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Manufacture and study the mechanical, thermal and physical properties of plastic wood

Rihab Nassr Fadhil^{1*}, Muna B. Jasim², Zainab Assif Abdullah³, Shatha H. Mahdi⁴ and Kareem A. Jasim⁵

^{1, 2, 4, 5} Department of Physics, College of Education for Pure Science / Ibn Al-Haitham, University of Baghdad, Baghdad, Iraq

³University of Technology- Iraq

*Corresponding author's e-mail: rihab.n@ihcoedu.uobaghdad.edu.iq

Abstract. This study focuses on evaluating the mechanical properties and thermal conductivity of unsaturated polyester (UPE) composites reinforced with Pistacia shells (Pi-S). Wood-plastic composites were prepared using UPE reinforced with Pi-S at different weight ratios (50%, 60%, 70%). The main objective of this work is to recycle Pistacia shells in significant proportions and assess the impact of using Pi-S as reinforcing materials in UPE. Mechanical tests, such as Shore D hardness, impact resistance, and compressive strength, were employed to evaluate the mechanical properties of the composites. The results showed that the 50% weight ratio achieved the highest values in all tests compared to other ratios (60%, 70%). Impact resistance increased to 10.15 KJ/m² at the 50% weight ratio, followed by the 60% weight ratio with the highest impact resistance. The results also indicated a slight decrease in Shore D hardness with an increase in the weight ratio and a decrease in compressive strength. Regarding thermal conductivity, the highest thermal conductivity value was at the 50% weight ratio, with a value of 0.68118762 W/mk. It then decreased at the other weight ratios but remained higher than the thermal conductivity of pure unsaturated polyester. This technique allows for the full utilization of Pistacia shells in the wood-plastic industry, contributing to various applications such as wooden and plastic flooring, surfaces, doors, and more.

1. Introduction

Wood has been used since ancient times in construction and building, and it continues to be widely utilized in construction and industrial projects today. Wood stands out for its numerous qualities, including abundant sources, ease of shaping, connecting, and assembling. Additionally, it is lightweight compared to other construction materials, with the note that its lightweight nature does not compromise its load-bearing capacity. Other significant factors include its good insulation properties for both heat and sound. Structures constructed from wood have the potential to endure for extended periods, even reaching hundreds of years, if properly maintained [1]. Despite the numerous benefits of wood, it suffers from expansion and contraction due to humidity, along with other negative effects such as decay and infestation by bacteria and insects. Despite the diversity in tree types, wood sources remain limited, making the improvement of wood technology and the use of wood-plastic materials a fundamental challenge [2]. Wood is a fibrous composite material consisting primarily of hydrocarbons, cellulose, and lignin, making it versatile for various applications. In addition to these key components, wood also contains small amounts of gum, starch, resins, wax, and organic acids. Wood can be categorized as either softwood or hardwood [2]. Polymers offer numerous advantages compared to other materials,



primarily due to their unique combination of hydrogen and carbon atoms. This composition makes the polymer Thermoset highly versatile and exceptionally durable, making it suitable for intense summer sunlight, extremely low winter temperatures, and rainy seasons. Moreover, it remains unaffected by microorganisms and boasts a long lifespan. With all these characteristics, petroleum-based polymers find diverse applications in various fields [3]. Undoubtedly, the emergence of the wood-plastic composites industry is the result of an innovative interaction between two historically unrelated industrial sectors—forest products and plastics. The knowledge bases, experiences, and future perspectives of these industries differ significantly. This industry successfully utilizes composite material technology to incorporate fine wood particles, derived from Pistacia shell residues. These particles are then combined with resin possessing desirable properties that are unattainable in any other individual material. This process involves skillfully blending different materials in composition or form. While these materials retain their individual characteristics, they synergistically coordinate with each other, creating unique properties in composite materials that cannot be achieved from each material separately. Additionally, this technology ensures full utilization of solid waste generated from the wood industry, commonly known as wood-plastic, contributing to various important and necessary applications such as wood-plastic flooring, aquatic surfaces, doors, and more [4].

2. Experimental Parts

2.1. Matrix Material

Unsaturated polyester resins result from the condensation of unsaturated acids or anhydrides with diols, either with or without diacids. The inherent unsaturation in these polyesters becomes a focal point for subsequent cross-linking [5, 6]. Demonstrating remarkable versatility, unsaturated polyester resins have become a pivotal thermosetting system in a wide array of applications [7, 8]. These resins are compounded with various fillers and reinforcements, and their curing process involves the use of free radical initiators. The outcome is the production of thermoset articles with a diverse range of chemical and mechanical properties, dependent on the specific selection of diacids, diols, cross-linking agents, initiators, and additional additives [9]. This thermosetting polymer, originating from Saudi Arabia, typically presents itself as a clear liquid material that solidifies upon the introduction of a catalyst, such as methyl ethyl ketone peroxide (MEKP) [10, 11], in a ratio of 98:2. This colorless liquid exhibits moderate viscosity and a density ranging from 1 to 1.3 g/cm³ at 25°C, along with a distinctive pungent odor.

2.2. Reinforcement Material

In this study, a specific type of reinforcement material, namely Pistacia shells (Pi-S), was utilized. These shells are characterized by their hard texture and exhibit a light-yellow color. The initial preparation involves cleaning the Pistacia shells with water, followed by a drying process in an oven at 60 °C for two hours. Subsequently, the Pistacia shells (Pi-S) are meticulously broken down into coarse particles, as depicted in figure 1, to be incorporated into the study.



Figure 1. Illustrates a photograph of Pi-S.

2.3. Method

Unsaturated polyester resin (UPE) was formulated by introducing the hardener at a ratio of (2:98) and agitating the mixture for two minutes using magnetic stirring at a speed of 500 revolutions per minute. The UPE was further strengthened with monofiller materials, as outlined in table 1, with weight percentages of (0%, 50%, 60%, 70%) for the production of wood-plastic composites. The amalgamation underwent manual stirring for 5 minutes before being poured into molds constructed from pre-prepared silicone rubber, adhering to international standards for each specific test. Subsequently, the samples were allowed to cure at room temperature for a day, facilitating easy removal from the molds. International specifications for each test are detailed in table 2, while figure 2 provides visual representations of the wood-plastic composite samples.

Table 1. The weight proportions of the wood-plastic composites.

UPE	100%	50%	40%	30%
Pi-S	0%	50%	60%	70%

Table 2. Presents the global standards for each test.

Test	Standard specification
Impact strength	ISO-179
Thermal conductivity	Lee's Disk
Hardness	ASTM-D2240
Compression	ASTM-D690



Figure 2. Shows a photograph of wood-plastic composite samples.

2.4. Tests

2.4.1. Thermal conductivity (K). describes the transfer of heat within a material from high to low-temperature regions. It is characterized by Fourier's law (Equation 1), where q is the heat flux, k is thermal conductivity, and dT/dx is the temperature gradient. This law is crucial in engineering for applications like thermal insulation and heat exchangers [12-14].

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

The thermal conductivity (KT) is calculated using Equation 2 [15], considering temperatures (T_A and T_B), sample thickness (dS), disc radius (r), and heat energy (e).

$$KT ((T_B - T_A)/dS) = e [T_A + 2/r (d_A + 1/4 dS) T_A + 1/2r dS T_B] \quad (2)$$

2.4.2. Hardness. is a material property that resists deformation, such as penetration or scratching, and can also encompass resistance to bending, scratching, and corrosion. Shore hardness, measured on the Shore D scale using a Durometer, gauges a material's resistance to penetration by an indenter, akin to a needle with a spring. The Shore D hardness test employed an Italian-made digital device, the "time group, INC., TH210." Five readings per sample were taken, and the average calculated to minimize measurement errors. The device, located in the Department of Applied Sciences at Technological University, consists of a 2.54 mm sharp-tipped needle indenter connected to a digital scale ranging from 0 to 100 units [16-18].

2.4.3. Impact Strength. Impact Strength, abbreviated as I.S, plays a crucial role in assessing the mechanical resilience of polymer materials subjected to rapid impact loads in real-world scenarios, such as free-fall impacts, direct collisions, or sudden strikes. Mechanical impact tests are conducted to simulate these situations, allowing for the study of the mechanical behavior of polymer composites under impact conditions [19]. This strength parameter is defined as the ratio of absorbed energy during impact 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 hinge primarily on the outcomes of impact strength tests [20]. The formula for calculating Impact Strength (I.S) is expressed as follows [20]:

$$I.S = \frac{E_s - E_o}{A} * 1000 \text{ (kJ/m}^2\text{)} \quad (3)$$

Where: I.S: Impact Strength ($J \cdot m^{-2}$), A: Cross-sectional area (m^2), E_o : Zero reading (without the sample) (J) and E_s : Fracture energy of the tested sample.

Fracture toughness is significantly influenced by particle shapes, sizes, chemical composition, intermolecular bonding, surface characteristics, and weight or volume fraction. Moreover, the behavior of composite materials is notably affected by the concentration of fillers [21]. The Charpy impact test method, utilizing the TMI Impact Testing Machine Model 43-1 in Amityville, New York, USA, was employed to measure Impact Strength. The testing procedures were carried out at the Department of Applied Sciences, Technological University.

2.4.4. Compression. Compression, specifically compressive strength, defines a material's ability to withstand maximum stress under axial loading [22]. This factor holds significant importance in the production of composite materials like wood-plastic composites, where susceptibility to failure from compression-induced bending stresses is a key consideration. The compressive behavior of composite materials, a pivotal mechanical property, undergoes extensive examination by researchers. It is delineated by two failure modes: shear and buckling. The latter is particularly noteworthy in the inner layers of composites, contributing to progressive failure due to shear deformation [23, 24]. Reinforcement materials play a crucial role in enhancing the compressive strength of composites, influenced by factors such as interfacial bonding strength, cohesion strength, defect quantity, and gap dimensions, collectively impacting the material's resistance to compression [25]. To quantify compressive strength, the following equation is employed [26]:

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

Where: σ : Compressive strength (Pa), F_m : Maximum load applied to the sample (N) and A: Cross-sectional area of the sample (m^2).

Compressive strength measurements were conducted using a Ley Bold Harris No. 36110 model hydraulic press machine of American origin. These tests took place at the Department of Applied Sciences, Technological University.

3. Results and Discussions

3.1. Thermal conductivity (K)

The results of thermal conductivity for wood and plastic composites are illustrated in figure 3. Thermal conductivity increases when reinforced with a weight fraction of 50%, reaching 0.68118762 W/mk compared to the pure sample. However, when the weight fraction of reinforcement exceeds 50%, thermal conductivity decreases slightly with an increase in filler content, while the composite materials remain insulating. The thermal conductivity of composite materials depends on the quantity and properties of the added reinforcing materials 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 [27, 28]. In insulating materials, thermal conductivity depends on phonon vibrations within the network structure. Several factors affect thermal conductivity, including the direction of heat transfer, whether perpendicular or parallel to the reinforcing material, manufacturing technique, porosity of the composite material, its density, and the density of the reinforcing material [29]. Resins lack free electrons, so their thermal conductivity depends on structural vibrations within their internal build-up, which increase with rising temperatures. This increase may also be associated with changes in crystalline structure. If the polyester structure is modified by adding reinforcing insulating materials, it can lead to alterations in the crystalline structure of the substance. These changes in structure can enhance the material's ability to transfer heat. Additionally, an increase in density usually results in an increase in the density of insulating materials in reinforcing materials. Higher density means a larger number of atoms or molecules within a certain volume unit, leading to increased condensation and oscillation in crystal structures, ultimately resulting in increased thermal conductivity.

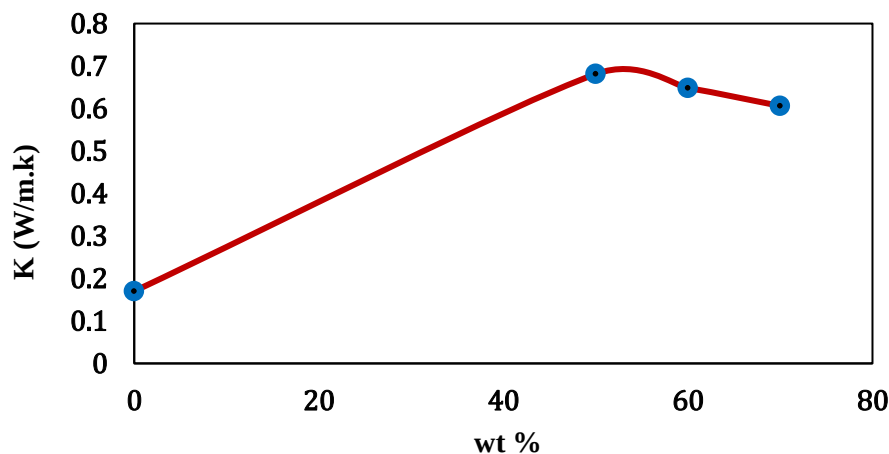


Figure 3. displays the thermal conductivity values for composites made from wood and plastic.

3.2. Hardness

Five measurements were taken for each experimental point, and the average value was calculated. Subsequently, the hardness was determined based on these averaged values. The decrease in hardness observed when adding reinforcement materials to unsaturated polyester can be attributed to several factors. One significant factor is the impact of incorporating coarse Pistacia vera, which has the potential to weaken the polyester when present in large quantities, thereby increasing the porosity of the composite. Additionally, uneven distribution of these added materials within the polyester can contribute to a reduction in hardness. Clustering of coarse materials can particularly compromise the

mechanical properties of the base material. Furthermore, as depicted in figure 4, the quantity of added materials demonstrates a notable influence on hardness, with an increase in the weight fraction of reinforcement materials correlating with decreased hardness. Specifically, Figure 4 illustrates a decline in hardness corresponding to an increase in the weight ratio of the reinforcement material. This decline is gradual for weight fractions of 50% and 60%, while a sharp decline is evident at a weight fraction of 70%. Consequently, hardness values at weight fractions of 50% and 60% are deemed acceptable based on this analysis. In light of these findings, it is suggested that the optimal weight fraction for reinforcement materials is 50%.

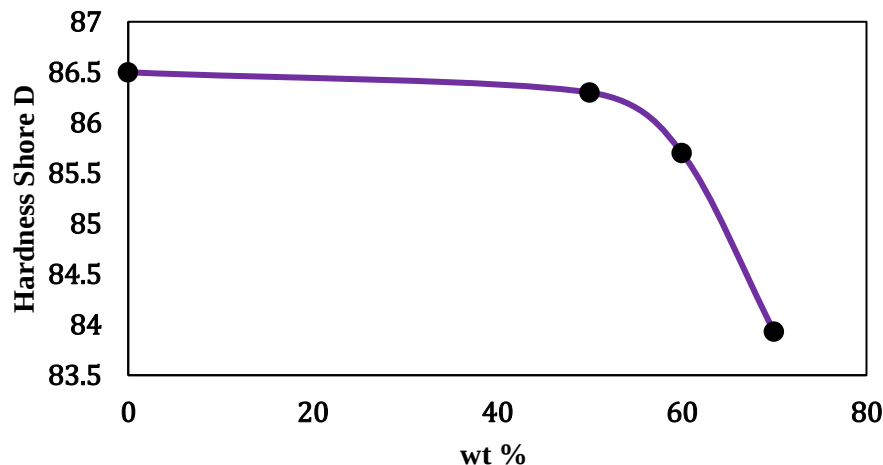


Figure 4. Shows the Hardness Shore D values of wood-plastic composites.

3.3. Impact Strength

Impact strength testing was conducted on wood-plastic composite samples with varying weight fractions of materials. Figure 5 illustrates that the fracture energy rises at a weight fraction of 50% followed by 60%, but sharply declines at 70%. The measurement uncertainty of the device was ± 0.01 . The absorbed energy is influenced by both the composition of the materials used in sample fabrication and the external stress resistance applied to the samples. The mechanism of material failure under rapid stresses is a key mechanical property of interest to many researchers. Certain polymeric materials, such as unsaturated polyester, may exhibit resilience to static stresses but become more brittle under rapid stresses [30, 31]. The increase in fracture energy at 50% weight fraction can be attributed to good adhesion at the interface between the base material and the reinforcement material [32]. Additionally, it may result from strong interactions between unsaturated polyester resin and the reinforcement material, leading to the formation of cross-links that protect or cover the particles, thereby impeding crack propagation. Consequently, based on this analysis, the impact strength value at 50% weight fraction is deemed acceptable. The decline in impact strength at 70% weight fraction observed with the addition of reinforcing materials to unsaturated polyester can be ascribed to various factors. One notable factor is the influence of incorporating actual, coarse pistachios, which holds the potential to undermine the polyester, especially in substantial amounts, consequently augmenting the porosity of the compound. This increase in porosity can lead to a reduction in the overall structural integrity of the material, thereby impacting its impact strength. Additionally, the presence of coarse Pistacia shells might introduce discontinuities or weak points within the material, facilitating crack initiation and propagation under stress, further exacerbating the decrease in impact strength. Therefore, careful consideration of the type and quantity of reinforcing materials is crucial to maintaining or enhancing the mechanical properties of the composite material. Considering these findings, it is recommended that the optimal weight percentage of reinforcing materials be 50%.

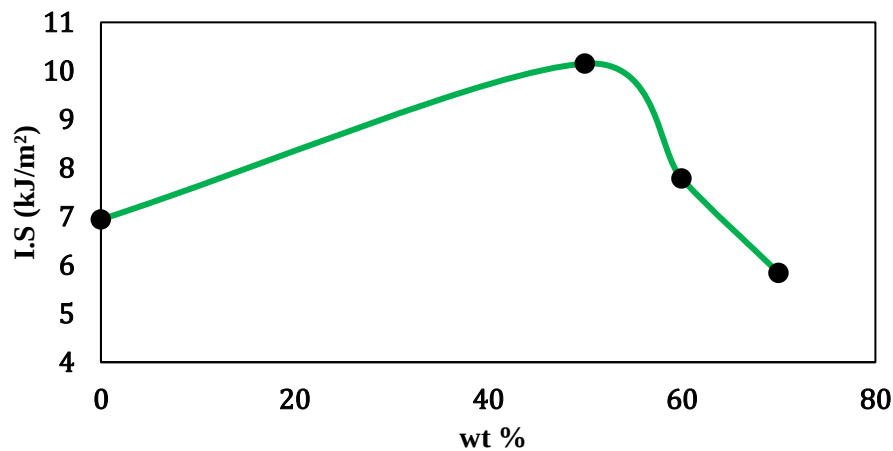


Figure 5. Shows the Impact Strength values of wood-plastic composites.

3.4. Compression

Compressive strength refers to a material's capacity to withstand axial compressive forces, with failure occurring once these limits are exceeded. Thermoset resins like unsaturated polyester boast high compressive strength, presenting a notable advantage [33]. Figures 6 and 7 demonstrate a decline in the compressive strength of composite specimens as the weight fraction of reinforcement materials increases. The measurement uncertainty of the device was ± 0.05 . This reduction can be attributed to the viscosity of the polymeric liquid when combined with high proportions of Pistacia shell particles. Elevated viscosity impedes proper wetting of the particles before polymer hardening, resulting in weak cohesion between the polymer and particles and consequently reduced compressive resistance values. The interface, delineating the connection between reinforcement and base materials [34], plays a pivotal role in stress transfer mechanisms. Effective stress transfer hinges on the strength of the bond between these materials; without it, stress transfer is impeded, rendering the reinforcement materials as discontinuities within the base material [35]. Interface properties are chiefly influenced by the base material's capacity to wet the reinforcement materials, known as wettability. Wettability dictates how well a liquid can spread over a solid surface. Enhanced wettability facilitates greater interfacial contact area between the base and reinforcement materials, thereby facilitating stress transfer [36].

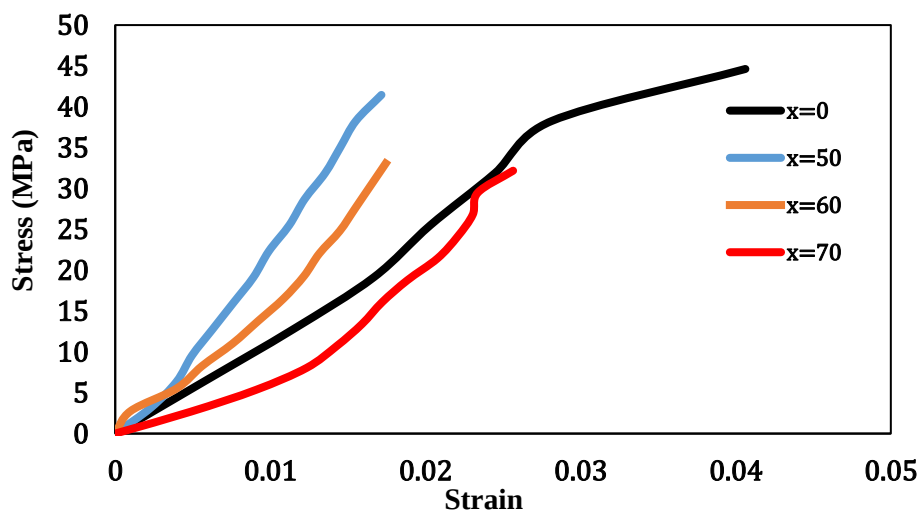


Figure 6. Shows the Stress vs. Strain values of wood-plastic composites.

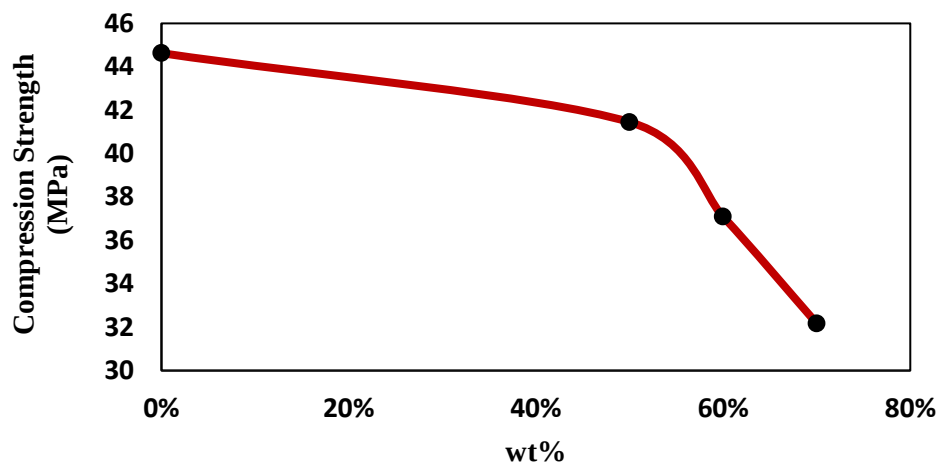


Figure 7. Shows the Compression values of wood-plastic composites.

4. Conclusions

In conclusion, this research has successfully demonstrated the fabrication of wood-plastic composites using unsaturated polyester resins reinforced with materials containing Pistacia shell particles. These composite materials exhibit promising properties suitable for a variety of applications, including flooring, roofing, and plastic doors. The study revealed that thermal conductivity increases at a weight fraction of 50%, reaching its peak before decreasing at weight fractions of 60% and 70%. Nonetheless, plastic composites retain excellent heat insulating qualities. Despite a slight decline in hardness with increasing reinforcement ratio, the composite materials maintain satisfactory levels of hardness, rendering them suitable for diverse applications. Moreover, the research revealed a notable enhancement in impact strength at a reinforcement ratio of 50% and 60%, followed by a decline at weight fractions of 70%, indicating the composites' effectiveness in withstanding pressures and mechanical impacts. Although compressive strength experienced a slight reduction at a 50% weight fraction, these composites remain a viable choice for load-bearing structural elements. The primary objective of this study has been realized: the creation of environmentally friendly wood-plastic composites utilizing plant waste. These compounds not only mitigate the environmental footprint of plant waste but also promote sustainable practices by recycling such waste and advancing the development of eco-friendly materials in alignment with the growing imperative for environmental conservation.

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