

## Improving the mechanical and thermal properties of unsaturated polyester resin by adding aluminum oxide $\text{Al}_2\text{O}_3$

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In this manuscript, a composite material was developed using unsaturated polyester resin as the base matrix and aluminum oxide as a reinforcing agent. The study focused on evaluating key mechanical properties, including hardness, compressive strength, and impact resistance. To investigate the effect of filler concentration, samples were prepared with varying  $\text{Al}_2\text{O}_3$  weight fractions ranging from 1% to 10%. The results indicated that the optimal improvement in mechanical performance occurred at an  $\text{Al}_2\text{O}_3$  content of 6%. The influence of processing temperature was examined by curing the composite samples at four different temperatures: 7°C, 25°C, 80°C, and 150°C. At 25°C, the composites demonstrated notable enhancements in impact resistance, compressive strength, and hardness, accompanied by a reduction in Young's modulus. At other processing temperatures (7°C, 80°C, and 150°C), the mechanical properties exhibited varying trends, with some increasing while others decreased. It was observed that thermal conductivity increases with increasing and decreasing temperature compared to room temperature. These findings suggest that both filler content and processing temperature significantly influence the mechanical and thermal behavior of  $\text{Al}_2\text{O}_3$  reinforced unsaturated polyester composites.

**Keywords:** Polyester, polymeric composites, aluminum oxide ( $\text{Al}_2\text{O}_3$ ), mechanical properties, compressive strength, Impact strength, hardness, Modulus of elasticity, Thermal conductivity.

**Покращення механічних та термічних властивостей ненасиченої поліефірної смоли шляхом додавання оксиду алюмінію  $\text{Al}_2\text{O}_3$ .** *Kawther Mahfoudh, Ebtehad Zeki Sulyman*

У цій роботі був розроблений композитний матеріал з використанням ненасиченої поліефірної смоли як базова матриця і оксид алюмінію як армуючий агент. Дослідження було зосереджено на оцінці ключових механічних властивостей, включаючи твердість, міцність на стиск та удароміцність. Для вивчення впливу концентрації наповнювача були приготовлені зразки з різною часткою  $\text{Al}_2\text{O}_3$  в діапазоні від 1% до 10%. Результати показали, що оптимальне поліпшення механічних характеристик відбувається при вмісті  $\text{Al}_2\text{O}_3$  6%. Крім того, було вивчено вплив температури обробки шляхом затвердіння композитних зразків при чотирьох різних температурах: 7°C, 25°C, 80°C та 150°C. При 25°C композити продемонстрували помітне поліпшення удароміцності, міцності на стиск та твердості, що супроводжується зниженням модуля Юнга. За інших температур обробки (7°C, 80°C та 150°C) механічні властивості демонстрували різні тенденції: деякі з них збільшувалися, а інші зменшувалися. Крім того, було відмічено, що теплопровідність збільшується з підвищенням та зниженням температури порівняно з кімнатною температурою. Ці результати свідчать, що як вміст наповнювача, так і температура обробки істотно впливають на механічні та термічні властивості композитів з ненасиченого поліестеру, армованого  $\text{Al}_2\text{O}_3$ .

## **1. Introduction**

The use of composite materials in their simple forms has been known since ancient times, with the Assyrians using them to build ziggurats, the Egyptians also used straw to make bricks to protect them from cracking during the drying process [1]. Composite materials consist of two or more different, heterogeneous materials. They exhibit superior properties compared to the properties of each of their constituent materials [2]. Composite materials can be prepared by combining the two materials together, provided that no chemical reaction occurs between them, so that each material retains its original properties [3]. Composite materials can be obtained using inexpensive materials as an alternative to more expensive ones [4]. The resulting composite exhibits superior properties and performance at a lower cost, characterized by a range of desirable properties, including lightweight, high strength, thermal and electrical insulation, mechanical and chemical resistance, design flexibility, and good resistance to environmental conditions, among other characteristics. More than two million tons of these materials are used annually in the manufacture of structural products such as tanks and aircraft [5]. Unsaturated polyester resin is a type of thermosetting resin; it is not used in its pure form in technical applications because it is brittle and not very effective. However, when reinforced with reinforcing materials such as glass fibers, glass waste powder, and carbon fibers, some of the mechanical properties of the brittle unsaturated polyester material change, which in turn affects the failure mode. Due to global changes, it has become difficult to imagine a world without polymers. They are widely used in industrial applications due to their desirable properties not found in other mineral materials. Polymers are characterized by their lightweight, ease of manufacture, resistance to corrosion and solutions such as acids and bases, and ease of use [8]. Therefore, the researchers studied some of the mechanical properties of a composite whose base material is polyester reinforced with glass powder at different weight ratios. They found that increasing the proportion of glass powder leads to increased hardness and compressive strength values and decreased impact values. When the temperature increases, all values decrease [9].

The researchers studied the effects of temperature and acidic and basic solutions on the elastic modulus values of hybrid composites

composed of phenol-formaldehyde resins of epoxy and Novolac types, reinforced with silica and alumina, and a small amount of asbestos fibers. The researchers also studied the effect of adding two types of fillers (wood shavings and chopped reeds) to unsaturated polyester using a hand-molding method to prepare composites. Composites of unsaturated polyester with wood shavings and another with chopped reeds were prepared, and their mechanical properties, including flexural strength and Young's modulus, were evaluated [11]. At room temperature (25°C), the samples were immersed in water for 30 days to ensure complete saturation. Mechanical tests such as measuring flexural strength and Young's modulus were then carried out. The results showed that the composite containing chopped reeds showed the highest values: flexural strength was 24.5 MPa and Young's modulus was 5.1 MPa [12],

The researchers also studied the mechanical properties of columns composed of recycled low-density polyethylene (LDPE) as the base material. Recycled LDPE was extracted from waste bags, wood sawdust was used as a filler, and the shape was formed using an injection molding method. The results showed that tensile strength decreased, while stiffness increased with increasing sawdust reinforcement. The researchers also studied the mechanical and physical properties of an epoxy composite as a base material with sulfur added at different weight percentages; they found that impact toughness, hardness, and compressive strength increased, while thermal conductivity decreased [14].

## **2. Experimental**

### **2.1. Basic Material**

Unsaturated polyester of Turkish origin from TURKUAZ POLY ESTER has a density of 1.17 g/cm<sup>3</sup> and a viscosity of 350-500 N·s/m<sup>2</sup> at room temperature. It is a type of thermosetting polymer. It hardens and turns into a solid material upon adding the hardener, which contains two types of hardening agents: the first is considered an initiator of the polymerization process, which is ethyl peroxide (a colorless liquid); the second substance is tin 2-ethyl hexanoate, which acts as an accelerator for the decomposition of the initiator [15]. It is characterized by its oily consistency and purple color. The hardener is added to the unsaturated polyester and mixed in a ratio of 2:1 of resin to hardener, when the hardener and catalyst are



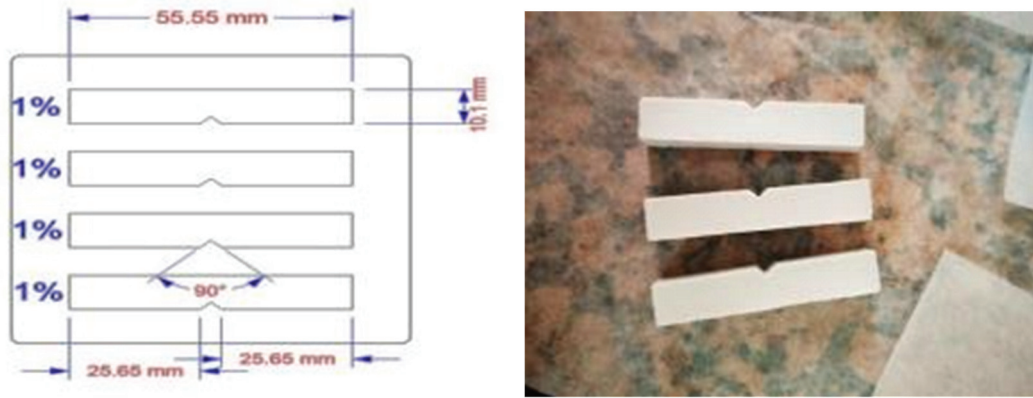


Fig. 2: Diagram and shape of the specimen for impact resistance testing

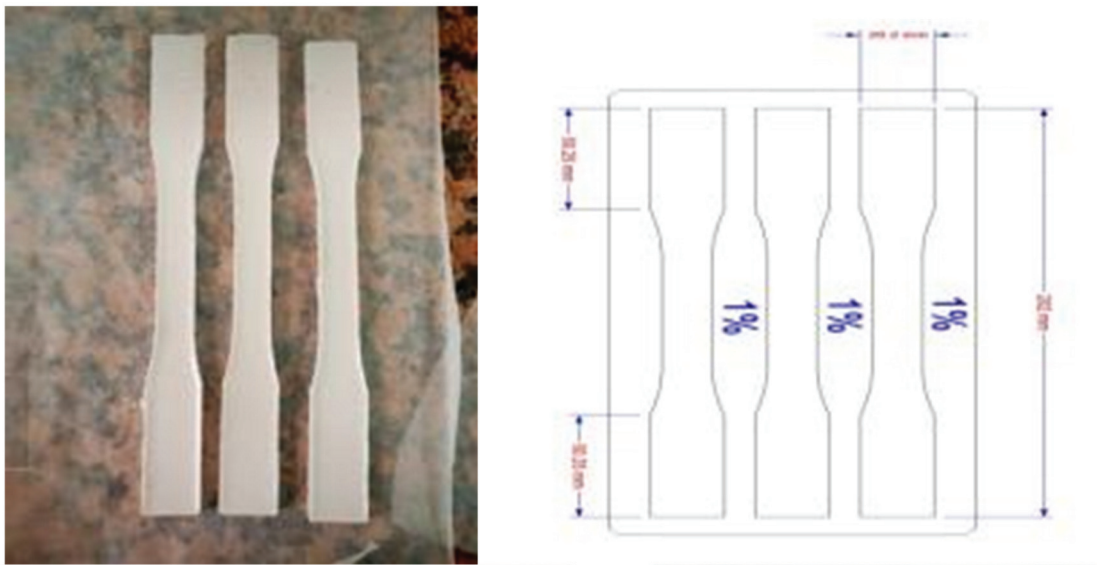


Fig. 3. Shape, scheme and design of the specimen for elastic modulus

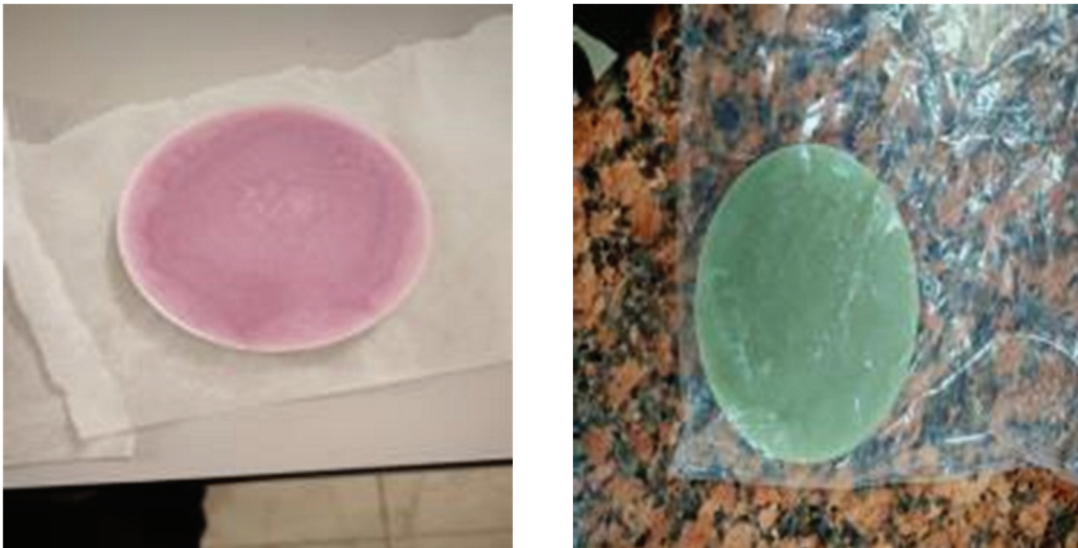


Fig. 4. Device and sample shape for measuring thermal conductivity

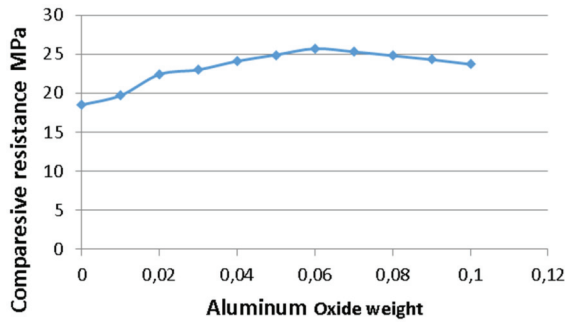


Fig.5. Compressive strength of unsaturated polyester before and after reinforcement at a temperature of (25) °C.

ducted to examine the properties of the composite material under the influence of axial loads in both directions. A universal testing machine, provided by ELE\_England, was utilized to measure this property, with a load capacity of 50 KN.

*Thermal conductivity:*

To measure thermal conductivity, a disk device with samples of 11.3 mm in diameter and 1.2 mm in thickness is used (Fig. 4).

### 3. Results and discussion

#### 3.1. Mechanical Properties

##### 3.1.1 Compressive Strength

Samples of pure unsaturated polyester reinforced with different proportions of aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) were prepared and their various mechanical properties were studied. Different percentages of aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) were added as a reinforcement material to unsaturated polyester, and its compressive strength was measured at 25°C. It was observed that the compressive strength of the unsaturated polyester varied with the increasing percentage of aluminum oxide, reaching its peak value at a concentration of 6% (Figure 5). The compressive strength of the material before and after the consolidation process is calculated using the equation [25]:

$$Compressive\ strength\ [MPa] = \frac{Force}{area} \quad (1)$$

Force is the the applied force [N],

area is the cross-section area of the sample, which is in the shape of a cylinder [m<sup>2</sup>]

The compressive strength values decrease as the temperature rises to 150°C. Conversely, these values increase when the samples are cooled to 7°C. This inverse relationship can be attributed to the effects of temperature on the properties of materials (Figure 6).

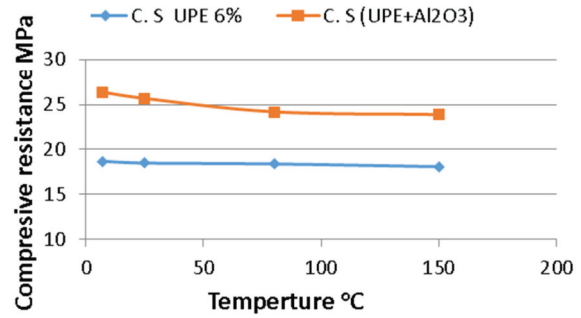


Fig.6. Comparison of compressive strength for pure and reinforced unsaturated polyester resin at temperatures of 7, 25, 80, 150 °C.

##### 3.1.2. Impact Resistance Test

Impact strength testing of polymers is a very complex test due to the multiplicity of impact strength tests; it is also a fundamental test in quality control laboratories and design laboratories for plastic items. The Izod test and the Garbi test are among the most important tests in this field. It is a process that measures the ability of a material to resist fracture when subjected to an applied force measured in kilojoules or joules. The strength of samples can be improved by using fillers which fill voids and prevent deformations in the sample [27]. Impact testing is very important from a practical perspective, as they allow the calculation of the absorbed energy required to fracture and crack the specimen used in the test. This value is extracted directly from the testing device and can also be calculated using the following relationship [28].

$$Impact\ strength\ (I.S) = \frac{Fracture\ energy}{Area\ (m)^2} \quad (2)$$

When unreinforced materials are subjected to sudden stress, they tend to fracture quickly due to the breakdown of bonds within the polymer chains (Figure 7). To enhance their durability, these materials are reinforced with additional components that are interwoven into the polymer chains, thereby increasing the energy required for fracture. Composite materials undergo two distinct stages: the first stage involves the breakdown of cohesion and strength of the bonds connecting the molecules within the polymer chains, while the second stage pertains to the pulling and breaking of the reinforcing materials within those chains. The energy required to break the reinforced material chains exceeds the energy needed to break the bonds in the polymer chains before the reinforcement process.

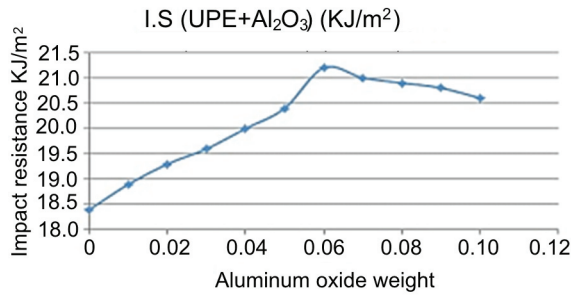


Fig. 7. Impact resistance of unsaturated polyester before and after reinforcement at a temperature of 25°C.

The concentration of 6% Al<sub>2</sub>O<sub>3</sub> in samples is the optimal percentage for heat treating compared to other concentrations for heat treating. At a temperature ranging from 7°C to 150°C, the impact resistance values decrease as the temperature decreases. This reduction is due to the restricted movement of the polymer chains, which hinders their ability to move freely. Conversely, the impact resistance increases with rising temperature particularly at 150°C. This increase is attributed to the disintegration of bonds between overlapping molecules, which enhances the movement of the polymer chains. As a result, the material can absorb some energy, facilitating the distribution and dissipation of the energy required for fracture. This is illustrated in Figure 8, which depicts mechanical dissolution.

### 3.1.3. Hardness Test

Materials can be scratched and penetrated during application of harder equipment; therefore, hardness is a crucial surface mechanical property. It is defined as the ability of a material's surface to resist permanent deformation resulting from processes such as cutting, abrasion, and scratching [29]. Hardness tests are employed to measure a resistance of the material to plastic deformation on its surface. Precise tips made of hard materials are utilized to penetrate the harder material. The hardness of a material is influenced by heat treatment and elevated temperature, as well as the strength of the bonds between atoms and molecules and the type of surface. Reinforcing of unsaturated polyester with aluminum oxide results in higher hardness values. This increase is attributed to the enhanced entanglement and cohesion between unsaturated polyester and aluminum oxide, along with the cross-linking that restricts the movement of unsaturated polyester molecules, thereby enhancing hardness and increasing resistance to deformation [32]. This effect can be observed in Figure 9.

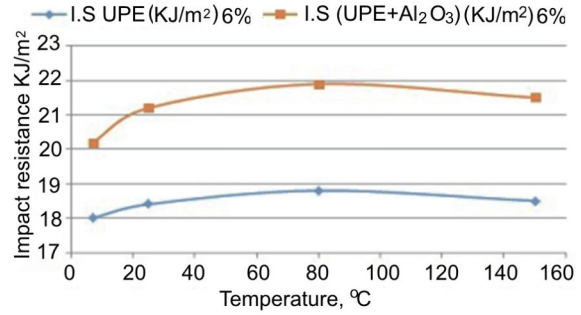


Fig. 8. Impact resistance of unsaturated polyester before and after reinforcement at T of 7, 80, and 150 °C.

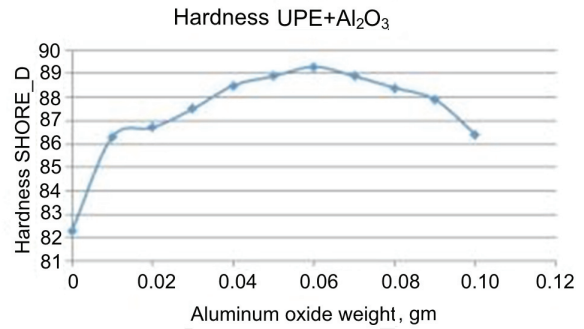


Fig.9. Hardness of unsaturated polyester depending on Al<sub>2</sub>O<sub>3</sub> content

When heat treatment was conducted at various temperatures (7, 80, and 150°C) for samples with a composition of 6% Al<sub>2</sub>O<sub>3</sub> (which was identified as the optimal percentage compared to the other samples), it was observed (Figure 10) that the hardness values at temperature ranging from 150°C to 80°C were lower than those at 25°C. This phenomenon can be attributed to the fact that an increase in temperature results in greater softness of the material due to the movement of molecules and the weakening of the bonds between them. Consequently, this reduces the material's resistance to scratching and puncturing, as evidenced by the examination of some of its mechanical properties. Conversely, when the temperature decreased to 7°C, an increase in hardness values was noted, attributed to the polymer becoming more constrained and losing its mobility. This restriction enhances the material's resistance to scratching and puncturing.

### 3.1.4. Elasticity test (Young's modulus)

The modulus of elongation, also known as Young's modulus, is a material property that expresses a material's resistance to deformation; it is defined as the ratio of stress to strain in a material when subjected to a load [34]. When a material is subjected to stretch-

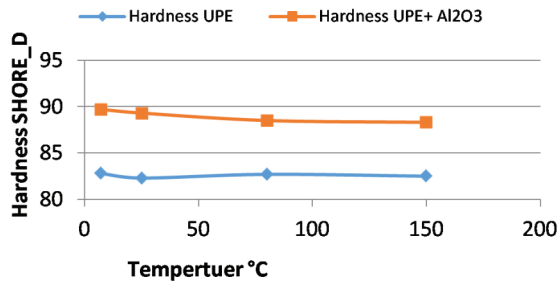


Fig.10. Hardness test of unsaturated polyester before and after reinforcement at 7, 25, 80 and 150 °C

ing, compression, or deformation, it exhibits a partial change in dimensions. The modulus of elasticity determines how a material responds to deformation. This is essential for engineers and materials scientists, as it helps in designing structures and materials capable of withstanding certain loads and stresses while maintaining their shape and function. In addition, Young’s modulus is a key factor in the development of advanced materials, such as composites and metals, which are designed with specific properties to suit specific applications. Resins are brittle materials, which gives them very low tensile strength. When reinforcing materials are added, tensile strength can be significantly improved, as the particles of reinforcing material help withstand the applied loads. Through experiments, the highest tensile strength was obtained at a weight percentage of 6% Al<sub>2</sub>O<sub>3</sub> and a temperature of 25°C, as shown in Figure 11.

When samples with a weight percentage of 6% Al<sub>2</sub>O<sub>3</sub> are heat treated at various temperatures (7, 80, and 150 °C), the elasticity values decrease at the higher temperature range (150-80 °C) due to the disintegration of the polymer chains. Conversely, at lower temperature, such as 7 °C, the elasticity values also decline, but this is attributed to the restriction of bonds and the limited movement of the polymer chains, resulting in increased brittleness of the material [35], as illustrated in Figure 12.

### 3.1.5. Thermal Conductivity

It is defined as the ability of a material to transfer heat between two conductors that differ in temperature, where one of them has a higher temperature than the other [36]. An increase in thermal conductivity is observed after reinforcing unsaturated polyester with aluminum oxide compared to the measurements taken before reinforcement. Polymers contain free electrons that facilitate heat transfer, and

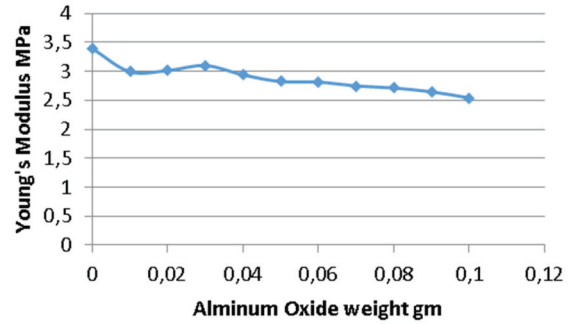


Fig. 11. Young’s Modulus of unsaturated polyester before and after reinforcement at a temperature of 25 °C.

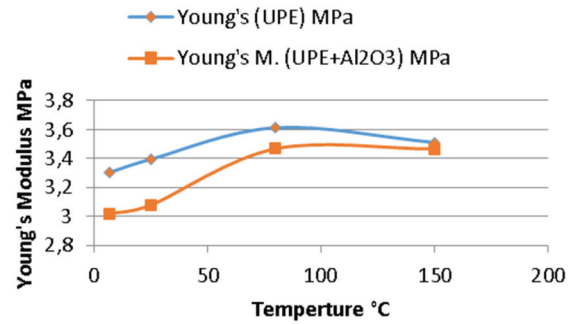


Fig. 12. Elastic modulus of unsaturated polyester before and after reinforcement at 7, 25, 80, 150 °C

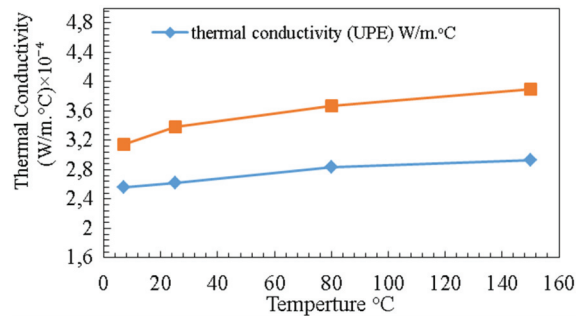


Fig.13. Thermal conductivity of unsaturated polyester before and after reinforcement at 7, 25, 80 and 150°C.

thermal conductivity is influenced by molecular vibrations and results in an increase in conductivity. To evaluate thermal conductivity, the Arrhenius equation (3) can be used, as shown in Figure 13.

$$k(T) = K^{\circ} \exp\left(-\frac{Ea}{KBT}\right) \quad (3)$$

### 3.1.6. Scanning Electron Microscope (SEM)

Figure 14 shows SEM images of both pure polyester and a polyester mixture with Al<sub>2</sub>O<sub>3</sub>. The aggregation of the polyester grains around Al<sub>2</sub>O<sub>3</sub> particles caused the average grain size to grow from 215.28 nm for pure polyester to

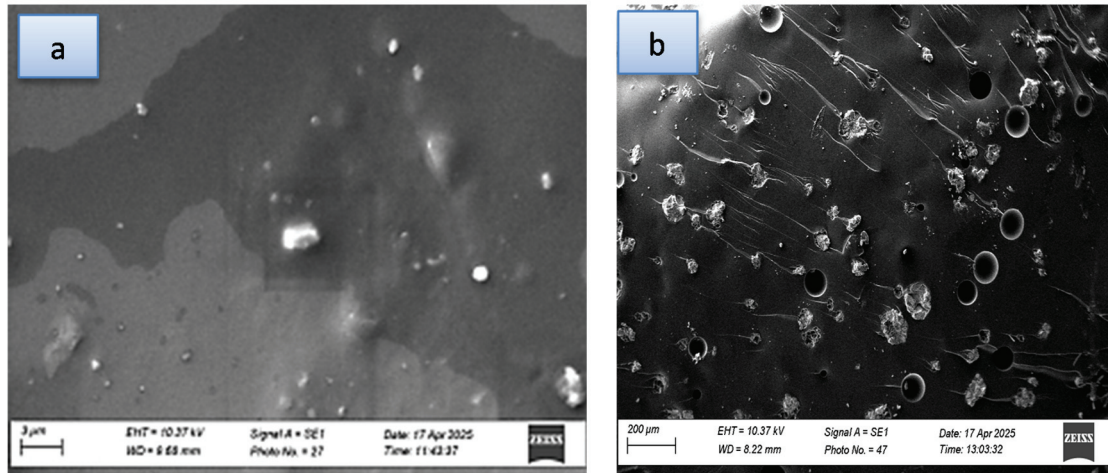


Fig.14. Scanning electron microscope images: a) pure polyester, b) polyester and  $\text{Al}_2\text{O}_3$  mixture.

516.81 nm for the mixture. The incredibly uniform dispersion of the  $\text{Al}_2\text{O}_3$  is also seen in the image of the sample surface. Additionally, it shows how the mixing process caused several cavities to develop on the sample surface.

### 3.1.7. Infrared spectroscopy (IR)

The hydroxyl and carbonyl groups, the bond stretching  $\text{C}=\text{C}$ , the bond stretching  $\text{CO}=\text{C}$ , and the stretching vibrations  $\text{OH}$  were among the most significant functional groups found in the UPE [38], according to the IR of the material prior to reinforcement. Following reinforcing with  $\text{Al}_2\text{O}_3$ , the IR of UPE did not significantly alter, confirming that this material's behavior is restricted to that of fillers. This is because the substance is chemically stable and inert; therefore, adding it to UPE might only slightly alter the beams' wave numbers.

## 4. Conclusion

The results obtained showed that adding  $\text{Al}_2\text{O}_3$  as a reinforcement material to unsaturated polyester and then heat treating it at 7-80-150 °C led to an increase in the indicators of mechanical properties such as hardness, compressive strength, and shock resistance, while the elastic modulus became lower. In addition, the properties (shock resistance, modulus of elasticity) were calculated when treated at temperatures of 80 °C and 150 °C. These values decreased as the samples cooled. The compressive strength and hardness decreased when treated at temperatures of 80 150 °C, while they increased as the samples cooled. It was found that the thermal conductivity of the unsaturated polyester increased with increasing temperatures, reaching 80-150 °C due to the

effect of reinforcing the unsaturated polyester with  $\text{Al}_2\text{O}_3$ . The final result showed that at a temperature of 80 °C, the material possessed the best physical (mechanical) properties.

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