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Enhancing Mechanical and Thermal Properties of Unsaturated Polyester Resin with Luffa Fiber Reinforcements: A Volumetric Analysis

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ABSTRACT

This study investigates the influence of Luffa Fiber (LF) inclusions on the mechanical and thermal characteristics of unsaturated polyester resin composites. LFs, manually extracted from luffa plants, are integrated at volumetric fractions of 10%, 15%, 20%, and 25% into the resin using a hand lay-up technique at ambient conditions. Subsequent machining prepares the samples for mechanical analysis. It is observed that mechanical properties enhance progressively with increased LF incorporation. The optimal impact resistance reaches 2.34KJ/m^2, with maximum hardness and compressive strength values of 81.5N/mm^2 and 43.9MPa, respectively. Concurrently, a notable reduction in thermal conductivity is evident, particularly at the 25% LF volume, where it measures approximately 0.105W/m.°C. These findings indicate that the LF-reinforced polyester composites exhibit potential for varied engineering applications. Particularly, their augmented mechanical robustness suits components such as sofa parts and door handles, while their improved thermal insulation properties render them suitable for building insulation. This investigation underscores the viability of LF as a reinforcing agent in polymeric composites, offering a balance of enhanced mechanical strength and thermal efficiency, thereby broadening the scope of their application in engineering domains.

1. INTRODUCTION

Plant fibers, with their long-standing history in diverse applications ranging from industrial to medical, have garnered renewed interest in contemporary research. This resurgence is primarily driven by escalating greenhouse gas emissions from industrial activities, significantly contributing to global warming. Concurrently, there is an increasing global consciousness regarding environmental issues, prompting a shift towards sustainable alternatives to fossil resources. This paradigm shift is further necessitated by the progressive depletion of oil reserves, underscoring the urgency for alternative energy sources and raw materials [1]. The present research investigates the effects of reinforcing polymer-based composites with LFs at varying volume fractions, specifically 10%, 15%, 20%, and 25%. The primary objective is to ascertain the impact of these volume fractions on the enhancement of certain mechanical properties within these composites.

The focus on natural fibers in recent studies stems from their environmental compatibility and their reinforcement capability in polymer materials. These fibers, owing to attributes such as light weight, low density, non-hazardous nature, renewability, widespread availability, and cost-effectiveness, have become increasingly appealing for engineering applications. Consequently, fiber-reinforced composites have gained traction globally, manifesting in various forms like strips and circular sections [2]. The scope of applications for fiber-reinforced materials is vast and varied, encompassing uses in civil engineering for building construction, in the automotive industry for components of ships and radars, and in the medical field, among others [3]. Among natural fibers, LFs have emerged as a popular choice in composite development. The chemical composition of LFs predominantly includes cellulose (57-74%), hemicellulose (14-30%), lignin (1-22%), and other components (0-12.8%). The luffa plant, belonging to the Cucurbitaceous family and commonly known as the vegetable sponge, cylindrical gourd, or kitchen sponge, thrives in regions like China, Japan, India, and Central and South America [4].

While mono-reinforced composites such as those reinforced with luffa cylindrica fibers have demonstrated enhanced properties, hybrid composites have exhibited superior characteristics [5, 6]. Investigations into the hybridization of LF with other fibers or reinforcements have been conducted. For example, research by Sakthivel et al. focused on the reinforcement of polypropylene with LFs and coir in particulate form. It was observed that the inclusion of lignocellulosic-based reinforcements enhanced mechanical properties and ensured compatibility between the materials [6]. Similarly, Srinivasan et al. assessed the impact of fiber treatment and the integration of SiO_2 nanoparticles on

composite properties. The treatment of fibers was found to enhance the fiber/matrix interface quality, and the addition of SiO_2 nanoparticles led to improved mechanical properties [7]. In another study, Panneerdhass et al. explored the reinforcement of epoxy resin with LF and groundnut shell particles, examining their impact on tensile, compressive, flexural, and impact strength [8].

The potential of hybridizing LF with luffa particulates, which could leverage the inherent synergy of the same material, remains an area ripe for exploration, with the anticipation of promising results. This approach is particularly advantageous in various Asian countries where both fibers and particulates are readily available. Furthermore, a study by Mwaikambo and Ansell [9] highlighted the distinct properties of LFs, such as high tensile strength and stiffness, coupled with a significant water absorption capacity compared to other natural fibers, rendering them suitable for reinforcing polymer-based composites.

Beyond their application in composites, LFs have diverse uses. They are employed in wastewater treatment, serve as auxiliary materials for color absorption in solutions, and are used in household cleaning due to their natural woven structure with inherent gaps. Additionally, LFs are integral to the manufacturing of specific automotive components and footwear, among other applications [10].

2. MATERIALS USED

2.1 The matrix material (unsaturated polyester)

Unsaturated polyester (UPE) is a transparent liquid with moderate viscosity and a density of 1.2 g/cm^3. It can be processed to become solid by adding a transparent hardener, which is a compound of methyl ethyl ketone peroxide at a ratio of 2g per 100g of resin. Additionally, a cobalt catalyst, a dark-colored liquid in the form of droplets, is added at a ratio of 0.2g per 100g of resin to accelerate the curing process. After half an hour, it begins to transform into a gelatinous material (Gel) at room temperature.

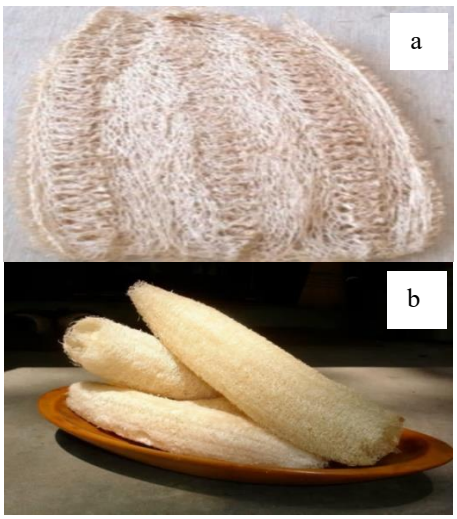

Figure 1. Luffa Fiber (a) before cutting (b) after cutting

2.2 Rienforcement material

In this work, we were able to obtain Luffa Fibers (LFs) from the Luffa plant found in Iraq, specifically in Anbar Governorate, using special mechanical methods. It was used as a reinforcement material due to its good mechanical and thermal properties, its abundant availability in nature, and its low cost. The fibers were cleaned and washed with distilled water, then dried using a hot air oven at a temperature of 100°C for 15 minutes. Afterward, they were cut and placed in a mat form according to the volume fractions to fit the mold size, as illustrated in Figure 1.

3. SAMPLE PREPARATION

The hand lay-up molding method was used to prepare the samples. Specifically, an aluminum mold with the desired sample dimensions was utilized. The samples were prepared according to the predetermined volume fractions for this research, including (10%, 15%, 20%, and 25%). The unsaturated polyester (UPE) resin was mixed with the hardener at a ratio of 2g:100g using a glass rod in a gradual manner to eliminate bubble formation and achieve a homogeneous state. Pumpkin fibers were continuously added to the unsaturated polyester resin to achieve a volume fraction of fibers of 10%. This process was repeated for the other volume fractions. The process of preparing the samples can be summerized in Figure 2. To this end, the volumetric fraction of the fiber (Vf) can be calculated using the following mathematical relationship, which is associated with the weight fraction of the fiber (Ψ): [11]

$$Vf = \frac{1}{1+\frac{1-\Psi}{\Psi}\times\frac{\rho_f}{\rho_m}} \quad (1)$$

$$\Psi = \left(\frac{W_f}{W_c}\right) \times 100\% \quad (2)$$

$$W_c = W_f + W_m \quad (3)$$

where, $W_f, W_m, and\ W_C$ are the weight of the superposed material, the base material, and the reinforcement material, respectively, measured in (g).

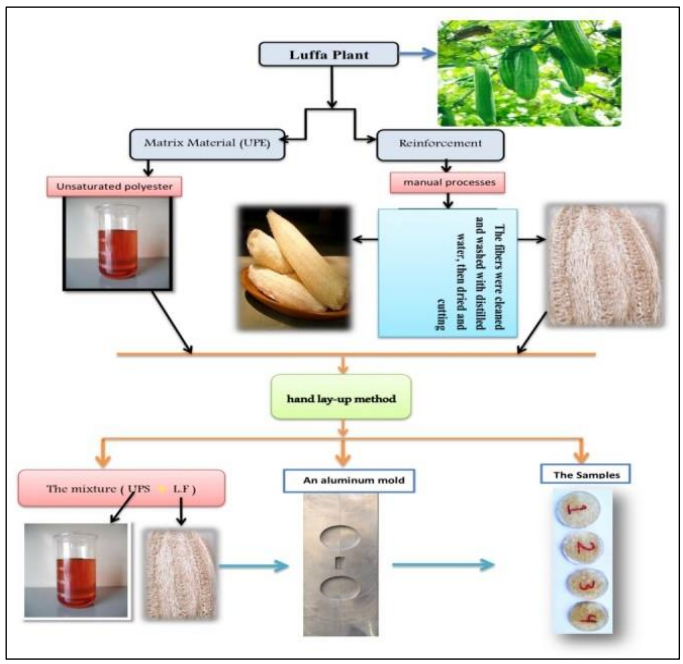

Figure 2. The process of preparing test samples

Moreover, ρ_f *and* ρ_m are the density of the base material and the density of the reinforcing material, respectively, measured in (g/cm^3).

The composite is gently poured into the prepared metal mold, and then the sample is left inside the mold to cure. Once the molding process is completed, the sample undergoes heat treatment, which is accomplished by placing it inside a hot-air oven at a temperature of 50℃ for a duration of 60 minutes. This ensures complete curing and allows for optimal polymer chain interlocking and the release of any stresses generated during the pouring process.

4. MECHANICAL TESTS

4.1 Impact test

The Charpy Test was used to measure the shock resistance of the prepared samples, and the testing device was manufactured by a Chinese company, namely (LAREE Your Testing Solution). This device is used to calculate the energy required for fracture, which can be used to determine the material's impact resistance. Particularly, the device consists of a pendulum and an energy scale. The device's hammer is raised to its maximum height, carrying an energy of 2.5 joules, then it is securely fixed. Next, the sample is placed horizontally between the device's supports in its designated place. The energy scale is zeroed first, and then the pendulum is released using the lever fixed on the scale, resulting in a swinging motion that converts potential energy into kinetic energy. Some of this energy is lost during the sample's fracture, and the scale's indicator reads the fracture energy of the sample (UC). Figure 3 illustrates the samples' impact resistance before and after testing. According to (ISO 179) standard specifications, the sample's dimensions are as follows: length of 55 mm, width of 10 mm, and thickness of 5 mm. The impact resistance (I.S.) is calculated using the following mathematical relationship [12].

$$I.S = U_C / A \tag{4}$$

where: U_C is the fracture energy measured in (KJ).

A: The cross-sectional area of the sample measured in m^2.

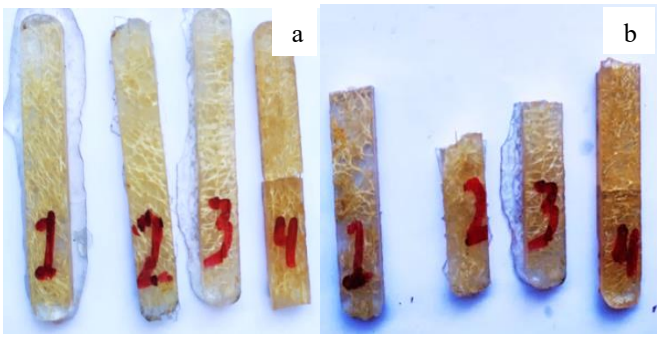

Figure 3. Impact samples: (a) before the test (b) after the test

4.2 Hardness test

Hardness measurements for the samples were conducted using the Shore D method, specifically the HUATEC GROUP Hardness Tester HT-6600C Shore D, manufactured by HUATEC, a Chinese company. The device consists of a needle-shaped indentation tool that penetrates the surface of the sample to record the hardness value. All hardness tests were performed at a laboratory temperature of 27℃. The samples were prepared according to the international American specifications [ASTM-D 2240] [13], as illustrated in Figure 4, which shows the prepared hardness test samples. In this regard, the hardness test of polymer samples allows us to determine the cohesion and durability of the material. Therefore, this test was conducted to measure the surface hardness of polymer materials and their fiber composites at various reinforcement ratios. More specifically, ten readings were taken for each sample, and the average of these readings was determined to obtain the hardness value. This test was conducted at a laboratory temperature of 27℃.

4.3 The compression test

In this test, a device was used to conduct tests for the samples of the prepared overlays, and this device was manufactured by a Chinese company, namely (Laree Technology Co. Ltd). Utilizing this test, the compression resistance of the samples was calculated when a compressive load was applied to them. In particular, the test was carried out when a compressive load was applied at a strain rate of (5 mm/min), and the results of the compressive strength were directly obtained through the device's graph, where the samples were taken with standard dimensions in accordance with the American standard specifications.

5. PHYSICAL PROPERTIES

5.1 Thermal conductivity

In this test, Lee's disk device was used, as shown in Figure 4. This device was manufactured by (Griffen & George) company and was used in the thermal conductivity test of the samples of the prepared composites. To read the temperature of the three discs (TA, TB, and TC) in (℃), thermometers were placed inside them, respectively. The heat is transferred from the heater to the next disc and then arrives at the last disc. By knowing the radius of the discs (r) (mm), their thickness (ds) (mm), the amount of current (I) of (0.25A), and a potential difference (V) of 6 Volt, the thermal conductivity can be calculated using the following two equations [14].

$$K\left(\frac{T_B - T_A}{T_S}\right) = e\left[T_A + \frac{2}{r}\left(d_A + \frac{1}{4}d_s\right)T_A + \frac{1}{2r}d_S d_B\right] \tag{5}$$

$$H = IV = \pi r^2 e(T_A + T_B) + 2\pi re\left[d_A T_A + d_s \cdot \frac{1}{2}(T_A + T_B) + d_B T_B + d_C T_C\right] \tag{6}$$

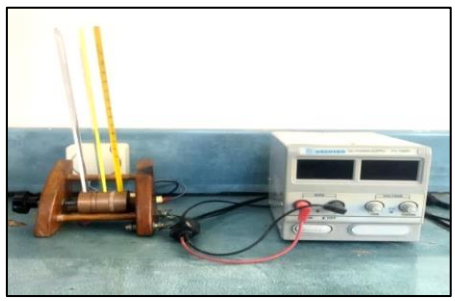

Figure 4. The thermal conductivity test device

The laboratory tests revealed an improvement in the mechanical properties, such as hardness, impact resistance, and compressive strength, with an increase in reinforcement ratios. Meanwhile, the thermal conductivity values decreased with an increase in the ratios, as shown in the Table 1 below.

Table 1. Experimental results of mechanical and physical tests

Volume Fractions of Luffa Fibers (%)	Mechanical Property			Physical Property
	Impact Strength (KJ/m^2)	Hardness (N/m^2)	Compressive Strength (MPa)	Thermal Conductivity (W/m.°C)
0	0.54	52.3	20.8	0.321
10	1.41	74.2	41.9	0.191
15	1.61	77.6	42.8	0.166
20	2.13	79.3	43.4	0.139
25	2.34	81.5	43.9	0.105

5.2 Impact test

The purpose of the impact resistance test is to measure the energy absorbed upon fracture for the prepared samples of polymer materials and their fiber composites with different reinforcement ratios in order to determine their ability to withstand external impact stresses.

The basis of this test relies on the fact that the potential energy (impact energy) is absorbed by the sample before the fracture occurs. Specifically, the impact resistance (G_c) was directly calculated for all prepared samples with different reinforcement ratios using the impact testing device based on the energy required for fracture divided by the cross-sectional area of the sample. This test was conducted at the laboratory temperature.

The results obtained and illustrated in Figure 5 show a significant improvement in the impact resistance for all the prepared samples when reinforced with Luffa Fibers, as the fiber reinforcement with a volume fraction of 10% increased by (0.87) from the pure sample. The reason for this improvement is attributed to the fact that the fibers work to reduce the main defects found in heat-molded polymers, such as shrinkage during casting, brittleness, and surface cracks. Consequently, the fibers enhance the mechanical properties of the material, including its impact resistance. Additionally, the momentum of the fibers leads to strengthening the intermolecular bonds under high loads, which in turn increases the impact resistance, which is in line with the findings of the researcher in the study [15].

Likewise, the rest of the samples increased at the other volume fractions of (15, 20, and 25) %, and the reasons for this improvement include the good adhesion between the reinforcing fibers and the polymer matrix, resulting in the formation of an interfacial surface, which leads to an increase in the material's resistance to external stresses and loads, thereby improving its mechanical properties, including impact resistance.

This composite structure allows the prepared material to withstand much higher impact stresses than it would withstand in the absence of reinforcement. The polymer matrix functions to transfer the impact stresses in the impact test to the reinforcing fibers, requiring the prepared material to have additional energy to fracture, which aligns with the research findings [16].

And the scanning electron microscope test, as shown in Figure 6, proves the extent of good adhesion between the loofah fibers and the unsaturated polyester of the prepared samples.

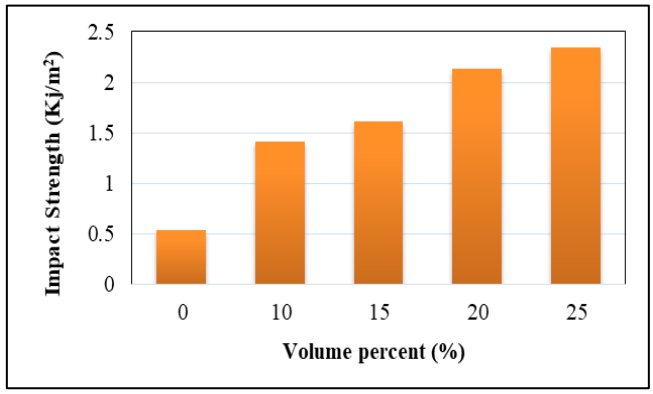

Figure 5. The relationship between volume percent and impact strength

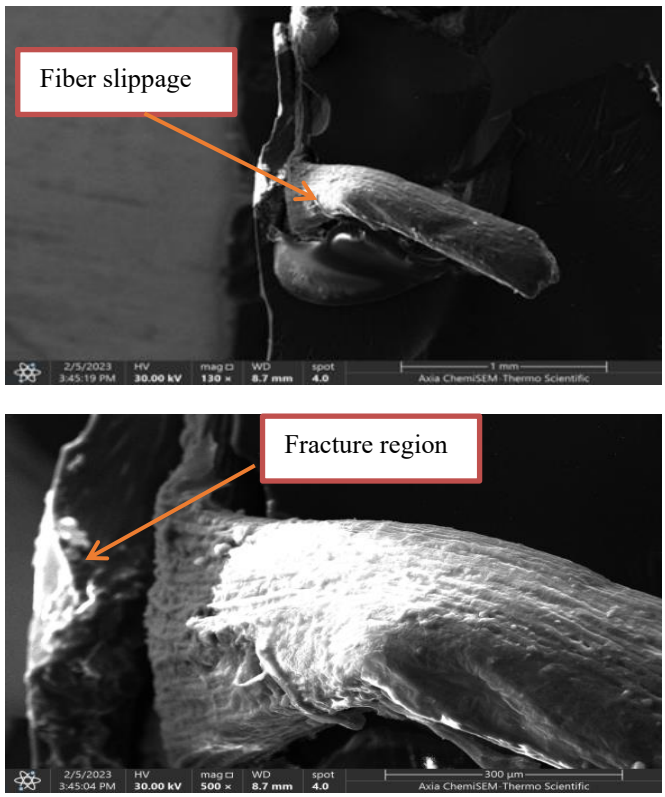

Figure 6. Scanning electron microscope images of Luffa Fiber samples for different reinforcement ratios, where the fracture area and the extent of Fiber slippage and bonding of the base material with the luffa are shown

5.3 Hardness test

The hardness test of polymer samples allows us to determine the cohesion and durability of the material. Therefore, this test was conducted to measure the surface hardness of polymer materials and their fiber composites at various reinforcement ratios. Readings were taken for each sample, and the average of these readings was determined to obtain the hardness value. This test was conducted at a laboratory temperature of 27°C.

The results obtained and indicated in Figure 7 regarding the hardness values of the prepared samples show a significant

improvement in the hardness property for all samples when reinforced with flax fibers. The reason for this improvement is attributed to the presence of those reinforced fibers, which are characterized by their high hardness. This is consistent with the researcher in the study [14], as the external stresses exerted on the base material are transferred to the reinforced fibers through the interfacial surface. These fibers hinder the movement of the polymer chains, leading to an improvement in mechanical properties, including the hardness property. Consequently, this increases the resistance of the materials reinforced with these fibers to scratching and penetration. Additionally, the reinforcing fibers make the polymer material more rigid, thereby increasing the hardness values of the prepared composite material. Furthermore, these fibers create a strong adhesion force between them and the resin through a narrow and strong area called the interfacial surface, which enhances the durability of the prepared samples. Moreover, the high percentage of the reinforcing material within the used fiber composition enhances the hardness of these fibers, resulting in increased resistance to external stresses exerted on them and thus increasing the hardness of the prepared composite materials. This result is in accordance with the researchers in the study [17].

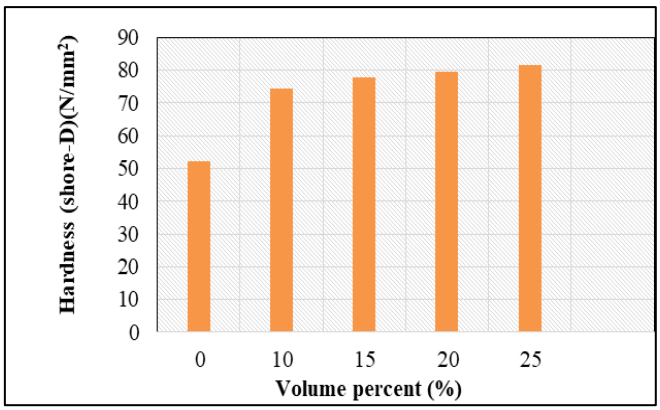

Figure 7. The relationship between hardness values and volumetric fraction of samples prepared from unsaturated polyesteric resin reinforced with Luffa Fibers with different reinforcement ratios

5.4 Compressive test

The aim of this test is to find out the strongest stress that the samples prepared from the polymeric materials and their fibrous overlays can bear under the influence of the vertical pressure applied to them, and it can be calculated by dividing the applied force by the unit area of the cross-section of the sample. In this test, all samples were tested at laboratory temperature.

From Figure 8, the compressive strength at the volume fraction (10%) began to increase by (21.1 Mpa) from the pure sample. The reason for the improvement in the compressive strength is the presence of these fibers, as the load is distributed on the fibers and transferred from the base material to the fibers across the interface.

Moreover, at the volume fraction (15%), the fibers began to improve by (0.9 Mpa) from the volume fraction 10%. At 20 and 25%, the compressive strength improved significantly, and the reason for this is that the fibers began to increase inside the base material, which impedes the movement of the polymeric chains, leading to an increase in the material's resistance to the external stresses imposed on it.

This result agrees with the researcher in the study [18], Where it was found that the compressive strength rises sharply when increasing the percentage of added fibers, due to the distribution of the load on the fibers and the efficiency of the bonding between the base material and the reinforcing fibers, which raises the value of the compressive strength.

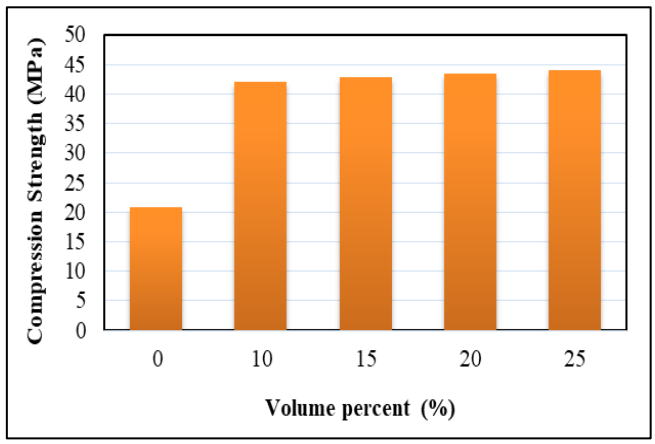

Figure 8. The relationship between volume fraction and compressive strength for the prepared samples

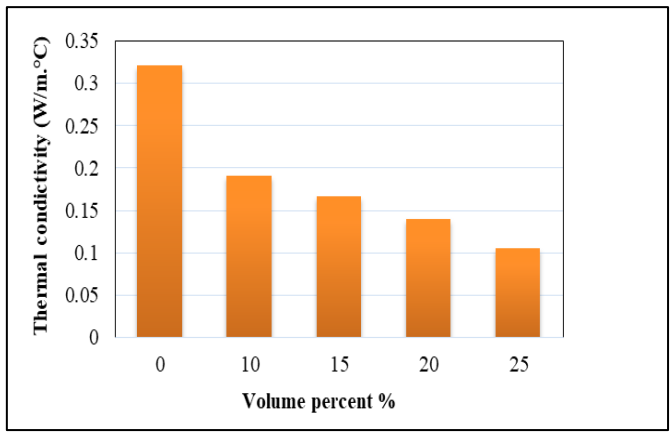

Figure 9. The relationship between thermal conductivity and volume fraction of the prepared samples

5.5 Thermal conductivity test

The thermal conductivity coefficient values were calculated using Eqns. (5) and (6), and the test was conducted for all samples at the laboratory temperature.

The results shown in Figure 9 regarding the thermal conductivity values of the samples prepared from unsaturated polyester resin reinforced with Luffa Fibers with different reinforcement ratios showed that the thermal conductivity decreases for all samples when reinforced with Luffa Fibers. The reason for this decrease is that the ability to isolate here depends on the ability of the fine fiber hairs to transfer thermal energy, as the elastic waves (phonons) travel through the base material and the hard part of the reinforcing fibers by the vibrational movement of the atoms, and when the phonons reach the capillary part of the reinforcing fibers, they suffer obstruction in their movement due to the difference in the structural construction of this medium because it has atoms and bonds that differ from the previous medium, which leads to a decrease in the values of thermal conductivity. This

outcome agrees with the researchers in the study [19], Where they found that the values of thermal conductivity showed a decline with the values of the bulk fraction of the support material, and the phonons are transmitted by the vibrational movement of the atoms, and for this there is an obstruction when the phonons reach the support material.

6. CONCLUSIONS

The most important conclusions reached in this research are:

- The mechanical properties (impact resistance and hardness) of the composite samples are improved as a result of the effect of adding Luffa Fibers to the polymeric binder.
- The compressive strength of the prepared samples increases with the increase in the reinforcement ratios. Where the increase in compressive strength was 100%.
- Any addition beyond 10% had no effect on compressive strength.
- The thermal insulation ability of the prepared composite materials and for all samples increases as a result of adding support materials to them.
- Depending on the above outcomes, the Luffa Fibers can be used in some mechanical applications that require high mechanical properties and good thermal insulation properties.

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