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RESEARCH ARTICLE

Characteristics of Mechanical Strength of Hybrid Reinforced Plastic Waste Mixed with Wood Waste

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ABSTRACT - Commercial products made of plastics or wood have always been in high demand until now. Consequently, waste from these products has increased, accumulated, and catastrophically impacted the environment. Through recycling, waste products are not only reduced but will also be easily available for improvement or manufacturing new products. This research focused on the fabrication of lightweight composites using plastic waste (PW) and wood waste (WW) as reinforcement and epoxy as a matrix suitable for tile applications. It was revealed that the density of PW-WW polymer composite increased with increasing PW loading up to a 4.0 ratio at 1.070 g/cm^3 with a porosity of 0.05%. Optical microscope analysis at 100X magnification showed good bonding between the reinforcements (PW and WW) and matrix (epoxy). With a maximum bending strain of 2.41%, the 3.0 ratio achieved the highest bending strength of 2069.20 N, followed by the bending stress at 8.28 MPa. The PW-WW polymer composite with a composition ratio of 3.0 showed a maximum tensile force of 313.8 N and a tensile strength of 1.79 MPa. The composite with a 4.0 ratio had the greatest impact strength (1.67 kJ/m²), followed by the composite with a 3.0 ratio (1.44 kJ/m²). In summary, a 3.0 ratio is the best polymer composite composition for tile applications.

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1.0 INTRODUCTION

Due to the expanding human population, carbon overload, and environmental problems, people need to be more conscious of and accountable for recycling waste. Waste disposal is one of the primary problems facing the urban surroundings in most countries today [1]. Solid waste disposal is a severe and widespread issue in industrialized and developing nations, both in urban and rural areas [2]. A recent report by the Organisation for Economic Co-operation and Development (OECD) stated that the amount of plastic waste produced worldwide has doubled in the last 20 years. Of this waste, only 90% is recycled properly, while the rest ends up in landfills, incinerators, or seeps into the environment. OECD also claimed that about half of the waste produced is plastic [4]. Plastics account for 60% to 80% of marine trash, and Malaysia was rated 28th in the world for plastic pollution in 2021 [5]. Plastic waste is a significant environmental issue due to its extensive use, lingers in the environment, and damaging ecosystems [6]. Malaysia is home to one of the largest plastics manufacturing industries, with more than 1,300 plastic companies worldwide. Global plastic producers received resin shipments worth RM 30 billion in 2016 [7].

Plastic waste has grown into a major environmental problem on a global scale as a result of its extensive usage, inappropriate disposal, and sluggish rate of environmental degradation [8]. Plastics are strong and non-degradable, and they end up accumulating in the environment over time. Plastic waste can persist in landfills, rivers, seas, and ecosystems for hundreds to thousands of years, endangering human health, animals, and marine life [3,9]. Over time, larger plastic objects break down into smaller pieces called microplastics, which are less than five millimeters, which will eventually fill lakes and oceans, soil, and even air. They pose threats to ecosystems and public health as they can absorb pollutants, accumulate toxins, and be consumed by living species [10]. Larger plastic waste and microplastics are improperly collected and disposed of, which are the main sources of plastic pollution. The leakage of microplastics from industrial plastic pellets, road markings, synthetic textiles, and tire wear is a major source of concern [15]. In addition to damaging soil, waterways, and landscapes, improper disposal of plastic waste contributes to land pollution and destruction of natural habitats. Environmental pollution can be exacerbated by the release of hazardous substances into the environment through plastic waste [11].

The low biodegradability of plastic has always been its major drawback. Therefore, recycling is the best treatment for plastic waste these days, and it entirely sustains mankind and the environment [13]. Plastic waste offers a lot of potential for creating new products with extraordinary added value. Demand for recycled products, such as plastics, papers, metals, and alternative materials, will escalate as a result of their diverse applications in various sectors. Since the 1950s, 8.3 billion metric tonnes of plastic were produced and 60% (4.9 billion tonnes) of that ended up in lowlands or polluting the environment[12]. As a result, most industries have introduced recycled materials into their products to reduce waste and

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hazards and enhance the value of life. It is vital for humans to realize that improper waste disposal and management presently will have adverse impacts on health, nature, and even man-made infrastructures [14].

Conventional covering systems have been the foremost widely used technique in several countries before the introduction of recent products. The exploitation of plastic and wood waste mixtures in tile applications will unravel numerous setting drawbacks. This approach definitely supports zero-waste campaigns, green movements, and a sustainable environment. New or modified environmentally friendly merchandise will be successfully materialized as waste materials are inexpensive and readily available [16]. P. R. Oliveira (2020) stated that the term composite is defined as a material consisting of two or many elements with properties that are completely different from any of the original materials. It can be classified as reinforced with fibers, particulates, and laminates. Wood-plastic composite (WPC) is also characterized as lightweight material and simple to mold, permitting complicated shapes without seams and with specified colors and uses. Among the most obvious benefits of this waste material is the minimal risk of use. In the case of reinforcement in composites, apart from reducing the price of the product, it also helps to reduce waste [17]. The combination of composites with polymers is restricted to low operating temperatures below 30°C, such as polypropene (PP) and polyester (PE), so as not to harm the wood particles (Chen et al., 2023). Moreover, wood fibers and plastics are potential replacements for costly reinforcements in composite fabrication.

2.0 LITERATURE REVIEW

Only a small fraction of the plastic waste is mostly potable and alternative bottles have been found. The remaining amount of plastic waste needs to be disposed of. Most of this plastic waste has accumulated in landfills [18]. To mitigate plastic waste management and disposal capacity, there is a growing interest in the development of newer, promptly perishable plastics and the biodegradation of typical plastic waste for circular [19]. Many materials are capable of reinforcing polymers, such as cellulose in wood, which is a naturally occurring product [20]. Although many forms of fibers are used as reinforcement in composite laminates, glass fibers account for more than 90% of reinforced plastics due to their low cost and relatively good strength-to-weight characteristics. A composite material is made by combining two or more materials that often have very different properties but are able to work together to give the composite unique properties. Most composites are made of only two materials, and one of the materials is a matrix or binder. It surrounds and binds together fibers or fragments of the other material and is known as reinforcement. Within the composite, different materials can be easily distinguished as they do not dissolve or blend with each other.

Natural composites exist in both animals and plants [21]. Wood is a composite; it is made of long cellulose fibers with a polymer held together by a much weaker substance called lignin. Daniel Friedrich (2022) studied changes in the key mechanical properties from the post-process hot pressing of commercial WPCs with different fiber contents. The study showed that mechanical properties were positively impacted by hardwood materials as opposed to softwood and fewer fibers. Hardwood floors should be used in WPC construction whenever feasible. These materials are more load-bearing and also sustainable [22]. On the same note, Daniel Friedrich (2022) reported that the physical properties of hot-pressed WPC, particularly the density, were somewhat affected by the fabrication methodology. Due to volatile chemical constituents that escape in hot weather, there is a noticeable loss of weight. Although the density is less susceptible to heat pressing, further study can attempt to further stabilize this physical parameter to produce more heat-resistant materials [23]. If hot pressing is conducted at a moderate temperature and for a shorter period of time, the detrimental effects of hot pressing on WPC semi-finished goods are reduced.

D. Guo et al. (2022) studied the preparation and mechanical failure analysis of wood-epoxy polymer composites (WEPC). The outcomes indicated excellent mechanical performance, where MOR, MOE, impact strength and compression strength were 137.3%, 110.5%, and 86.5%, respectively, better than untreated wood [24]. Due to a large part of the epoxy polymer's ability to spread mechanical stress, the modulus and strength of WEPC increased. The addition of high-strength polymers was found to increase the mechanical characteristics of the cell wall by up to 15%. The enhanced resilience was ascribed to the rise in longitudinal cell division, in addition to the "crack propagation" and "debonding" between the multilayer cell wall components. The findings also indicated that the samples' tensile strengths increased gradually, which was in line with the increase in the mechanical strength of WEPC (compressive strength and MOR). This implied that the mechanical strength of the epoxy polymers had a significant impact on the mechanical strength of WEPC. Furthermore, adding higher-strength epoxy resins to wood increased the strength of WEPC (such as 1BTM samples) [24]. A.R. Bhat et al. (2023) examined the tribo-mechanical properties of natural fiber-reinforced polymer composites. The outcome of the study demonstrated that many natural fibers and their composites are still underutilized, and there appears to be a lot of potential. It is also important to look at different indigenous species containing a substantial amount of natural fibers. Subsequent research endeavors could center on polymer composites and the amalgamated impacts of diverse natural fibers [25].

The special qualities and benefits that epoxy resins provide have drawn attention to studies that use them to bind plastic and wood waste in composite products [26]. Owing to its exceptional mechanical and adherence qualities, epoxy resins are a good choice for binders when it comes to strengthening WPC. It has been shown in earlier research that adding epoxy resins to WPC formulations could greatly increase the composite materials' tensile strength, flexural strength, and impact resistance [27]. A strong connection between the wood/plastic particles and epoxy matrix improves load transfer in composite construction, which escalates its mechanical performance. Epoxy resins can improve the weatherability and durability of WPC as they provide superior resistance to chemicals, moisture, and environmental deterioration [28].

In another research, Milad Bazli et al. (2022) reviewed the durability of fiber-reinforced polymer-wood composite members subjected to challenging environments, such as UV radiation, humidity, and temperature changes. Based on the results, the epoxy-modified WPC outperformed the standard WPC in terms of resistance to deterioration, water absorption, and dimensional stability. The PF resin-bonded samples exhibited superior mechanical qualities compared to the UF resin-bonded samples. Another previous study was reported by P. Prabhu et al. (2022) on the mechanical, tribology, dielectric, thermal conductivity, and water absorption behavior of Caryota woven fiber-reinforced coconut husk biochar strengthened WPC. The study highlighted the significance of using biochar produced from coconut husk biomass fiber for the production of environmentally friendly, high-toughness composites. The mechanical and wear properties of the epoxy resin were enhanced by the addition of fibers. On the other hand, mechanical, wear resistance, dielectric, and thermal conductivity were further increased when biochar particles were added to the resin. The highest possible tensile and flexural strength could be attained when the resin contained 5% of biochar particles [29]. The load-bearing effect decreased beyond 5wt%. The highest dielectric permittivity and thermal conductivity were reached when 7 wt% of biochar was added to the resin. Natural fibers have the potential to significantly improve the mechanical qualities of polymer composites. Reinforcement in hybrid form could be utilized to enhance wear characteristics [30].

Epoxy-based WPCs have potential uses in several sectors, including aerospace, automotive, marine, and construction. The suitability of epoxy-modified WPCs for particular applications, such as furniture, decking, cladding, and structural components, has been the subject of previous research. Studies of commercial viability evaluated epoxy-based WPCs' affordability and market acceptability in comparison to traditional materials, taking into account several variables, namely raw material availability, processing expenses, performance specifications, and environmental effects [31]. To minimize flaws in the finished composite material and provide a homogenous dispersion of wood/plastic fillers inside the epoxy matrix, processing processes must be optimized. Researchers have looked into a number of production techniques to create epoxy-based WPCs with regulated microstructures and enhanced mechanical qualities, including compression molding, resin transfer molding (RTM), and vacuum infusion [32]. Process factors, including curing temperature, pressure, and resin formulation, were optimized to guarantee appropriate curing and bonding between the matrix and filler components.

The unique blends of WPC features in terms of the aesthetic appeal of genuine wood, the durability of polymers, and the versatility of resin binders are becoming promising as potential tile materials. Referring to polymer and resin components, WPCs are less likely to warp, rot, and decay than traditional wood tiles. Due to its increased longevity, WPC tiles can be used indoors and outdoors in areas where moisture and humidity are frequently present, such as bathrooms, kitchens, patios, and pool decks [33]. By using resins and lightweight wood fibers or fillers, the composite material's overall density can be lowered while retaining its strength and longevity [34]. Overall, previous research using epoxy resins to bind plastic and wood waste has shown that epoxy-modified WPCs can be used as strong, long-lasting, and ecologically friendly materials for a variety of applications. More research and development work is required to optimize formulations, processing methods, and end-of-life disposal strategies and optimize the benefits of these composite materials. Although earlier research has examined the mechanical characteristics of separate waste materials in composite applications, there is a dearth of studies that particularly address the mechanical properties of plastic and wood waste when mixed in hybrid composites. Furthermore, most previous research has focused on traditional mechanical attributes, such as thermal and flexural strength, which has left gaps in knowledge about other important mechanical characteristics, including impact resistance and tensile strength [35]. By utilizing sophisticated analytical methods and methodical experimental research, these gaps may be filled, offering important new information for the creation of high-performing and environmentally friendly composite materials. Thus, this study aimed to fabricate lightweight composites from plastic waste (PW) and wood waste (WW) at an optimum ratio for tile application. Recycling not only reduces waste but also makes waste materials easily accessible for enhancing or creating new products. This study also focused on utilizing epoxy as the matrix, while plastic and wood waste acted as reinforcement in the composite for tile applications.

3.0 METHODOLOGY

3.1 The Preparation of Samples

The preparation of samples involved cutting, grinding, and mixing processes. The PW and WW were cut to fit by using a high-speed grinding machine (Model No: RT-34) into smaller particles at 0.5 ± 0.01 mm. The PW and WW were measured using Mettler Toledo electronic precision balance to weigh the samples with different composition ratios by weight (wt/wt%), as shown in Table 1 and Figure 1. The composition ratio of polymer composite is referred to Shoyu Luo et al. [34]. As can be seen in Table 1, the ratio was selected based on previous studies conducted on different filler loadings of polymer composites. Prior research has demonstrated that the composition ratios provided the necessary testing results.

Table 1. Different composition ratios of PW and WW for hybrid waste-reinforced plastic

Samples	PW (wt/wt%)	WW (wt/wt%)	Epoxy (wt/wt%)	Hardener (wt/wt%)
A	1.0	2.0	3.0	1.0
B	2.0	2.0	3.0	1.0
C	3.0	2.0	3.0	1.0
D	4.0	2.0	3.0	1.0

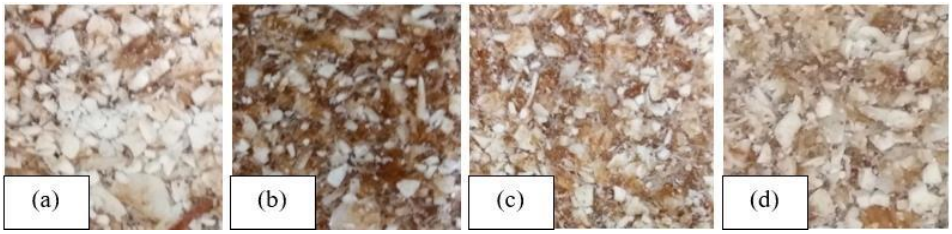


Figure 1. Different composition ratios of PW reinforced WW to hybrid waste-reinforced plastic: (a) sample A; (b) sample B; (c) sample C and (d) sample D

The PW and WW used in this research were first ensured to be dry and uncontaminated. Glue or tape stains on PW, or nail and screw marks on WW are common intolerable contaminations. After measuring the accurate amount of ground PW and WW for the mixing and stirring process, both materials were mixed together and stirred until they were mixed properly. The mixing and stirring time of both ground raw materials was 60 seconds. Epoxy resin is a versatile adhesive added to the blended raw materials to promote bonding between PW and WW and provide the necessary mechanical strength to fabricate tiles, whereas the hardener acts as an epoxy curing agent. After the mixing and stirring process, epoxy resin and hardener were mixed in a 500 ml plastic container with a ratio of 3:1 to form the matrix. Afterward, the stirred mixtures of PW and WW were blended with epoxy resin and hardener within 3 minutes. After the mixture was mixed thoroughly, the final mixture was spread over the middle of a square-shaped aluminum thick plate mold.

The mold was made of an aluminum frame with dimensions of 26 cm in length, 26 cm in width, and 0.5 cm in thickness. The aluminum mold plates were pre-coated with a layer of silicone spray lubricant before pouring the final mixture. This silicone spray was applied to prevent any staining of the fabricated tiles within the aluminum mold during removal after the curing process. After the final mixture was evenly spread within the mold, the sample was subjected to forced air drying using a blower to ensure that the fabricated tiles achieved a uniform thickness of 0.5 cm. Subsequently, the curing process lasted approximately 24 hours at room temperature (25°C). After three days, the fabricated tiles were unmoulded and prepared for further characterization and testing.

4.0 RESULTS AND DISCUSSION

4.1 Density and Porosity Analysis

Figure 2 shows the density results of all samples, revealing a descending trend as the proportion of PW increased. Samples 2.0 and 3.0 achieved the same and highest density of 1.096 g/cm^3, followed by Sample 1.0 (1.091 g/cm^3). In contrast, sample 4.0 exhibited the lowest density of 1.070 g/cm^3. This variation can be attributed to a higher percentage of PW in sample 4.0, which resulted in lower matrix content, primarily composed of material with a higher density of 1.1 g/cm^3, than the reinforcement provided by PW and WW. Since the fillers have a lower density than the epoxy resin, the density of the composite decreased as the filler content increased. On the other hand, the porosity of the composite increased as the filler content increased as there was less interfacial bonding between the fillers and epoxy resin composition. The increasing WW content in PW resulted from improper mixing and poor bonding of WW, which caused the void formation of and increased porosity.

The presence of PW and WW as fillers in the epoxy matrix led to a reduction in sample density, making it more lightweight. Marsi et al. (2020) suggested that this phenomenon may be attributed to the increased air content within the sample [21]. Figure 3 displays the apparent porosity of all samples, showing a fluctuating trend with increasing PW ratio. Sample 3.0 exhibited the highest apparent porosity of 0.14%, followed by sample 1.0 (0.10%). In contrast, samples 2.0 and 4.0, which had an equal proportion of PW, showed the lowest apparent porosity of 0.05%. The apparent porosity increased when the PW loading ratio reached 3.0. Composites with decreased porosity were deemed to have better interfacial bonding and fewer microvoids. This could be due to poor bonding between the polymer composite mixture and matrix at the interface area.

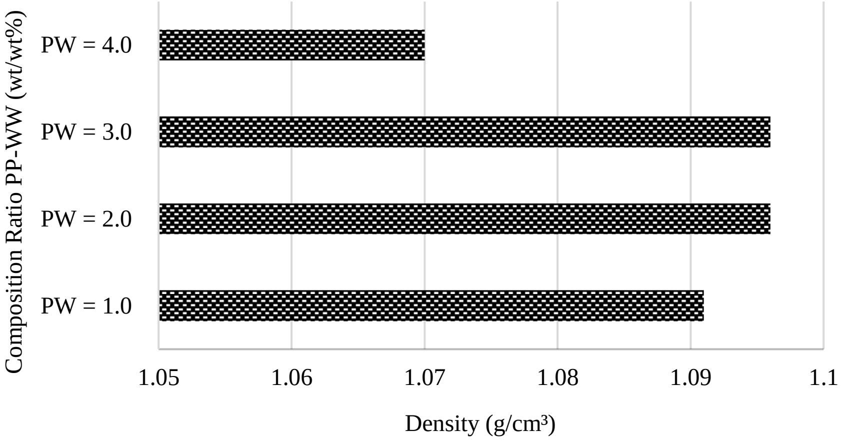


Figure 2. Density results of different composition ratios of PW reinforced WW to produce hybrid waste reinforced plastic

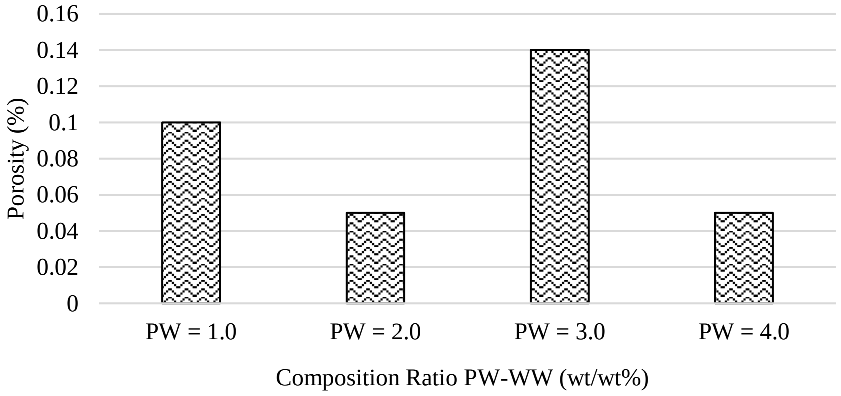


Figure 3. Apparent porosity results of different composition ratios of PW reinforced WW to produce hybrid waste reinforced plastic

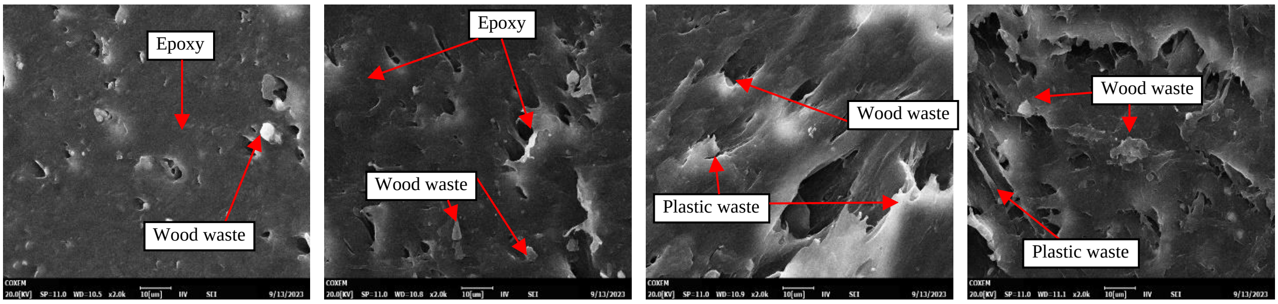
Subsequently, the porosity of 0.2 ratios produced the lowest density among others. When WW was added, density decreased, but porosity increased, exhibiting large holes comparable to those found in the compositions using RH in micrographs [36]. This is further corroborated by earlier research, which found that in addition to having a lower density than the matrix materials, fiber aggregation and cavities caused by the lack of matrix impregnation to the fibers were the contributing factors. Except for epoxy resin, which displayed a different tendency, all materials exhibit similar decreasing behavior [37]. Abbas Tiambo et al. (2023) attributed the increase in apparent porosity to the presence of fiber reinforcement [38]. This reinforcement led to the creation of fibre-matrix interfacial areas, consequently giving rise to the formation of voids within the sample [22]. Likewise, Schyns et al. (2020) noted that the increasing porosity with higher fiber content causes the fibers to aggregate during the mixing process, resulting in the entrapment of water-filled spaces that eventually transform into voids. This outcome was determined through a method employing the Archimedes principle to calculate the actual density of the samples. By comparing this actual density with the theoretical density of the samples in the absence of voids, the void volume fraction or apparent porosity was derived [23]. However, it is important to note that this technique hinges on precise knowledge of the fibre and matrix densities as well as the weight fraction of the specimen, which may introduce some degree of measurement uncertainty.

When the filler particles have high filler content, the epoxy resin may not be able to fill the gaps that emerge between them, as concluded by J. Rendon et al. [37]. This could lead to poor flow with high filler content as there is not enough epoxy resin or the viscosity is higher. A study by Dennis Schab et al. (2022) found that the material system retained air due to bubbles resulting from volatile byproducts produced during the curing process of high-viscosity polymer resin paired with tightly wrapped resin-wetting fiber [39].

4.2 Optical Microscope (OM) analysis

Based on the optical microscope (OM) analysis at 10x image magnification, the examination of matrix-reinforcement bonding in each sample was performed after conducting the tensile strength tests. The best bonding result was observed in sample D, displaying a robust matrix-reinforcement bond, as depicted in Figure 4 (d). Conversely, Figure 4 (a) for sample A revealed the PW extracted from the sample, leaving behind a deep cavity, indicative of inadequate adhesion between the reinforcement and matrix. In Figure 4 (c), sample C displayed matrix debris formed around the fractured PW, which had split rather than being pulled out from the matrix, suggesting suboptimal adhesion. Low bonding was observed in sample B, as illustrated in Figure 4 (b). This sample exhibited a higher occurrence of PW extraction from the matrix, resulting in wider and deeper voids. This outcome may be attributed to insufficient epoxy content, leading to weaker bonding between the matrix and a greater amount of PW.

As seen in Figure 4, a cluster of fibers and patches with restricted filler dispersion in the epoxy matrix was visible. According to Martinus et al. (2022), the build-up of PW waste filler and micro gaps within the matrix results from inadequate epoxy matrix, preventing the filler from being wettable efficiently [40].



(a) (b) (c) (d)

Figure 4. OM analysis of matrix-reinforcement bonding in 10x image magnification by different composition ratios of PW reinforced WW to produce hybrid waste reinforced plastic

4.3 *Bending Strength*

Figure 5 depicts the relationship between bending force and time for varying ratios of PW. Clearly, the highest maximum force value of 2069.20 N was observed for sample 3.0, followed by sample 4.0 (1186.61 N). The longitudinal crack propagated was due to the splitting of longitudinal cells, and the transverse crack propagated was due to the transverse shattering of longitudinal cells. Transverse breakage of longitudinal cells was substituted with transverse breakage of longitudinal cells/polymer after the epoxy polymer was added, which needed higher strains for breaking [24]. Subsequently, sample 2.0 exhibited a force value of 912.02 N, and sample 1.0 could withstand a force value of 813.95 N. This phenomenon may be due to the formation of robust bonds between the nanoparticle layers and the PP matrix. Comparable results have been reported in studies on the properties of polymer/wood flour/nano clay composites. This trend was also reflected in the flexural strength values [24]. An apparent trend was observed for flexural strength results, with sample 3.0 ratio demonstrating the highest bending stress value of 8.28 MPa, followed by sample 4.0 (4.75 MPa). According to Bhat et al. (2022), a composite's interlaminar shear strength can decrease by 5–10%, tensile strength can drop by up to 20%, and flexural strength can drop by 10% when there is an increase of 1% void/space [25]. This may affect the bending strength as the composition of the ratio increases, where the percentage of void decreases.

Sample 2.0 exhibited a bending stress value of 3.65 MPa, and sample 1.0 could hold up to 3.26 MPa. Smaller-sized particles provided greater surface area for contact with the plastic-coupling agent matrix compared to larger-sized particles. The mechanical behavior of PW mixed with WW was influenced by the even dispersion of lignocellulosic materials in the polymer matrix. These results were closely correlated to the OM results, which showed that breakage and debonding were the main reasons for failure. Furthermore, the presence of fillers was clearly observed in the composite, which was dispersed around the damaged fiber. This suggested that the nanofiller was bonded to the fibers, enhancing the composite's strength. Fracture surface area increased as particle size increased, requiring less energy to break a specimen containing larger particles. Larger particles can also introduce larger flaws in the composites, contrasting with the smaller flaws created by smaller particles, thereby reducing the strength of the composite [25].

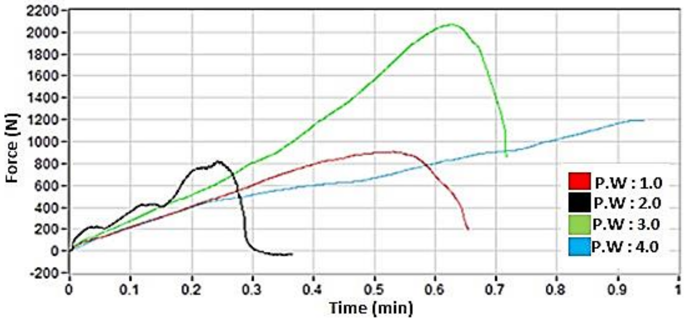


Figure 5. Mechanical test results of different composition ratios of PW reinforced WW to produce hybrid waste reinforced plastic

This result is consistent with previous research in which a maximum flexural strength of 24.6 MPa was achieved for 10% component, and the strength declined as the percentage approached 15% [41]. As the fiber percentage increased to

15% RH, the composite's strength declined. This was the consequence of the matrix and reinforcement not adhering effectively at the higher fiber contents. Although rice husk is commonly used as a reinforcing filler in polymer composites, its loading beyond the required level may result in poor dispersion and reduced interaction between the matrix and polymer. A polymer composite's overall performance and flexural properties may be adversely affected by the addition of excessive WW, leading to various issues [41]. Additionally, previous research has found that when filler loading increases, the impact strength reduces. The poor interfacial region is where an impact-induced fracture spreads [42]. It was demonstrated that strong filler matrix adhesion restricted the mobility of the matrix molecules; hence, reducing the impact strength.

4.4 Tensile Strength

In Figure 6, it can be seen that the PW ratio of 3.0 could sustain a greater maximum load of 313.81 N, while the 4.0 ratio could resist the load of 274.59 N. The 2.0 PW ratio could withstand a load of 168.68 N, while the 1.0 PW ratio could withstand a load of 143.18 N. According to previous research, the plastic matrix and poor surface adhesion between the wood fibers are the cause of the durability decrement. When the percentage of wood fibers in the PW mixed composite increased from 50% to 90%, its durability decreased by 50%. Thermoplastics packed with wood fibers have less durability. It has been reported that fiber strength, modulus, fillers, fiber length and orientation, fiber-matrix interfacial bonding, and fiber content are the primary determinants of a composite material's tensile qualities. Prior work has examined the tensile characteristics of short PEFB fiber used as reinforcement in phenol-formaldehyde resins [28]. A greater proportion of fiber serving as reinforcement presents a possibility for phase separation and fiber agglomeration, which lowers the effective aspect ratio. An increase in the proportion of fiber in the sample causes a decrease in the adhesion between the fiber and matrix, resulting in weak interfacial binding and inefficient load transmission.

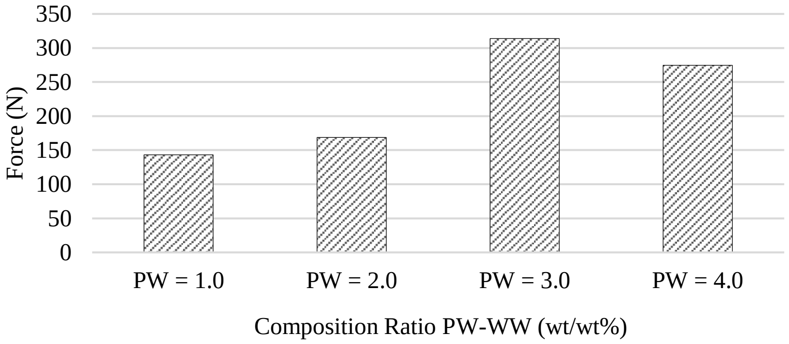


Figure 6. Tensile force results of different composition ratios of PW reinforced WW to produce hybrid waste reinforced plastic

The tensile strength results in Figure 7 showed clearly that the 3.0 PW ratio could withstand the highest tensile strength of 1.79 MPa, while the 4.0 PW ratio could resist the tensile strength of 1.57 MPa, followed by the 2.0 PW ratio (0.96 MPa). The lowest tensile strength of 0.82 MPa was exhibited by a 1.0 PW ratio. Four curvatures of plastic deformation and four linearities of elastic deformation were visible in the early stages. The epoxy stretched as the applied stress increased, tearing apart the wood waste and leaving the PW hole exposed so that it could be pulled out of the matrix until it broke. Due to weak interfacial bonding between the epoxy resins and PW and WW waste composite, as well as incorrect bonding between PW and WW, the decreasing trend of tensile strength was seen up to a 3.0 ratio. Prior research has verified that the epoxy matrix did not adhere to the fiber instead, de-bonding, a discontinuity caused by inefficient stress transfer at the fiber interface had occurred [43]. This is consistent with earlier research, where additional fiber could not continuously improve the tensile strength [44]. Inappropriate connections between the fibers occurred when there were many fibers and matrices, where they tended to break down within the polymer.

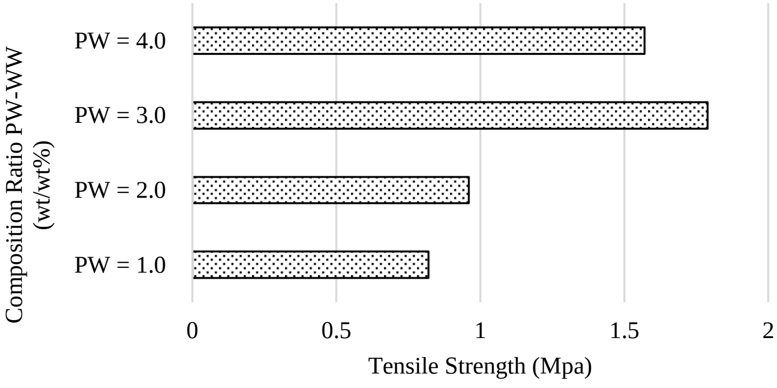


Figure 7. Tensile strength results of different composition ratios of PW reinforced WW to produce hybrid waste reinforced plastic

The consistent dispersion of WW waste filler promoted a mechanical interlocking process by connecting the fibers and matrix. This mechanism affected the extent to which the composite's load-bearing strength increases under tensile stress.

According to Jitha et al. (2021), the material strength of the composite will increase and be enhanced by energy absorption [45]. The lowest member of the tertiary composite system is the matrix, which fractures under load. Furthermore, there is a possibility that more fibers will be scattered onto the splitting surface, which will erode the bonds [46]. To transfer stress across the thickness of the material more effectively, there must be a strong interfacial adhesive with the reinforcing layers as the interior rice husk core distributes weight to the outside layers under tensile stress [47]. The efficiency of the fiber matrix bond decreases with increasing fiber concentration, which is associated with a decrease in mechanical characteristics. Inadequate interfacial bonding hinders effective load transmission, which leads to rapid breakdown [48].

4.5 Impact Strength

The impact strength results of various PW ratios are shown in Figure 8. It was evident that the sample ratio of 4.0 could tolerate a higher impact strength of 1.67 kJ/m^2, while the PW ratio of 3.0 could withstand 1.44 kJ/m^2. The PW ratio of 2.0 could resist 0.97 kJ/m^2, and the PW ratio of 1.0 could withstand 0.28 kJ/m^2. The PW mixed WW composite may fail if there are wood fiber ends present in the body of the material. The reason for this is that the ends of wood fibers function as notches and produce significant stress concentrations that can potentially cause microcracks in ductile matrix materials, such as HDPE. These microcracks combine to form a major crack in the fiber upon loading. Furthermore, it appears that the interactions between nearby fibers restrict matrix flow, which causes the matrix to become embrittled. These actions will impact the fracture mechanism and reduce the composites' impact strength.

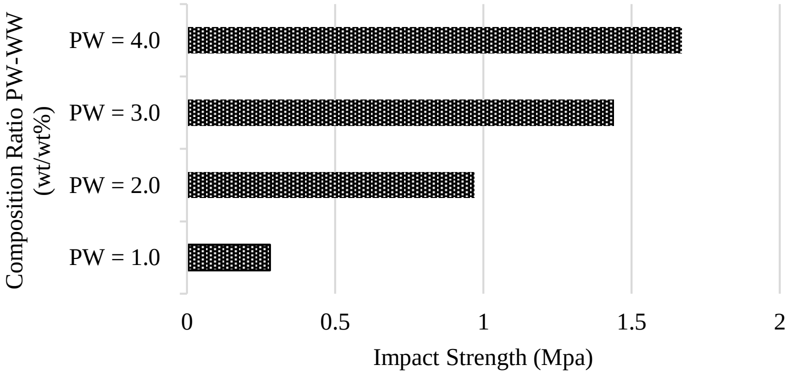


Figure 8. Impact strength results of different composition ratios of PW reinforced WW to produce hybrid waste reinforced plastic

Stephen Osakue et al. (2020) claimed that the polymer addition to the matrix significantly boosted the impact durability of the composite [49]. The impact energy was measured when the PW-WW specimen was struck by a hammer. After that, the energy was absorbed by the specimen until it yielded. Consequently, a portion of the samples was removed from the matrix when the hammer was used, and they were rather bent than broken. Plastic deformation would occur at the sample's notch when the hammer hit the specimen. According to Mohammed (2018), the reinforced polyester matrix composites' capacity to absorb energy improved noticeably when polymers were added to the matrix, greatly increasing the composites' hardness. The impact strength of 0.4 PW-WW began to decline as high PW fiber content resulted in inadequate filler dispersion in the composite. This exponential increase could be explained by the tensile breakage of microfibrils and the decohesion of the fiber/matrix low shear stress interface, resulting in considerable energy absorption due to the longitudinal propagation of cracks and numerous fractured sites.

The impact strength results of the four samples with a 4.0 PW ratio had a greater energy of 0.085 J, as shown in Figure 8. This could be attributed to strong matrix bonding. The energy of the 3.0 PW ratio was 0.073 J and the 2.0 ratio was 0.05 J. The 1.0 ratio recorded the lowest fracture energy with an impact energy of 0.014 J. These microcracks combined to form a major crack in the fiber upon loading. Furthermore, it appeared that the interactions between nearby fibers restricted matrix flow, which caused the matrix to become brittle. These actions would affect the fracture mechanism and reduce the composites' impact strength.

As stated in the previous study, the impact strength of pure epoxy was the lowest; however, the impact strength was enhanced by using PEFB as filler [50]. PW was used as filler in epoxy resin composites, although it did not affect the material's features and enhanced the manufacturing procedure. Figure 9 unequivocally demonstrates that the energy absorbed increased steadily when the PW ratio in epoxy resin increased. The energy-absorbing epoxy resins exhibited greater adhesion and filler dispersion until a ratio of 0.4, resulting in the highest impact strength and the least internal damage under stress. The lack of interfacial adhesion between the PW and WW may have contributed to the samples' unexpected failure upon impact. The filler and polymer matrix produced micro-spaces when impact was applied due to insufficient interfacial bonding, leading to a large number of microcracks. A comparative study demonstrated that the impact strength of polymer composite abruptly declined when the amount of fiber increased up to 20 wt% due to all the merging components. The composite effectively wasted more energy [51].

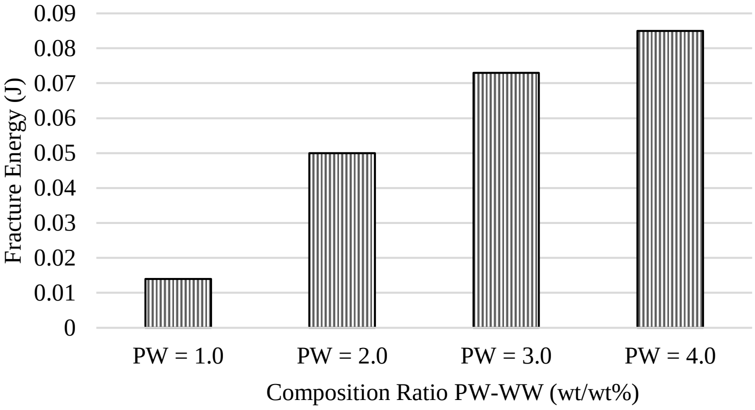


Figure 9. Impact strength results of different composition ratios of PW reinforced WW to produce hybrid waste reinforced plastic

According to Bisht et al. (2020), inadequate interfacial bonding causes microcracks to form at the point of impact between the filler and the matrix polymer, which makes the fractures in the composite readily spread [42]. The effect of the type of polymer matrix and its molecular structure have an impact on resistance as well. The interaction between the polymer and wood waste produces a synergistic effect, which improves the overall toughness of the composite. It showed that the hybrid composite made of glass fiber had lower RH, presumably as a result of the manufacturing process and the interlaminar or interfacial adhesion between the fiber and matrix [52].

6.0 CONCLUSION

In conclusion, the evaluation of the physical properties of the PW-WW polymer composite indicated that 3.0 was the optimum ratio. According to the density and porosity test, composite samples with different ratios showed a decrease in density and an increase in porosity. The density of the composite with a 3.0 ratio was 1.096 g/cm^3, and the apparent porosity was 0.14%. Due to its superior mechanical performance, PW-WW polymer composite is a good choice for tile application. Tensile, flexural, impact, compressive, and sound absorption tests demonstrated the mechanical performance of PW-WW polymer composite. When compared to other ratios, the composite with a 3.0 ratio had the best performance. At 2069.20 N, the sample exhibited the highest bending strength and the lowest strain percentage of 813.85 N. The same sample also indicated a maximum load of 313.81 N with a maximum tensile strength of 1.79 MPa. Contrary to the impact strength, the highest impact strength of 1.67 kJ/m² and fracture energy of 0.085J were recorded by composite with 0.4 ratio. Thus, it was justifiable to utilize a PW ratio of 3.0 as reinforcement and epoxy resins in tile production due to the promising mechanical properties. By reducing waste and environmental harm, the use of PW-WW as recycled waste materials could develop prefabrication technology. Additionally, PW-WW composite applications result in beautiful furnishing, flooring, and walls in buildings. The application of hybrid reinforcements, surface modification, coupling agents, and processing parameter optimization are some potential remedies for these issues. Further research is needed to improve the production process and properties of PW-WW reinforced polymer composites, making them a viable alternative to synthetic fibre-reinforced polymer composites.

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