Experimental Investigation on Mechanical and Physical Properties of Hybrid Plastic/Wood Composites as Echo-friendly Structural and Decorative Materials

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This study focuses on producing wood-plastic composites using unsaturated polyester resin reinforced with Pistacia vera shell particles and wood industry waste powder. Composites with reinforcement ratios of 0%, 20%, 30%, and 40% were prepared and tested for thermal conductivity, impact strength, hardness, and compressive strength. The results revealed that thermal conductivity increases with reinforcement, while maintaining good thermal insulation, reaching a peak value of 0.633453 W/m·K. Hardness decreased with increased reinforcement, reaching a minimum nominal hardness value of 0.9479. Meanwhile, impact strength and compressive strength improved, with peak values of 14.103 k/m² and 57.3864568 MPa, respectively. The main aim is to manufacture eco-friendly wood-plastic composites suitable for structural use, addressing environmental concerns by recycling wood waste. This research aims to contribute to sustainability by creating materials for decorative elements or secondary roofing, minimizing the environmental impact of wood waste, and promoting eco-friendly alternatives for daily use.

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1. Introduction

Wood-plastic composites represent a significant advancement in materials engineering and environmental technology. It combines the sustainability and eco-friendliness of wood with the durability and flexibility of polymers. This material comes at a time when the world is witnessing a growing awareness of the importance of environmental conservation and waste reduction. In the context of growing global environmental consciousness and the pursuit of reducing harmful emissions, the wood composites industry is actively exploring eco-friendly materials for its products. By incorporating plastics and utilizing waste wood-based fillers, the manufacturing of wood-plastic composites (WPCs) can be recognized as an environmentally responsible technology [1]. WPCs encompass composite products produced by combining plant fibers (whether wood or non-wood), thermoplastic or thermoset resins, along with a limited set of additives. These composite materials present several advantages, including improved mechanical properties characterized by increased strength and stiffness, reduced density and abrasion when compared to inorganic filler composites [2-4]. Furthermore, in contrast to solid wood, WPCs offer enhanced water and decay resistance, superior acoustic performance, lower weight, reduced production expenses, and are biodegradable [5-6]. Plastic and wood waste have emerged as significant environmental concerns. Plastic poses a particularly grave challenge due to the substantial volume of waste it generates, its non-biodegradable nature, and its rapid consumption of natural resources, given its short lifespan. This is further exacerbated by the increased material usage in its production and the resulting waste. A similar, albeit to a lesser extent, concern applies to wood, as it contributes to the depletion of trees and forests. The predominant disposal methods for wood waste involve burning or simply discarding it, leading to additional resource consumption and environmental pollution. In response to these pressing issues, numerous global initiatives have been implemented, particularly in developed countries. These efforts aim to capitalize on such waste materials, particularly in light of the growing demand for alternatives to virgin resources [7]. Wood plastic composite (WPC) is a product derived from a combination of plastic and wood components. WPCs represent a composite material experiencing rapid growth in utilization, comprised of a blend of wood waste and polymeric substances [8]. Several endeavors to develop WPC products have been based on the Cradle-to-Cradle philosophy. In this methodology, the material undergoes recycling at the end of its life cycle to produce a new product, thus seamlessly closing the loop and emulating the cyclic processes observed in natural ecosystems [9]. As a result, this practice reduces the amount of solid waste and helps preserve natural resources. Consequently, it leads to cost savings, reduced energy consumption, and less depletion of virgin materials. Furthermore, this approach ensures sustainability for the coming years, allowing for the continued use of resources by future generations [10]. Over the past decade, WPC has emerged as a prominent subject of research. Its popularity has grown significantly due to its numerous advantageous properties that have garnered the attention of researchers. These advantages include high durability, low maintenance requirements, satisfactory relative strength and stiffness, cost-effectiveness compared to alternative materials, and the environmentally friendly aspect of being a natural resource [11]. Furthermore, additional strengths and advantages have been highlighted by Wechsler and Hiziroglu [12]. WPCs are highly resistant to biological deterioration, making them suitable for outdoor applications where untreated timber fails. Their appeal lies in the availability of fine wood waste, ensuring sustainability and improved thermal and creep performance compared to unfilled plastics. WPCs find applications in structural building elements like profiles, sheathings, decking, roof tiles, and window trims. While not as stiff as solid wood, they outperform unfilled plastics in stiffness, and their use doesn't require special fasteners or design modifications, performing similarly to conventional wood [13]. Many studies have been conducted in the field of WPC recently to enhance their properties for various applications and to align them with forest products. In 2015, Janis et al. have investigated the use of by-products from the compressed wood industry, such as birch sawdust, to enhance polypropylene. The study demonstrated that the addition of birch sawdust improves the properties of WPCs, but some properties are negatively affected [14]. A study in 2018 involved the preparation of polymer composites reinforced with cellulose materials, studying their physical properties by reinforcing polypropylene with wheat straw, barley husks, rice husks, sunflower stalks, and flower discs. The results indicated that reinforcing polypropylene, whether individual or hybrid, with minute powders of used agricultural waste generally improved surface mechanical properties [15]. In 2019, Raya et al. have studied the tribological properties of composites of resins (epoxy/wood fines (Reed)). The composite was prepared by hand casting with weight fractions 0, 20, 30, 40, 50% in addition to studying the effect of variations in the fines' size (60, 150, and 212 µm). The results showed improvements with an increase in the percentage of wood fines [16]. In 2020, Raya et al. have prepared and studied some mechanical properties of WPCs. The results showed improvements in hardness, impact resistance, wear rate, tensile test, and creep test by adding reed fines to polypropylene [17]. In 2021, Geeta et al. have investigated the use of an alternative wood source (pellets) to reduce the transportation costs of raw materials for manufacturing WPCs. WPCs were manufactured using wood sawdust and wood pellets, and the results showed slight differences in mechanical properties. Our research serves as support for existing research studies [18]. The process of preparing WPCs from wood waste and Pistacia vera shell residues is a crucial step towards reducing waste accumulation and making better use of available resources. It allows us to recycle materials that were previously overlooked, reducing the pressure on forests and natural resources. With its strength and resistance, WPCs can be utilized in a variety of applications, thereby diminishing the reliance on non-renewable petroleum-based materials.

This research sheds light on the vast potential of WPCs across multiple domains and aims to gain a better understanding of their preparation and enhancement for sustainability. It is situated within the context of achieving a balance between the economy and the environment, where WPCs can serve as an innovative solution to meet human needs without polluting the environment or depleting natural resources.

2. Experimental Parts

2.1 Matrix Material

Unsaturated polyester (UPE) is a low-molecular-weight linear polymer that outperforms its saturated counterpart due to its excellent resistance to solvents and ambient moisture, attributed to the cross-links between its polymer chains. This thermosetting polymer typically exists as a clear liquid material and solidifies when a catalyst, such as methyl ethyl ketone peroxide (MEKP) [19-20], is added in a ratio of 98:2. Saudi origin. It is a colorless liquid with a medium viscosity and density (1 to 1.3 g/cm^3) at 25°C, pungent odor.

2.2 Reinforcement Material

Reinforcement materials are distinguished by their high resistance, making them essential in composite materials, where they serve to strengthen and enhance the matrix material. When reinforcement material is added, changes occur in the mechanical and physical properties while preserving the desired characteristics of composite materials [21]. Two types of reinforcement materials, Pistacia vera and Timber industry waste powder, were employed in this study.

The hard shells of Pistacia vera (P.V) with a light-yellow color are cleaned with water and then dried in an oven at 60°C for two hours. After that, the P.V shells are broken into coarse particles, as illustrated in Fig. (1).

Timber industry waste powder (T.I.W.P.) was obtained from carpentry shops in Baghdad. It is a brown-colored powder that has been sifted through a 53-micrometer sieve. Figure (2) illustrates a photographic image of the timber industry's waste powder.

Fig. (1) A photograph of P.V

Fig. (2) A photographic of the T.I.W.P.

2.3 Method

The research consists of two stages: in the first, unsaturated polyester (UPE) resin was prepared by adding the hardened in a ratio of 2:98 and mixing for two minutes using a magnetic stirrer method at 500 rpm. In the second stage, the UPE resin was reinforced with hybrid reinforcement materials as shown in table (1) with weight fractions of 0%, 20%, 30%, and 40% to prepare WPCs. The mixture was stirred using a magnetic stirrer at 500 rpm for 5 minutes.

Table (1) The weight fractions of the WPCs

Wt. % for Reinforcement	0%	20%	30%	40%
UPE	100%	80%	70%	60%
P.V	0%	10%	15%	20%
T.I.W.P.	0%	10%	15%	20%

The mixture was poured into molds made of silicone rubber material, pre-prepared according to international specifications for each test. The samples were left at room temperature for one day to solidify, and then they were easily removed from the molds. Table (2) provides the international specifications for each test. Figure (3) shows a photograph of WPC samples.

Table (2) The international specifications for each test

Test	Sample shape	Sample Dimensions	Standard Specification
Impact strength		55x10x5 mm^3	ISO-179
Thermal conductivity		4x40 mm^2	Lee's Disk
Hardness		4x40 mm^2	ASTM-D2240
Compression		20x10x10 mm^3	ASTM-D690

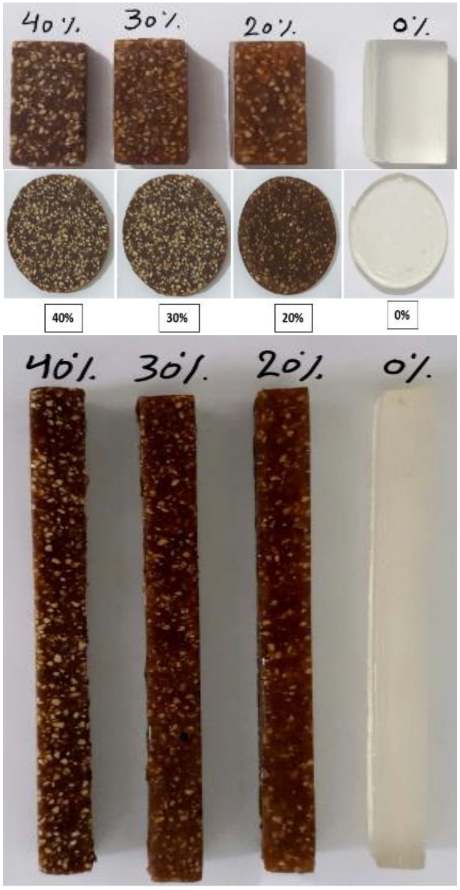

Fig. (3) Photographs of WPC samples

2.4 Tests

Thermal conductivity (K) is the phenomenon by which heat is transferred within a material from regions of high temperature to regions of low temperature [22]. The property that characterizes a material's ability to conduct heat is called thermal conductivity [23]. The fundamental law governing heat conduction is Fourier's law, which can be expressed as follows [24]:

$$q = -k\frac{dT}{dx} \quad (1)$$

where q represents the heat energy flux per unit area per unit time (W/m²), k is the thermal conductivity of the material (W/m.K), dT/dx is the temperature gradient (K/m)

In this equation, q represents the rate of heat transfer through a material due to the temperature difference, with a negative sign indicating that heat flows from high temperature to low temperature regions. The temperature gradient (dT/dx) represents

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how temperature changes with distance along the material, and k is a material-specific constant that quantifies how readily the material conducts heat [25-27]. This law is fundamental in understanding and quantifying heat transfer in various engineering and scientific applications, such as in the design of thermal insulation, heat exchangers, and other systems where heat management is critical.

The thermal conductivity (K_T) is calculated using the following equation [28]:

$$K_T\left(\frac{T_B-T_A}{d_S}\right)=e\left[T_A+\frac{2}{r}\left(d_A+\frac{1}{4}d_S\right)T_A+\frac{1}{r}d_ST_B\right] \quad (2)$$

where K_T is thermal conductivity (W/m·K), T_A and T_B are temperatures of the copper discs A and B (°C), d_S is thickness of the sample (mm), r is radius of the disc (mm), e represents the heat energy passing through the unit area of the disc per unit time, with units (W/m²·K)

Hardness is a property of a material that enables it to resist deformation, usually by penetration or scratching. However, the term hardness can also refer to resistance to bending, scratching, and corrosion. Shore hardness is a measure of a material's resistance to penetration by an indenter, similar to a needle, loaded with a spring. Shore hardness is used to measure the hardness of hard plastic and most other polymer materials, typically using the shore D scale. The shore hardness test is performed using a device called a Durometer, where hardness is measured by the depth of penetration of the indenter under a specific load [29-32].

The shore D hardness test was conducted using a digital device of Italian origin, known as "time group, Inc., TH210". Five readings were taken for each sample, and the average was calculated to minimize measurement errors. The device consists of an indenter, which is a sharp-tipped needle with a length of 2.54 mm, connected to a digital scale that ranges from 0 to 100 units. This test was conducted at the Department of Applied Sciences, University of Technology (Baghdad).

In many real-world applications, polymer materials often face rapid impact loads, such as free-fall impacts, direct collisions, or sudden strikes. The purpose of conducting mechanical impact tests is to directly simulate these situations and study the mechanical behavior of polymer composites under impact conditions [33]. Impact Strength is defined as the ratio of the absorbed energy during the impact process to the cross-sectional area of the sample at the point of fracture. The strength and fracture resistance of polymer materials under high-speed stress primarily depend on impact strength tests [34].

Impact Strength (I.S) is calculated using the following equation [34]:

$$I.S=\frac{E_S-E_0}{\mathrm{A}}\times 1000\ (\frac{\mathrm{kJ}}{\mathrm{m}^2}) \quad (3)$$

where $I.S$ is impact strength (J/m^2), A is cross-sectional area (m^2), E_0 is zero reading (without the sample) (J), E_s is fracture energy of the tested sample

The particle shapes, sizes, chemical composition, intermolecular bonding, surface characteristics, and weight or volume fraction all have a significant impact on fracture toughness. Additionally, the concentration of fillers significantly influences the behavior of composite materials [35].

Impact Strength was measured using the Charpy impact test method, utilizing the TMI Impact Testing Machine Model 43-1 (USA). The testing was conducted at the Department of Applied Sciences, University of Technology (Baghdad).

Compressive strength, as defined, represents the maximum stress a material can withstand under axial loading [36]. It is a crucial design factor in the manufacture of composite materials, such as wood-plastic composites, because these materials are subjected to bending stresses that can lead to failure due to compression.

The compressive behavior of composite materials is one of the most important mechanical properties, extensively studied by researchers. It is described through two failure modes: shear mode and buckling mode. Buckling mode is particularly significant in the inner layers of composite materials, leading to progressive failure due to shear deformation [37-38]. The compressive strength of composite materials is enhanced by reinforcement materials, with factors including interfacial bonding strength, cohesion strength, defect quantity, and gaps affecting the composite's compressive resistance [39]. Compressive strength is calculated using the following equation [40]:

$$\sigma = F_m/A \quad (4)$$

where σ is compressive strength (Pa), F_m is maximum load applied to the sample (N), and A is cross-sectional area of the sample (m²)

Compressive strength measurements were conducted using a hydraulic press machine of the Ley Bold Harris No. 36110 model (USA). These tests were performed at the Department of Applied Sciences, University of Technology (Baghdad).

3. Results and Discussions

Figure (4) illustrates the results of thermal conductivity for wood-plastic composites. Thermal conductivity increases slightly with an increase in the filler content, but the composite materials remain insulating. The thermal conductivity of composite materials depends on the quantity and properties of the reinforcing materials added to the base material, the nature and strength of the interfacial bonds between the reinforcing materials and other components of the composite, as well as the size of the gaps between these components [41-42]. In insulating materials, thermal conductivity relies on phonon vibrations within the lattice structure. Several factors affect thermal conductivity, including the direction of heat conduction, whether it is perpendicular or parallel to the reinforcement material, the manufacturing technique, the porosity of the composite material, its density, and the density of the reinforcement material [43]. Resins lack free electrons, so their thermal conduction depends on structural vibrations within their internal structure, which increase with rising temperatures. The hybrid reinforcement materials added to unsaturated polyester in this study are insulating materials, but a slight increase in thermal conductivity was observed. This could be attributed to the properties of the unsaturated polyester, particularly its glass transition temperature, which is equal to 125.5°C [44], and its high melting point. The reason for this increase may also be related to changes in the crystalline structure. If the structure of polyester is modified by adding insulating reinforcement materials, it can lead to alterations in the crystalline structure of the material. These changes in structure can enhance the material's heat transfer capability. Additionally, an increase in density typically results in insulating reinforcement materials increasing the material's density. Higher density means more atoms or molecules within a given volume unit, leading to increased condensation and oscillation in crystalline structures, ultimately leading to an increase in thermal conductivity.

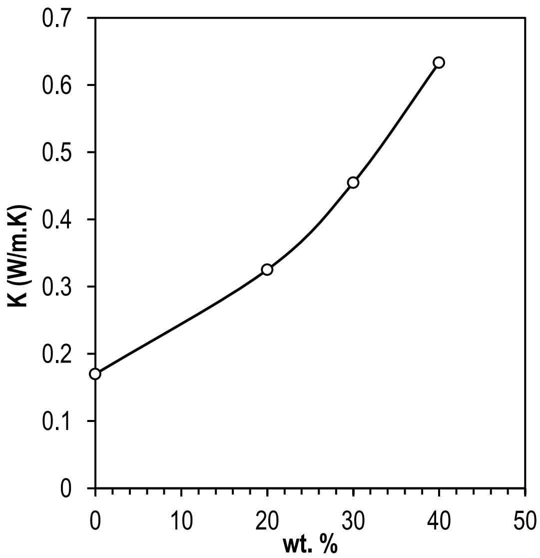

Fig. (4) Thermal conductivity values of WPCs

Figure (5) illustrates a decrease in nominal hardness attributed to an increase in the weight ratio of reinforcement material. The nominal hardness, determined by dividing hardness values by the maximum value, exhibited a range from 1 to 0.9479. A slight decrease was observed at weight fractions of 20% and 30%, while a sharp decline occurred at a weight fraction of 40%. Therefore, the hardness values at weight fractions of 20% and 30% are deemed acceptable, falling within the specified hardness range of 1-0.9872. This analysis suggests that the optimal weight fraction for reinforcement is 30%. The decrease in hardness when adding hybrid reinforcement materials to unsaturated polyester can be at tributed to several factors. One of these factors is the impact of adding coarse Pistacia vera, which can weaken the polyester when distributed in large quantities, increasing the porosity of the composite. Additionally, fine powder from the timber industry waste can lead to the dispersion of the polyester and make it less rigid. The reason might be the fine powder from the timber industry waste, and when it is incorporated extensively into the polyester, it may reduce the bonding between the particles, thus decreasing polyester hardness. Uneven distribution of the added materials in the polyester can also result in reduced hardness. When there are clusters of coarse materials or fine powder, it can affect the mechanical properties of the base material. Furthermore, it is noticeable from Fig. (5) that the quantity of added materials can have a significant impact on hardness, as an increase in the weight fraction of the added materials was observed to reduce hardness.

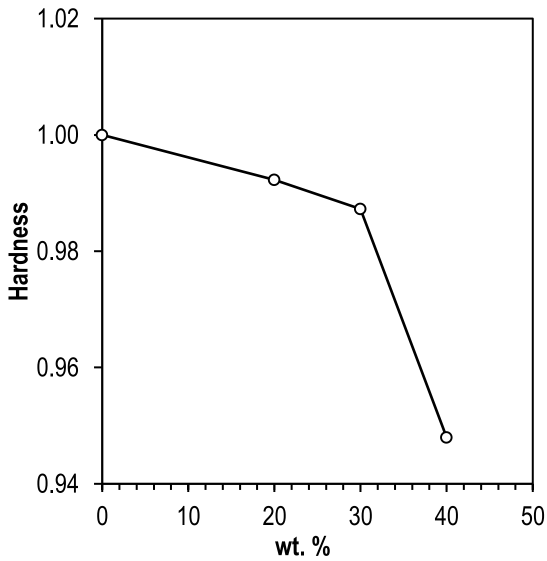

Fig. (5) Hardness values of WPCs

The Impact strength test was conducted on samples of WPCs reinforced with varying weight fractions of hybrid materials. It was observed from Fig. (6) that fracture energy increases with an increase in the weight fraction of hybrid reinforcement materials. The absorbed energy depends on the nature of the components of the materials used in sample fabrication, as well as the external stress resistance applied to the sample. The mechanism of material failure due to rapid stresses it experiences is one of the most significant mechanical properties that many researchers have shown interest in studying. Polymeric materials may exhibit resilience to static stresses and appear more brittle under the influence of rapid stresses, such as UPE [45-46]. The increase in fracture energy can be attributed to good adhesion in the interface region between the base material and the reinforcement material [47]. Another explanation is that the increase in fracture energy may result from strong interactions between UPE resin and the hybrid reinforcement material due to the formation of cross-links that protect or cover the particles, thereby preventing crack propagation. The particles filling the gaps between polymer chains, which occupy the interstitial polymer regions, create an inhomogeneous mixture that hinders the movement of polymer chain segments and can further enhance mechanical properties.

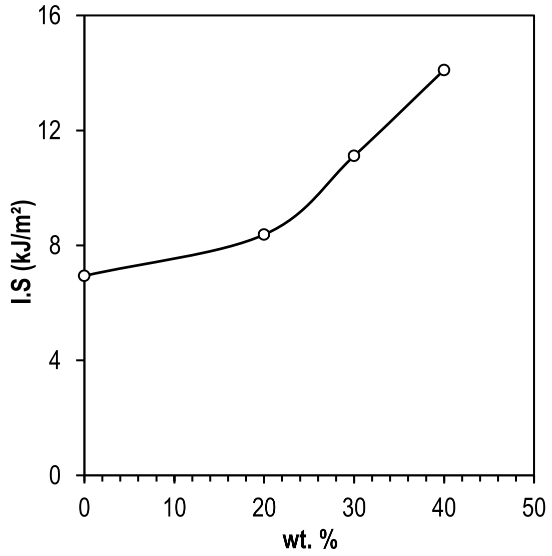

Fig. (6) Impact Strength values of WPCs

Compressive strength is the ability of a material to withstand axial compressive forces. When the limits of compressive strength are reached, the material fractures. One of the advantages of thermosetting resins like UPE is that they possess high compressive strength [48]. From Figures (7) and (8), it can be observed that the compressive strength of composite samples increases with an increase in the weight fraction of hybrid reinforcement materials. This may be attributed to several factors, including an increase in cohesion and adhesion, resulting in improved cohesion and adhesion between the unsaturated polyester matrix and the coarse particles of Pistacia vera and Timber industry waste powder. This improved cohesion can enhance compressive strength by preventing particle slippage and allowing particles to withstand higher loads before failure occurs. Another factor is the formation of cross-links when Timber industry waste powder particles interact with the UPE matrix, cross-links may form between them. These cross-links enhance the material's strength and its ability to resist compression. The reason could also be attributed to better stress distribution if the coarse particles of Pistacia vera and Timber industry waste powder are uniformly distributed within the matrix, this can lead to better stress distribution at the internal structures of the material. This means that stresses are transferred more effectively and distributed more uniformly, increasing compressive strength. Additionally, the coarse particles of Pistacia vera may increase compressive strength by providing additional support points and contact areas for the even distribution of pressure within the material. Furthermore, Timber industry waste powder may absorb some of the pressure and act as a filler for voids within the material, increasing its resistance to compression.

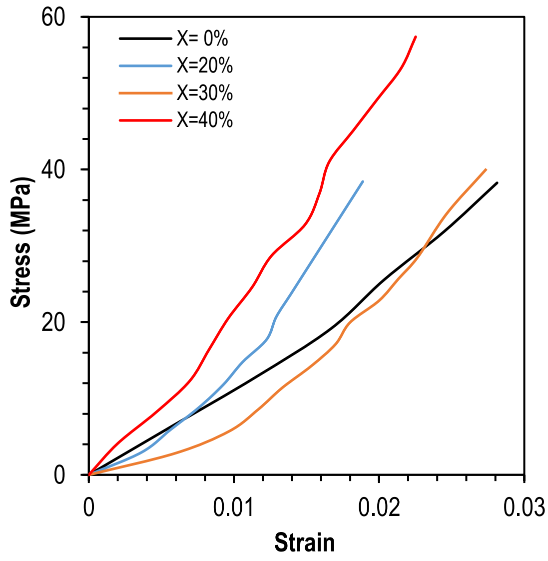

Fig. (7) Stress vs. Strain values of WPCs

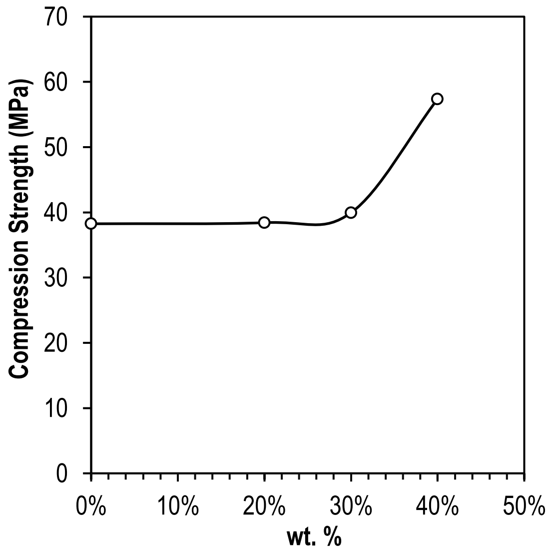

Fig. (8) Compression values of WPCs

4. Conclusions

In conclusion, this research successfully produced wood plastic composites (WPCs) using unsaturated polyester (UPE) resin reinforced with Pistacia vera shell particles and wood industry waste powder. The composites demonstrated favorable properties for structural and decorative applications. Higher reinforcement ratios increased thermal conductivity, suggesting potential as thermal insulators. Despite a slight decrease in hardness with increased reinforcement, the composites remained suitable for various applications. Impact resistance significantly improved with higher reinforcement percentages, indicating effective stress and impact tolerance. Compressive strength also increased, making these composites suitable for load-bearing structures. The study achieved its primary aim of creating environmentally friendly wood-plastic composites from wood waste, contributing to sustainable practices, and providing versatile materials for diverse applications.

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