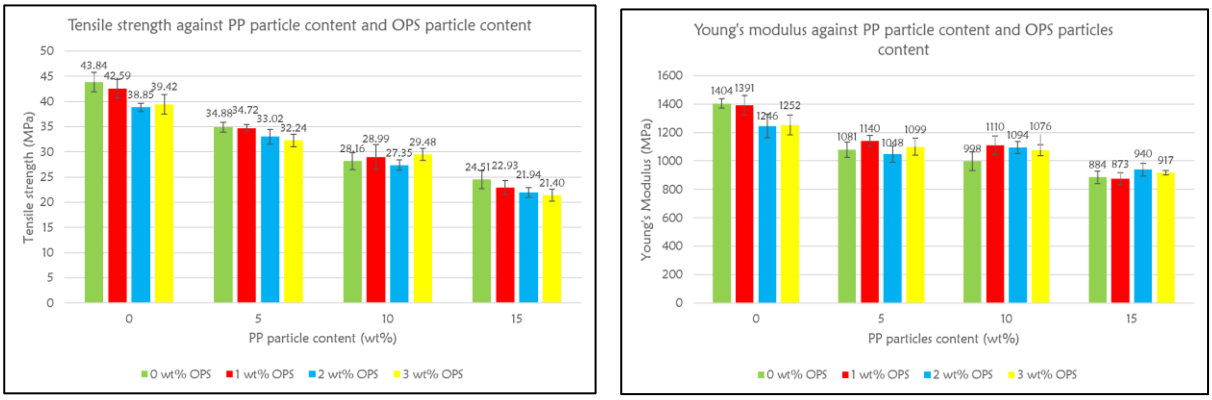
(c) (d)

Figure 6: Optical microscopy of specimens with (a) 0 wt% PP particles and 3 wt% OPEFB fibres, (b) 5 wt% PP particles and 3 wt% OPEFB fibres, (c) 10 wt% PP particles and 3 wt% OPEFB fibres, and (d) 15 wt% PP particles and 3 wt% OPEFB fibres

3.3 PP Particle, OPEFB Fibre and OPS Particle Reinforced Epoxy Composite

1 wt %, 2 wt% and 3 wt% OPS particles were added into the composite specimens containing PP particle content of 0 wt%, 5 wt%, 10 wt% and 15 wt%, along with 3 wt% OPEFB fibres to determine the effect of OPS particles content on the tensile properties. The contents of PP particles, epoxy and OPEFB fibres were maintained as in the previous stage. As depicted in Figure 7 (a), it revealed a negative correlation between the PP particle content and tensile strength at PP particle content of 0 wt%, 5 wt% and 15 wt%. Nonetheless, at PP particle content of 10 wt%, when the OPS particle contents are 1 wt% and 3 wt%, the tensile strengths of the composite are 28.99 MPa and 29.48 MPa which show improvements of 2.96% and 4.68% compared with 0 wt% OPS. The Young's modulus is not affected by the inclusion of OPS particles as the Young's modulus values remain consistently similar for all OPS particle content.

Incorporating OPS particles enhances the tensile strength of the hybrid composite by providing an effective surface contact area with the epoxy matrix and improving mechanical locking between the OPS particles and matrix. This allows stress to transfer effectively to the particles through enhanced interfacial adhesion. Fine-sized OPS particles which are below 300 µm offer superior tensile properties compared to coarse-sized particles (Aini et al., 2018). However, the irregular shapes and sizes of OPS particles may cause local stress concentration, potential crack initiation and propagation. Agglomeration of OPS particles within the matrix can result in uneven distribution of the reinforcing phase, creating weak spots in the composite where stress transfer may be ineffective (Zare, 2016).



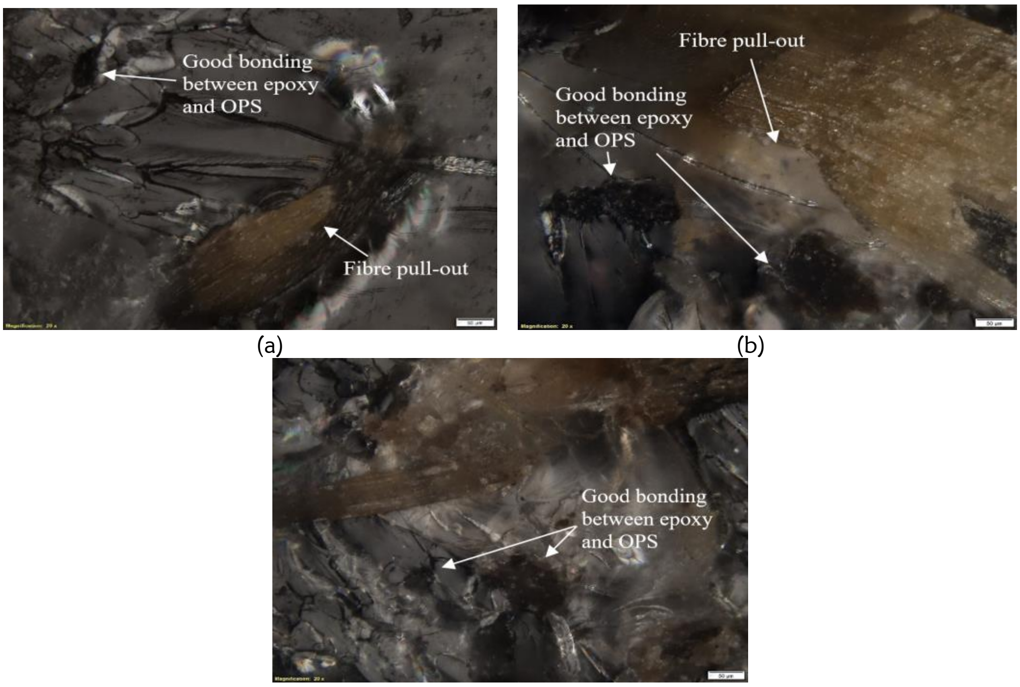
(a) (b)

Figure 7: (a) Tensile strength (b) Young's modulus against PP particle content and OPS particle content.

The composite specimens containing 1 wt%, 2 wt%, and 3 wt% OPS particles, along with 10 wt% PP particles and 3 wt% OPEFB fibres were subjected to optical microscopy as they showed improved tensile strength and considerable PP particle content. Microscopic images of the fractured surfaces indicate irregularly shaped and rough-surfaced OPS particles as shown in Figure 8. Alkaline treatment provides a rougher and cleaner surface for the OPS particles, hence, the interfacial adhesion between particles and matrix improved. No filler pull-out was observed, indicating strong interfacial adhesion between OPS particles and the epoxy matrix. Air bubbles that could create voids and cause structural defects were not observed. However, the irregular shape of OPS particles may limit stress transfer and deteriorate composite mechanical properties (Khalid, Ratnam, Chuah, Ali, & Choong, 2008). From the study of Liu et al. (2023), when the particles have an irregular shape, it might cause significant stress concentration at local edges and corners that eventually lead to local failure.

3.4 Feasibility of Hybrid Composite in Lightweight Construction Applications

At the third stage, the hybrid composite with 10 wt% PP particles, 3 wt% OPEFB fibres, and 3 wt% OPS particles exhibits a tensile strength of 29.48 MPa. While tensile strength is not the sole consideration in lightweight construction, it can serve as a useful indicator of the composite's suitability. It is also essential to consider other factors such as compressive strength, density, stiffness, hardness, impact strength as they also affect the material performance. For instance, compressive strength is one of the most significant indicators as it indicates the material's capacity to resist loads until reaching failure. (Jaya, 2020). Nevertheless, there is no mould for specimens of ASTM D695 compressive test in the laboratories as it would be more beneficial to this project. Stiffness or rigidity is also important for structural integrity and stability. Materials with high stiffness can resist deformation under load and provide better support for the structure. Table 2 compares common materials for conventional and lightweight construction with the hybrid composite in this research project. Its tensile strength falls between concrete and polymer composites and can be used in lightweight construction if defects like crack propagation, air bubbles, and agglomeration can be reduced.



(a) (b)

(c)

Figure 8: Optical microscopy of specimens with 10 wt% PP particles, 3 wt% OPEFB, (a) 1 wt% OPS particles, (b) 2 wt% OPS particles, and (c) 3 wt% OPS particles.

Table 2: Tensile strength of construction materials

Materials	Tensile strength (MPa)
Concrete	2-5
Structural steel	360-550
Hardwood	51.0-120.7
Softwood	45.4-117.7
Polystyrene	25-69
Low-density polyethylene	40-78
High-density polyethylene	14.5-38

Adapted from:

1. "A review on the tensile properties of natural fibre reinforced polymer composites," by Ku, Wang, Pattarachaiyakoop, & Trada, 2011, *Composites Part B: Engineering 42*(4), 858. Copyright 2011 by Elsevier Ltd.
2. "Disciplines Involved in Offshore Platform Design," by Samie, 2016, *Practical Engineering Management of Offshore Oil and Gas Platforms*, 2016, Gulf Professional Publishing. Copyright 2016 by Elsevier Inc.
3. "Study on the Fracture Toughness of Softwood and Hardwood Estimated by Boundary Effect Model," by Ji, Liu, & Li, 2022, *Materials 15*(11), p. 6. Copyright 2022 by the authors.

4 CONCLUSIONS

According to the research study of the influence of different filler types on the tensile properties of the hybrid composites, conclusions can be drawn that:

1. A negative correlation exists between the recycled household PP particle content and the composite tensile properties.
2. The tensile properties of the composite are improved by the inclusion of OPEFB fibres and OPS particles. In composites with PP particle loadings of 15 wt% and 25 wt%, the inclusion of 3 wt% of OPEFB fibres improves the tensile strength by 2.32% and 23.36% respectively. In composites with 10 wt% PP particles and 3 wt% OPEFB fibres, adding 1 wt% and 3 wt% OPS particles improves the tensile strength by 2.96% and 4.68% respectively.
3. Hybrid composites with 10 wt% PP particle, 3 wt% OPEFB fibre, and 3 wt% OPS particles have the most effective combination of overall filler content and provide sufficient tensile properties in lightweight construction applications.

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