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Utilization of Wood Flour Waste as a Filler on Polypropylene Random Pipes Industry

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ABSTRACT

Intending to minimize the cost of production of pipes intended for construction and building activities and waste recycling, this research studies the physical and mechanical characteristics of high-performance polypropylene random (PPR), a new material extracted from a homopolymer polypropylene. The PPR was filled with untreated and treated wood flour (WF) particles at various content levels 10, 20, 30, and 40 wt.%. The density, melt flow rate, tensile strength, tensile strain, modulus of elasticity, and hardness are used to evaluate the quality of the material. The hydrophobic character of WF resulted from degradation in the physical and mechanical properties. The results showed that the density, the modulus of elasticity, and the hardness increased with the percentage of treated wood flour (TWF). As the percentage of WF increased, the melt flow rate decreased. The tensile strength and strain increased to 27.7 MPa and 543.25%, respectively at 20 wt.% of WF, with 14.8% and 6.65% reached gains compared to the untreated wood flour composites (UWFC) (24.04 MPa and 495.6%). The enhancement of the mechanical properties is thanks to the formed strong links between the particles of WF and the PPR after the thermal and alkaline treatment with sodium hydroxide (NaOH). The removal of hydroxyl groups in the TWF enhances the interfacial bonding between the filler and the PP matrix in the resulting composites. When WF is treated, it is well dispersed; and facilitates the transfer of stress from the matrix to the fillers. The optimum percentage of WF to add into the inner layer of PPR pipes is at a composition of the filler of 20 wt.%.

Keywords: polypropylene random, wood flour, waste recycling, composite, tensile strength.

INTRODUCTION

In recent years, there has been a resurgence of interest in harnessing natural fibers, spurred by the promising advantages they offer, including decreased weight, reduced raw material expenses, recyclability, and reliance on renewable resources (Karimah et al., 2021). The utilization of natural fibers as a reinforcement in plastics is prevalent across various industries, including automotive and aviation. These fibers serve as cost-effective and environmentally friendly substitutes for other materials. There has been a substantial rise, as well, in the production and utilization of thermoplastic polymers like polypropylene. Polypropylene is a widely utilized thermoplastic polymer thanks to its remarkable attributes, including its versatility, cost-effectiveness, technological versatility, outstanding strength, toughness, and high melting point (Thakur et al., 2014). The α-modification, identified as the phase with the highest thermodynamic stability, is commonly

attained via crystallization from either a polymer solution or melt. This phase tends to dominate under standard processing conditions (Sobczak et al., 2012). Apart from the homopolymer form of polypropylene (HPP), a wide range of copolymers exists, with many incorporating ethylene and butylene. The properties of these copolymer systems depend primarily on the arrangement of monomers along the polymer chain. In this copolymer, the comonomers are randomly dispersed within the elongated propylene chains (Harding and Van Reenen 2006). As a result, conducting a thorough analysis of the copolymer's microstructure becomes essential for gaining a profound understanding of the catalyst system and the influence of polymerization methods on the chemical structure, thereby impacting the resulting material properties (Fan et al., 2009). The copolymerization of propylene with small amounts of ethylene, typically up to 7 wt.%, results in the formation of random copolymers known as PPR (Papageorgiou et al., 2013). The properties of polypropylene homopolymer are primarily shaped by its tacticity, molecular weight, and molecular weight distribution, all of which subsequently impact its crystalline structure (Shang-Guan., 2012). Nevertheless, the periodic inclusion of comonomer units disrupts the otherwise consistent arrangement of propylene units along the macromolecular chains (Shang-Guan et al., 2012). The addition of ethylene units to the primary polymeric chain results in decreased crystallinity compared to propylene homopolymers, leading to a reduction in both melting point and crystallinity. Due to the reduced glass-transition temperature in this polymer class, several advantages emerge, including heightened transparency, a degree of softness, lower sealing temperature demands, and a modest improvement in impact strength at lower temperatures (García-Peñas et al., 2017). In the production of pipes, plates, household appliances, and automotive components (Mai et al., 2012).

Wood flour, obtained from natural sources, is plentiful, lightweight, economical, and accessible in various forms. It can be seamlessly integrated into common matrices in significant amounts, offering both cost-effective and environmentally friendly solutions (Arao et al., 2014). The characteristics of wood-polymer composites depend on several factors, including the properties of the matrix, the type of wood fibers used, the ratio of reinforcement, the chemical interaction between wood fibers and the polymer, moisture absorption, and the conditions during implementation, among various other considerations (Berzin et al., 2018). The pronounced hydrophobic nature of specific thermoplastics, like polyolefins, leads to challenges regarding compatibility with hydrophilic lignocellulosic materials. Given that the mechanical and physical characteristics of these composites are inherently linked to the compatibility and interaction among their constituents, enhancing the interface and interphase interactions in thermoplastic composites is imperative (Kun et al., 2021). Diverse methods are employed to enhance the mechanical characteristics of composites. Two principal strategies for bolstering mechanical properties through fillers involve their treatment with coupling agents such as maleic anhydride (MAPP) (Kada et al., 2015; Arao et al., 2014; Adhikari et al., 2012). Or a chemical coupling agents such as alkaline treatment (Kun et al., 2021), typically polymers, are applied in minor quantities to treat a surface, facilitating bonding between the treated surface and other materials, such as wood and thermoplastics (Tabari, Nourbakhsh and Ashori 2011). Alkaline treatment effectively eliminates surface impurities and disrupts hydrogen bonds, thereby enhancing surface roughness (Khamtree, Ratanawilai, Ratanawilai 2020). Alkalization treatment emerged as the most cost-effective and straightforward technique for improving compatibility between the fiber and the matrix when compared to other chemical surface treatments of natural fibers (Olakanmi et al., 2016). According to Ray et al., (Ray et al., 2002) investigated that the fibrillation of the fibers is responsible for increasing the effective surface area available for wetting by the matrix, thereby enhancing interfacial bonding. Alkalization plays a role in breaking hydrogen bonds and augmenting the number of free hydroxyl groups on the fiber surface, consequently increasing fiber reactivity (Aboul-Enein et al., 2024). Wood flour-filled composites find their primary application in the construction and automotive industries. However, they are also utilized in packaging, the production of various household items, furniture, office equipment, and a wide range of other products (Ichazo et al., 2001). Wood-plastic composites (WPCs) are considered environmentally sustainable materials due to their composition. The wood component can be sourced from agricultural waste found in landfills, while the plastics primarily originate from consumer and industrial recycling

efforts, such as municipal solid waste initiatives (Dlova et al., 2021).

Numerous studies in the existing literature have indicated that the inclusion of wood flour particles in polypropylene can elicit various effects. These effects include the augmentation of the composite's modulus and a decrease in toughness. Such behavior stems from the interaction between the inorganic fillers and the polypropylene matrix (Lima et al., 2020). WF nanoparticles exhibit a pronounced inclination to cluster together because of their diminutive particle size, elevated surface energy and expansive surface area (Huang et al., 2004). To achieve exceptional performance from nanomaterials, it's essential to enhance the even dispersion of nanoparticles within polymer matrices and to strengthen interfacial adhesion (Eiras et Pessan 2009). Lima (2020) investigated the analysis of density and moisture content. The observed density of the wood-plastic composites (WPCs) fell within the range of 0.78 to 0.91 g/cm^3. The hardness increased from 52.2 to 56.6. This observation aligns with the findings of Taşdemır, Biltekin, Caneba (2009), who noted that the hardness of the composites increased in tandem with a corresponding rise in fiber content. Lima et al. (2020) found an increase of MOE, spanning from 0.22 to 0.29 GPa, displayed no significant differences among the different treatments. Conversely, the tensile strength exhibited variations within the range of 8.1 to 13.5 MPa. In the study conducted by Macedo et al. (2015), it was observed an increase of the density of the WPCs from 0.782 to 0.915 g/cm^3. In the research conducted by Al Maadeed et al. (2012) observed that the MFR experienced a decrease with the introduction of wood flour, and this decrease was more pronounced when the wood flour reinforcement was substituted with glass fiber. This phenomenon is likely attributed to the augmented weight and particle size of the fiber, contributing to an elevated viscosity of the composite. Generally, the incorporation of fibers into the matrix tends to result in a reduction in the melt flow rate (MFR) value due to the larger particle size of the fibers. The hardness properties of polypropylene (RPP) and hybrid composites were applied. The results indicate that composites exclusively reinforced with glass fiber in RPP exhibit higher hardness compared to other composite variations. Conversely, composites reinforced with wood flour demonstrate lower hardness in comparison to the other composite formulations. Murayama et al. (2019) reported that the introduction of plastic in higher proportions compared to lignocellulosic raw material led to a decrease in the mechanical strength of WPCs. Lee et al. (2004) The investigation examined the correlation between tensile strength and filler content, both with and without the coupling agent. In the absence of any coupling agent, the WPC specimens exhibited a maximum tensile strength of 38.06 MPa. The tensile strength decreased with increasing filler loading, with 40 wt.% of wood flour addition resulting in approximately a 9.2% strength reduction compared to pure polypropylene. This observation corresponds with previous research where 20 wt.% of WF addition led to a 9.5% strength reduction. The investigation also examined stress-strain curves of the composites at different filler contents, uncovering heightened brittleness in wood-plastic composite specimens as the filler loading increased (Väisänen et al., 2016). The bonding at the interface gradually weakened with filler loading increased. However, the tensile modulus exhibited improvement with the increasing filler loading, consistent with findings from previous studies. The addition of the coupling agent strengthened interfacial bonding, resulting in improved stress propagation and higher tensile strength.

In this investigation work, an industrial-grade polypropylene random was utilized as a new matrix, while wood flour served as a filler to develop biodegradable composites suitable for practical applications, particularly in the manufacturing of PPR pipes. The composites, both untreated (UTWFC) and treated with wood flour (TWFC), underwent comprehensive experimental testing to enhance our understanding of their physical and mechanical properties, including tensile modulus, tensile strength, hardness, melt flow index, and density. This research contributes to the utilization of recycling materials and the reduction of production costs.

MATERIALS AND METHODOLOGY

Raw materials

This study employs the commercial-grade polypropylene random RA 140 E (depicted in Fig. 1a) as the matrix material. In accordance with ISO 1183 and ISO 1133 standards, the density and melt flow rate at 230 °C/2.16 kg are reported as

0.905 g/cm^3 and 0.3 g/10 min, respectively. Detailed properties of the characterized PPR are presented in Table 1. The study involved the use of WF particles, as filler (Fig. 1b). The WF sawdust was collected from carpentry shops. A granometric test was carried out in order to separate particles according to diameters.

Preparation of the specimens

The wood flour was prepared by crushing sawdust waste and granulated in granulation machine, then WF at different size was obtained. Size of 80 µm was chosen to mixing with PPR. A part filler was chemically and thermally threated. WF was dried in 90 °C for 24 hours in order to eliminate the moisture. A quantity of WF was immerged in an alkaline solution containing approximately 20% NaOH by mass during 1 h. After this duration elapsed, the fillers were separated from the solution and washed with water to remove the NaOH.

The specimens were molded using the Beston Groupe injection machine with a clamping force of 1400 KN. Initially, the closing force was carefully adjusted to prevent any potential mold damage. Subsequently, the virgin PPR underwent a gradual heating process ranging from 180 °C to 220 °C, in increments of 10 °C, to prevent thermal shock to the material. The injection pressure was consistently set at 65 MPa, and additional details of the process are presented in Table 2. Plasticization of PPR occurred through friction between the screw and barrels, followed by injection into the mold. Composite specimens, containing 10%, 20%, 30%, and 40% by weight of WF, were produced using the same method and equipment. According to ISO 527-1, the dimensions of functional part specimens should be 20 × 4 × 2 mm. The specimens produced are presented in Figure 2.

Testing of the specimens

Density

Density tests were conducted using a ZLS 220A SCS densimeter following ISO 1183 standards. Two methods were employed for the density test: the first involved samples injected from the

Table 2. Main used process parameters

Parameters	Unit	Value
Injection temperature	°C	220
Injection pressure	Bar	65
Injection speed	mm/s	55
Hold pressure	Bar	45
Plasticization speed	RMP	200
Cooling time	s	10

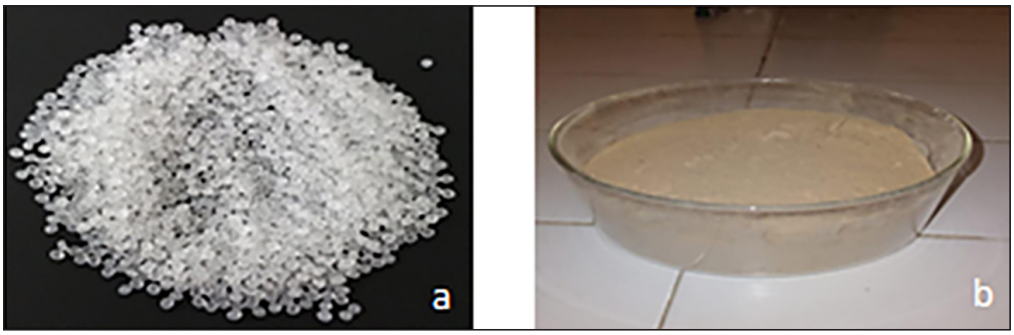

Figure 1. Polypropylene random PPR, (b) calcium carbonates WF

Table 1. Technical sheet of RA140E

Property	Typical value	Test method
Density	0.905 g/cm^3	ISO 1183
Melt flow rate (230 °C/2.16 kg)	0.3 g/10 min	ISO 1133
Tensile modulus (50 mm/min)	0.8 GPa	ISO 527
Tensile strain at break (50 mm/min)	500 %	ISO 527-2
Tensile stress at yield (50 mm/min)	25 MPa	ISO 527-2
Hardness	45	ISO 2039-1

Figure 2. The prepared testing specimens

injection machine, while the second utilized samples from the melt flow index machine. The procedure entails initially measuring the samples in air mode and subsequently switching to fluid mode to determine the density value. The ultimate results were derived from the average of five test samples.

Melt flow rate

The melt index rate was determined using the DVT EA DLC machine, interconnected with the density machine. In accordance with ISO 1133, 7 g of the virgin material was melted at 230 °C and extruded through an orifice using a weight of 2.16 kg. Samples for this test were acquired with a cutter at 120-second intervals. The results obtained were directly transferred to the software.

Tensile test

Following ISO 527 standards, the tensile test was conducted using the EM00 model TVM 20kn120N machine with a movement speed ranging from 1 to 120 mm/min, at a temperature of 23 °C. The applied tensile force was 5 KN, and the speed was set at 50 mm/min. Specimens were positioned between the two jaws, and the test proceeded until failure. The software was employed to obtain and record the results, including measurements of tensile strength, tensile strain, and Young's modulus from the generated tensile curve.

Hardness

Hardness testing was carried out using a PCE-HT210 shore D durometer specifically designed for plastics. Following ISO 2039-1 standards, five indentations were made in a single sample using a penetrator, penetrating into the plastic until the end, and the resulting value was displayed on the screen. The average hardness of five indentations in one sample was calculated, and subsequently, the average of five samples at each percentage was determined. This meticulous method was employed to ensure the accuracy of the obtained hardness values. The density, melt flow rate, tensile strength and hardness tests are depicted in Figure 3a–d, respectively.

RESULTS AND DISCUSSIONS

Characterization tests were conducted on the prepared specimens. The latter consisted of varying percentages of calcium carbonate WF, including 0, 10, 20, 30 and 40 wt.%.

Figure 3. (a) density test, (b) melt flow rate test, (c) tensile strength test, (d) hardness test

Density

The density of the specimens exhibited an increasing trend following the rise in the percentage of wood flour additives, shown in Figure 4. The average density for each percentage was computed based on four specimens. The initial control specimen, S0, had a density of 0.906 g/cm^3. Subsequently, for UTWFC a noticeable increase in density was observed, reaching 1.1 g/cm^3 at 40%. However, for TWFC, a slight increase in density was noted post-treatment, with values ranging from 0.906 to 0.92 g/cm^3. The coefficient of variation for density falls within the range of 0.4% to 0.32%.

The density of UTWFC increased with increasing WF levels. This phenomenon can be referred to the presence of water between the particles and matrix. The presence of the water can be referred to hydrophilic behavior of wood flour. However, the density did not show a significant increasing trend which can be attributed to the low density of WF particles after thermal treatment. Then, the moisture was eliminated. Lima et al. (2020) analyzed the density and moisture content as part of the experimental treatments, particularly focusing on the influence of varying proportions of polypropylene. The observed density of the the composite ranged from 0.78 to 0.91 g/cm^3. Despite the different levels of added WF, there were no statistically significant increases in density. Butylina, Martikka, Kärki, 2011 revealed that the moisture content of the manufactured WPCs were analyzed. Density values ranged from 1.04 g/cm^3 to 1.14 g/cm^3, with the highest density observed in composites containing UWFC. Those treated with wood fibers displayed slightly lower densities. Discrepancies in density among composites with identical wood, polypropylene, and maleated polypropylene proportions may stem from variations in the wood ingredients used during production (Hajibeygi et al., 2021), The density of WPCs influenced by other characteristics of the wood, such as porosity or moisture content. The formation of pores is a frequent phenomenon in WPC production and can be difficult to completely eliminate. Several factors contribute to the porosity observed, including the initial moisture content of the wood, the release of volatile organic compounds from lignin decomposition, and the presence of extractives (Papageorgiou et al., 2005). The moisture absorption capability of the composite, as indicated by its moisture content and/or water absorption coefficient, serves as a measure of its porosity.

Melt flow rate

MFR is illustrated in Figure 5. With an increase in the content of WF, a consistent reduction in MFR is observed. Notably, there is no significant difference between TWF and UTWF. The control specimen, S0, exhibited an MFR value of 0.301 g/10 min. As the WF content increased to 10, 20, 30, and 40 wt.%, the difference is not high between UTWF and TWF, which the corresponding MFR values were measured at 0.292, 0.285, 0.271 and 0.25 g/10 min, respectively. The coefficient of variation for MFR falls within the range of 0.32% to 0.17%.

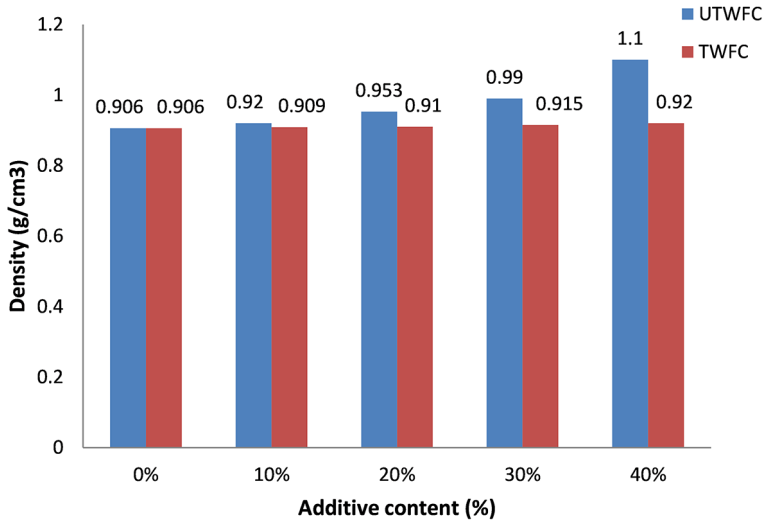

Figure 4. The results from the density test

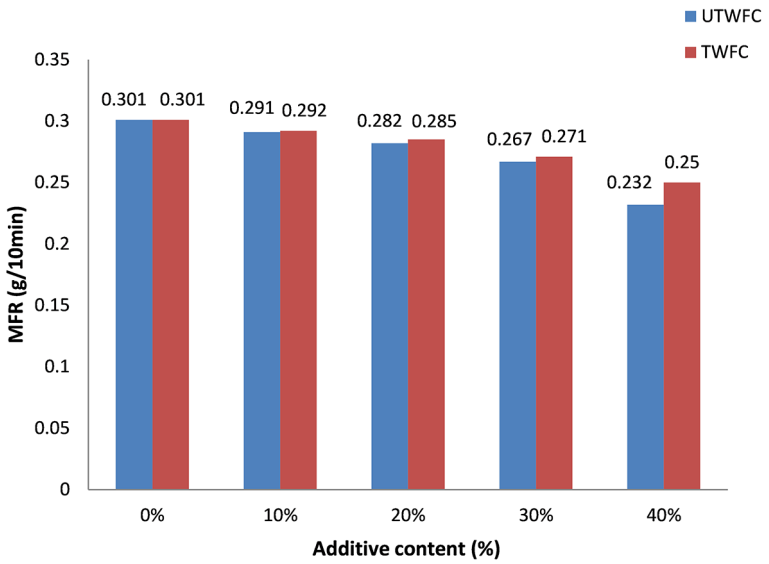

Figure 5. The results from the MFR test

The WF particles blocked the macromolecules movement then with adding more percentages this leads to decrease the MFR. Consequently, the filled PPR become more viscous. The same general behavior is found in a previous study. Al Maadeed et al. (2012) found that the MFR exhibited a decrease with the addition of wood flour, and this decrease was further pronounced after the wood flour treatment. This phenomenon can be ascribed to the heightened weight and particle size of the particles, leading to increased viscosity of the composite (Bicy et al., 2021). Typically, the addition of particles to the matrix leads to a reduction in the MFR value due to the larger particle size of the fibers. Similar findings have been reported by various researchers (Lu et al., 2006). Tasdemir Taşdemır, Biltekin, Caneba (2009) noted that the melt flow index exhibited a decrease as the concentration of wood flour increased with polypropylene. This is explained by the blockage of chain macromolecular movement by WF particles.

Tensile properties

A summary of the tensile properties for the blend of PPR and WF is provided, encompassing

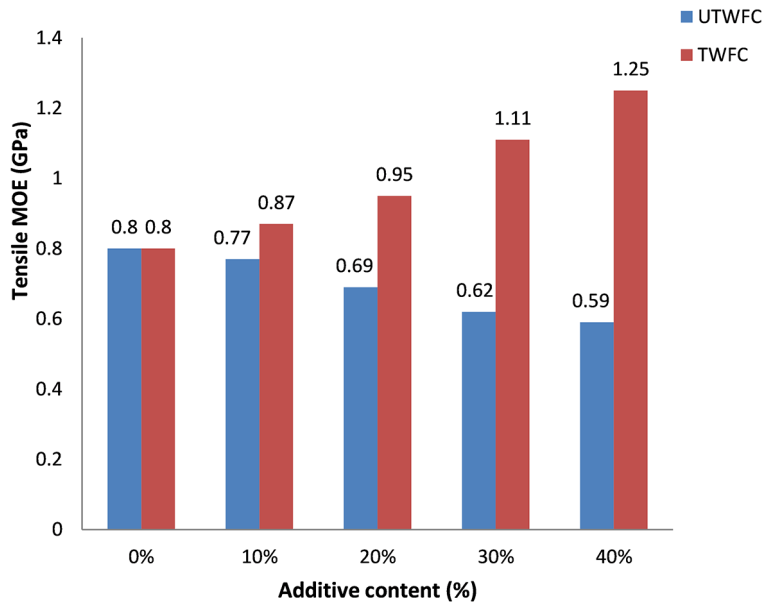

Figure 6. The results from the tensile strength test

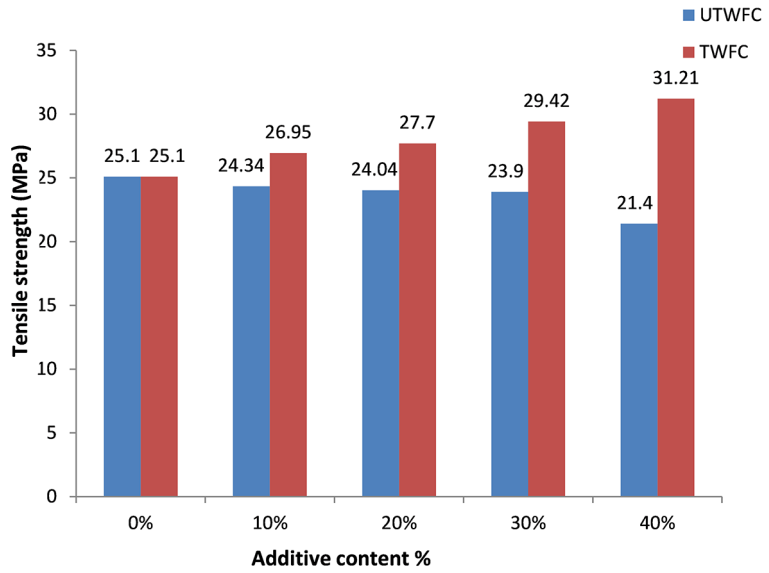

Figure 7. The results from the tensile strength test

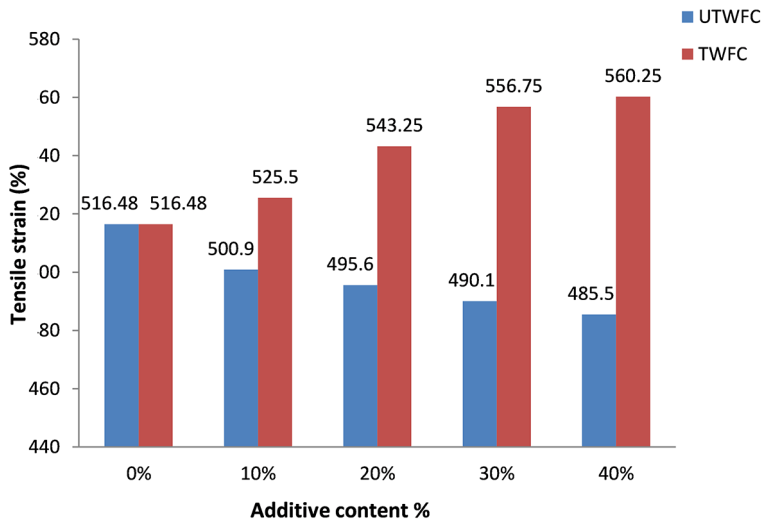

Figure 8. The results from the tensile strength test

elastic modulus, tensile strength, and strain, in Figures 6, 7, and 8, respectively. In the absence of any additives, PPR exhibited a modulus of elasticity (MOE) of 0.8 GPa, tensile strength of 25.1 MPa, and tensile strain of 506.25%. The introduction of TWF particles into PPR at varying loading levels (10%, 20%, 30%, and 40 wt.%) resulted in an observable increase in the tensile modulus of elasticity. The MOE values for these compositions were measured at 0.87 GPa, 0.95 GPa, 1.11 GPa and 1.25 GPa. The coefficient of variation for the MOE falls within the range of 0.4% to 0.23%. Conversely, NTWF revealed a decrease in MOE to 0.67 GPa at 40%. Incorporating NTWF at different weight percentages (10, 20, 30, and 40 wt.%) led to a decrease in tensile strength compared to control specimens S0 with a tensile strength of 25.1 MPa. However, the tensile strength experienced an increase after adding TWF, rising to 31.21 MPa at 40 wt.%. The coefficient of variation of tensile strength ranged from 0.33% to 0.23%. The impact on tensile strain was also assessed, and the results are displayed in Figure 8. The addition of NTWF at different weight percentages (10, 20, 30, and 40 wt.%) led to a reduction in elongation. As the WF content increased further, the yield point elongation declined, reaching 423% at 40 wt.%, respectively. With TWF content, the tensile strain increased to 560.25% at 40 wt.%. The coefficient of variation

of tensile strain varies from 0.33% to 0.25%. The enhancement in the modulus of elasticity can be attributed to WF which is a stiff and rigid material. When it is added to the polypropylene matrix, it essentially acts as a reinforcing agent; when the TWF is well dispersed and forms a strong bond with the polypropylene matrix, it enhances the load-bearing capacity of the matrix. This robust interaction facilitates the transfer of stress from the matrix to the fillers, leading to heightened stiffness (Peng et al., 2021). The tensile strength and strain decreased with adding more UWF percentages, and then the behavior of both decreased with adding TWF particles. The first behavior can be referred to the week bonds formed between matrix and filler. However the elimination of moister after thermal treatment and enhancement of links between WF and PPR because of chemical treatment formed strong bonds between matrix and filler (Chen et al., 2023). This phenomenon can be explained by the good dispersion of WF particles within the polymer matrix, they can help distribute stress more evenly. The filler particles can act as nucleation sites for crack propagation, allowing for more controlled and ductile deformation (Lazzeri et al. 2005).

Lima et al. (2020) found that the modulus of elasticity (MOE), ranging from 2.27 to 2.96 GPa, exhibited no a significant differences across the various treatments. On the other hand, the tensile strength showed variations within the range of 8.1 to 13.5 MPa. Murayama et al. (2019) revealed that the incorporation of plastic in higher proportions relative to lignocellulosic raw material resulted in a decline in the mechanical strength of wood-plastic composites (WPCs). However, the values of MOE and tensile strength remained satisfactory with treated WF, specifically 10% and 20 wt. %. Müller et al. (2014) investigated the stiffness is commonly employed as a key parameter to assess the impact of fillers and fibers on composite properties. The results reveal a significant increase in stiffness from approximately 0.35 GPa to around 4.5 GPa, indicating robust reinforcement with the incorporation of wood. Potential structural effects such as physical contact of particles. The dependence of mechanical properties on composition strongly corroborates this explanation. Achieving proper dispersion and strong adhesion between the wood flour (WF) particles and the polymer matrix are crucial factors in this regard. When a tensile load is applied to the composite, the stress is distributed more evenly throughout the material (Xiong et al. 2017). The rigidity of WF allows it to effectively bear a portion of this load, relieving the polymer matrix from carrying the entire burden. This load-sharing mechanism reduces the chances of matrix failure and, consequently, enhances tensile strength (Feng, Yang, Qian; 2021). For the other percentages, the behavior of tensile strength can be referred to interruption the crystallization process of PPR by WF particles. Consequently, the long chains become short (Qiu, Mai, Zeng; 2000). Lee et al. (2004) examined the correlation between tensile strength and filler loading, both with and without the coupling agent. When no coupling agent was used, the maximum tensile strength of the WPC specimens stood at 38.06 MPa. It was observed that as the filler loading (wt.%) increased in the composites, the tensile strength decreased. Specifically, the addition of 40 wt.% of WF resulted in a strength reduction of approximately 9.2% compared to pure polypropylene, a trend that aligns with findings from previous research where the addition of 20 wt.% of WF to PP led to a similar 9.5% reduction in strength compared to pure PP (Ichazo et al., 2001). The decline in strength is ascribed to the diminishing bonding strength between the WF and the non-polar (hydrophobic) PP. This is a consequence of the inherent incompatibility between non-polar polymers, especially thermoplastics, and polar (hydrophilic) wood flour (Satti et al., 2017). In contrast, Incorporating a coupling agent resulted in a notable enhancement in the maximum tensile strength of the specimens, reaching 51.66 MPa at the 40 wt.% of WF level. This addition significantly augmented the tensile strength compared to the pure PP specimens, marking a sharp contrast to specimens lacking any coupling agent. At 40 wt. % filler loading, the tensile strength surpassed that of pure PP specimens by 51.7%, owing to the heightened bonding strength between the wood flour and the PP, surpassing the intermolecular bonding of pure PP itself. It has been documented that the coupling agent used, maleic anhydride polypropylene (MAPP), can enhance compatibility between immiscible polymers by reducing interfacial tension (P.V.S. et al., 2021). Müller et al. (2014) revealed the relationship between the tensile strength of composites containing three types of wood fibers and wood content was depicted. Similar conclusions can be drawn as with the composition dependence of modulus. The strength exhibits an increase comparable to

stiffness, with the different fibers exerting varying influences on this property. Overall, these findings indicate the benefits of wood reinforcement when targeting stiffness and strength, resulting in significant reinforcement. However, quantifying the extent of this reinforcement through qualitative assessment alone is challenging. Additionally, the presence of wood flour particles can enhance tensile strain, allowing for more deformation before failure, thus contributing to the material's toughness (Zebarjad, Tahani, Sajjadi; 2004). The introduction of WF can lead to a change in the fracture behavior, making it more ductile and less prone to brittle failure, which in turn increases tensile strain (Elleithy et al., 2011). However, WF particles are typically much stiffer and less deformable than the polymer matrix. When incorporated in higher amounts, they can significantly increase the overall stiffness of the composite. This increased stiffness can make the material less ductile and more prone to brittle failure, reducing its ability to elongate before breaking (Baek, Cho, Ahn; 2014).

Lee et al. (2004) analyzed the stress–strain curves of the composites, both with and without the coupling agent, across various filler contents. It was noted that with an increase in filler content, the WPC specimens displayed amplified brittleness (Lovinger, 1983). Concurrently, the bonding at the interface gradually weakened with the increasing filler loading. Conversely, the young modulus demonstrated improvement as the filler loading increased, consistent with findings from previous studies. Generally, the creation of micro-voids between the WF and the polymer matrix is commonly considered a factor contributing to poor bonding strength, which disrupts stress distribution during tensile tests. The stress–strain curves of the composites with the coupling agent at different filler loadings showed that the inclusion of the coupling agent at a 3 wt.% level led to improvements in both the tensile strength and modulus of the composite (Kada et al., 2015). However, with the presence of the coupling agent, the composite displayed heightened brittleness. The coupling agent functioned to decrease the surface energy of the wood flour (Arao et al., 2014), The addition of the coupling agent modified the WF surface, making it non-polar and more compatible with the matrix polymer. This enhancement in interfacial bonding resulted in improved stress propagation and increased tensile strength (Wibowo et al., 2017).

Hardness

Figure 9 shows the average hardness values obtained from five specimens at various percentages of wood flour (WF). The incorporation of WF content resulted a no significant augmentation of hardness. The initial control specimen, S0, displayed a hardness value of 45.2. Subsequently, an increase in hardness was observed, reaching values of 45.27, 45.5, 45.68 and 45.9 with the addition of 10, 20, 30 and 40 wt.% of TWF, respectively. The coefficient of variation for hardness ranges between 0.19% and 0.36%. The hardness of PPR showed a slight increase with adding more rigid particles of WF which is distributed on the matrix rigid particles act as reinforcements, making the material harder (Choobbasti et al., 2019).

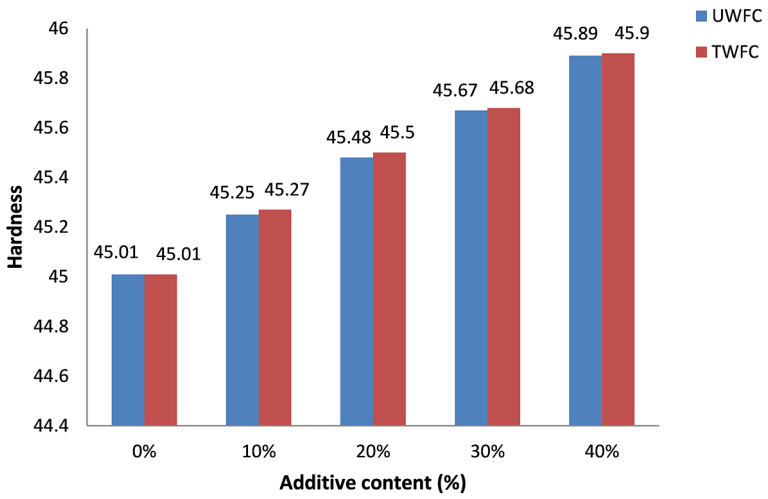

Figure 9. The results from the hardness test

Lima et al. (2020) observed an increase in the hardness from 52.2 to 56.6.This phenomen can be explained by the presence of WF which is a rigid material on the polymer surface. Taşdemır, Biltekin, Caneba; 2009 investigated that the hardness of the composites increased with a corresponding rise in fiber content. Al Maadeed et al. (2012) illustrated the hardness properties of polypropylene. According to ISO 1183, ISO 1133, ISO 527-2, and ISO 2039-1, the optimum percentage of WF to add to the inner layer of PPR pipes as a construction material, in respect to all the engineering properties is 20 wt.%. Moreover, when 30% of WF is added to PPR, the tensile properties reached 1.11 GPa, 27.7 and 556.75% in MOE, tensile strength and strain, respectively. Then, up of 20% the PPR material become rigid which is not good for PPR pipes applications.

CONCLUSIONS

The following key findings from the tests carried out on the physical and mechanical engineering properties, of 10, 20, 30, and 40 wt.% of treated wood flour added to the PPR matrix, are concluded:

- the density increased with increasing the percentage of TWF,
- the melt flow rate decreased with increasing the percentage of TWF,
- the modulus of elasticity increased with increasing the percentage of TWF,
- the tensile strength and strain increased with increasing TWF percentages,
- the hardness increased with increasing the percentage of TWF.

The improvement in mechanical properties can be attributed to the presence of TWF, a stiff and rigid material. When added to the polypropylene matrix, WF effectively acts as a reinforcing agent. Thermal treatment eliminated moisture and then chemical treatment improves bonds between filler and matrix. When WF is well-dispersed and forms a strong bond with the polypropylene matrix, it enhances the load-bearing capacity of the material. This strong interaction enables the transfer of stress from the matrix to the fillers, resulting in increased stiffness. It was concluded that the utilization of 20 wt.% of WF in the inner layer of PPR pipes, is the most suitable formulation as a construction material in pipes industry. A comparison of the PPR and WF composites is necessary, between this study and the utilization of a coupling agent.

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