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Effects of Silica Fume and Aluminum Alloy Mesh on Properties of Unsaturated Polyester/Polyurethane Blend

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Abstract

This work focuses on the preparation of a polymer matrix composite material, consisting of 90 vol% unsaturated polyester (UPs) and 10 vol% polyurethane (PU). The experiment was carried out in two stages. The first stage involved studying the effects of aluminium alloy (Al) mesh on the different ratios (5, 10, 15, and 20 vol%) of a polymer blend. The second stage entailed examining the additional effect of silica fume (SF) particles at different ratios (12 and 16 vol%). The results showed increases in (flexural strength, impact strength, hardness, and thermal conductivity), with higher metal mesh percentages, but when SF was added, thermal conductivity was lower compared to that of mesh, and hardness was higher than that of Al alloy mesh. The maximum values were as follows: B1 for flexural strength (180 MPa at 20 vol% Al alloy mesh, B1 for impact strength (9 kJ/m2) at 20 vol% Al alloy mesh, B3 for hardness (89 at 20 vol% Al alloy mesh and 16 vol%SF), and B1 for thermal conductivity (0.9 W/m x °C at 20 vol% Al alloy mesh).

Keywords: Aluminium Alloy Mesh, Polymer Blend, Polyurethane, Silica Fume, Unsaturated Polyester.

1. Introduction

Two unique components with different chemical and physical properties are mixed together to form a composite material. Together, they create a composite material that possesses superior qualities compared to its constituent parts. The component that is strengthened when the matrix surrounds it is known as the reinforcing phase [1]. The matrix is the continuous phase, whereas the reinforcing material or reinforcement is the discontinuous phase [2]. The flakes, particles, or fibers that make up the reinforcing phase's material. Usually, the matrix phase lasts continuously (the matrix completely surrounds the reinforcing elements and fills the spaces between them, creating a continuous medium) [3]. When a composite exhibits multiple discontinuous phases of distinct types, it is considered hybrid [4], [5]. By reinforcing at least two fiber layers in the polymeric matrix, composite materials made of polymers perform more efficiently. This process creates hybrid composites, an advanced material system with a variety of material properties. Only by understanding the connections between material architecture and mechanical qualities will the major challenge be overcome. None of the mechanical data point to a beneficial hybrid effect, with the exception of fracture energy [6]. A polymer blend is created by combining two or more different polymers to exploit the complementary properties of the constituent polymers and potentially achieve synergistic functionality [7]. Polymer blends are physical mixtures related to at least two polymers without/with chemical bonding between them [8].

One of the most significant classes of matrix polymers in composites that can crosslink is unsaturated polyester resins. Low densities, excellent weathering behavior, strong chemical resistance, and very low prices are the distinguishing features of unsaturated polyester (UPs) thermosets. Additionally, even after adding fibers and fillers, they are simple to produce and have extremely practical mechanical qualities [9].

UPs are utilized in many industrial applications, including shipbuilding, automotive, aerospace, and electronics, but UPs have low impact strength, weak resistance to fracture propagation, and limited elongation at break, making it inherently brittle [10]. Polyurethane (PU) is used to enhance the elasticity and resistance to brittle fracture of unsaturated polyester resin due to its exceptional elasticity and good impact strength [11]. An excellent combination of strength and flexibility can be found in aluminum wire mesh. It is resilient to a range of pressures without breaking, and it is sufficiently flexible to be bent or shaped as needed [12]. A byproduct of the manufacturing of silicon alloys such as ferromagnesium, ferrochromium, ferromanganese, and calcium silicon is silica fume (SF), sometimes referred to as micro-silica. In an electrical furnace used to produce silicon and ferrosilicon alloys, high-purity quartz is reduced with coal to produce SF as a byproduct. SF is inexpensive and has decent binder [13].

Moften et al. [14] have created composite materials by varying the ratios of iron (Fe) and aluminum (Al) wire mesh for reinforcement. A polymer blend including epoxy (EP) and polyester (UPs) was utilized as the matrix material. After combining different volumes of polyester and epoxy, the epoxy-to-polyester volume ratios were 95:5, 90:10, 85:15, 80:20, and 75:25. The blend was reinforced with metal mesh at volume fractions of 5, 10, 15, and 20%. The results indicate that the ideal ratios for ultimate tensile strength are 95% epoxy + 5% unsaturated polyester. Tensile strength and modulus of elasticity improve with increased volume percentage of metal mesh. 95% epoxy and 25% other materials made up the sample with the highest compressive strength (CS) rating. Farhan and Jaffer [15] made three polymer blends out of polyurethane (PU), unsaturated polyester (UPs), and epoxy (EP). Three groups were formed by selecting a concentration with different percentages of components: polyurethane/epoxy (PU/EP), epoxy/unsaturated polyester (EP/UPs), and blends of polyurethane and unsaturated polyester (PU/UPs). According to the experimental results, the thermal conductivity has the lowest value of (K) at ratios of (PU 40% / EP 60%), (EP 30% / UPs 70%), and (PU 60% / UPs 40%), respectively. These values are 0.53 J/m2×k and 0.31 J/m2×k. The current research aims to enhance the mechanical and physical properties of the UPs/PU blend by incorporating Al alloy mesh and silica fume.

2. Materials

2.1. Unsaturated polyester (UPs)

UPs, a polyester system in transparent liquid form that solidifies when 2% hardener is added, consists of two components: a base resin and a curing agent (hardener) (MEKP), supplied by the Saudi Industrial Resins (SIR) Company. Table 1 exhibits the mechanical properties of UPS according to the SIR company.

Table 1. Mechanical properties of unsaturated polyester.

Properties	Values
Density(g/cm^3)	1- 1.3 at [25ºC]
Percent Elongation %	< 2.6
Fracture Toughness (MPa-$m^{0.5}$)	0.6
Modulus of Elasticity (GPa)	2.06 – 4.41

2.2. Polyurethane Resin (PU)

A low-viscosity PU system in clear liquid form that solidifies with the addition of a hardener in a 1:2 ratio consists of two components: a base resin and a curing agent (hardener). The Polyurethane resin used for this experiment was provided by the UK-based Fosroc Company. Its density is between 1.1 and 1.3 g/cm^3.

2.3. Aluminum (Al) Alloy Mesh

Regarding the kind of metal to be utilized as reinforcement, Al alloy was the material of choice because of its affordability, great corrosion resistance, low density, high strength, and availability. The mesh fibers of Al alloy are shown in Fig. 1. The Al alloy mesh employed in this study had a fiber orientation of 0/90°. Aluminum wire mesh from Walcoom Company /China was chosen in this work.

Figure 1. Aluminum alloy mesh.

2.4. Silica Fume (SF)

This experiment utilizes Silica fume (SF) that was purchased from CONMIX company, United Arab Emirates. Table 2 displays the characteristics of SF.

Table 2. Typical characteristics of silica fume based on the information provided by CONMIX company.

Property State	Value
State	Amorphous sub-micron powder
Bulk density	500 to 700 kg/m^3 Minimum
Particle size	45 µm
Moisture content (H_2O)	Maximum 3%
Specific Gravity	2.10 - 2.40

3. Preparation of Composites

The hand lay-up method was used for preparing composite samples. All of the test samples' molds were made of silicone rubber. For each test, the molds' shapes and sizes were created in accordance with ASTM standard dimensions. In this experiment, the unsaturated polyester (UPs) resin (90 vol%) was combined with the polyurethane resin (10 vol%). First, the unsaturated polyester resin was mixed with the hardener (Methyl Ethyl Ketone Peroxide). Then, the polyurethane resin (PU) with its hardener (type is Nitofill UR63, Fosroc Company, United Kingdom) was mixed in the ratio (2:1) with the unsaturated polyester (10 min) to homogeneity and to remove any bubbles that may have formed during the mixing process by using the magnetic stirrer. The UPs/PU blend was reinforced by the

1. Volume percentages of Al mesh fibers were (5%, 10%, 15%, and 20%).
2. A polymer blend or Al alloy with the volume percentage of particles (silica fume) was calculated according to the required volume fraction (12 and 16%) in a polymer blend. Silica fume (SF) particles were slowly and continuously

mixed with the polymer blend for 5 minutes using a magnetic stirrer at room temperature to obtain a homogeneous mixture as well as to avoid bubbling during the mixing. Then, mesh wire was put in the mold, the mixture was poured, and it was left to solidify at room temperature for 24 hours. Table 3 shows the percentages of each sample.

Table 3. Prepared materials' symbols.

Symbols	Percentage of Each Material in the P. B
X	Unsaturated polyester 90% + Polyurethane 10%
B1	X+ Al alloy mesh
B2	X+ Al alloy mesh +12% SF
B3	X+ Al alloy mesh +16% SF

4. Mechanical tests

4.1. Bending test

The sample dimensions—thickness (5 mm), length (100 mm), and width (10 mm)—were used for the bending test in accordance with the ASTM-D 790 standard [16]. As indicated in Fig.2, the test was conducted using the English-made universal mechanical testing machine (Model RH1 5DZ, Tiniusoisen Ltd.). This test's primary goal is to use (1) to determine the maximum flexural strength.

$$\mathbf{FS = 3PL/2bh} \quad (1)$$

Where:

FS: Flexural Strength (MPa)

P: Bending Load (N). L: Sample length (m).

b: Width of sample (m). h: Thickness of sample (m).

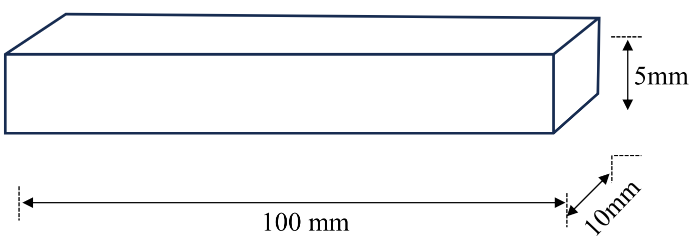

Figure 2. Bending test specimen

4.2. Impact test

Fig. 3 shows the sample's standard dimensions in accordance with ISO-179 [17]. The impact test was performed. This test quantifies the strength of the material and the percentage of its resistance to deformation, which may be computed using (2), representing the energy absorbed when an item with a specific mass collides with the sample's cross section at the fraction.

$$\mathbf{I.S = U/A} \quad (2)$$

Where:

I.S: Represents the impact strength (KJ/m²)

U: Represents fracture energy (J)

A: Cross-sectional area (m²)

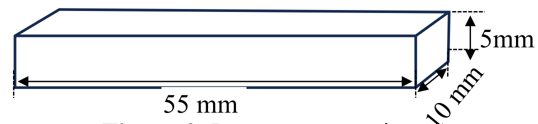

Figure 3. Impact test specimen.

4.3. Hardness Test

As indicated in Fig. 4, a Digital Micro Shore Durometer (QUALITEST HPE) that complies with ASTM D2240 was used to perform the hardness test [18]. Shore D was used for the purpose of testing sample hardness with a smooth and plain surface. To find the average value, seven hardness measurements were taken on the specimens at various locations.

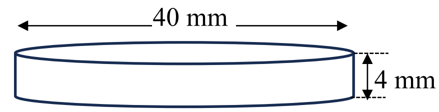

Figure 4. Hardness test specimen.

4.4. Thermal Conductivity Test

The conductivity of the samples subjected to heat testing was calculated using Lee's disc apparatus. This instrument has three brass discs (A, B, and C) and a heater. From the heater, heat is transferred through the sample to the next two disks (TA and TB) and finally to the third disk (TC). The discs' temperatures can be determined with thermometers. Those discs should have perfectly clean surfaces that make good contact in order to transmit heat as efficiently as possible. After the discs reached thermal equilibrium, which occurred around 45 min later, the temperatures were recorded. The electric circuit's current value was found to be approximately 0.25 A once the heater's supply power (6 V) was applied. The following formula is used for the calculation:

$$IV = \pi r^{(2)}\left(T_{(A+)}T_B\right) + 2\pi re\left[\left(d_{(A)}T_A\right) + d_s 1/2\left(T_A + T_B\right) + \left(d_B T_B\right) + \left(d_C T_C\right)\right] \quad (3)$$

Where:

I: electric circuit current value (A)

V: Voltage supplied (in volts)

r : disc radius (m)

e:heat loss(W/m x °C)

d1,d2,d3 : thickness of disc(m)

T1,T2,T3 :Temprature in the disc(ºC)

The value of (e), which represents the amount of heat passing through a sample's cross section in a unit of time (W/m x °C), has been calculated using (3). One can calculate the K-values using (4) [19].

$$K[(T_B T_A)/d_S] = e\left[T_A + 2/r\left(d_A + \left(1/(4d_s)\right)T_A + 1/2rd_sT\right)\right] \quad (4)$$

where K is the coefficient of heat conductivity (W/m x °C).

5. Results and Discussion

5.1. Bending Strength

Before reinforcement, the polymer is brittle; therefore, its flexural strength is low (metal mesh /particles). When metal wire mesh is added, flexural strength increases with a higher volume fraction. Adding metal mesh to the polymer matrix (polymer blend) improves the values of its shear stress. The reason for this is that when stress is applied to the metal mesh composite material, it is distributed to both the base material and the metal mesh that bear the bulk of it; in addition, the metal mesh is characterized by a high modulus of elasticity [20]. The maximum values of flexural strength were found to be B1 (180 MPa at 20 vol% Al alloy mesh) for the hybrid material, and B3 (163Mpa at 20vol% Al alloy mesh and 16 vol% SF), as shown in Fig 5. The higher elastic modulus of the SF in comparison to the matrix material could potentially account for the increase in bending strength. The bonding force (interaction) between the filler material and the matrix determines the bending strength in the major part [21]. Stress is more evenly distributed over the length of the fibers in fiber-reinforced composites. While this uniformity increases bending strength and resistance to deformation, the presence of metal mesh or particles can provide an uneven distribution of stress. Particles may cause microstructural weaknesses or distort fiber alignment, which can lead to weak spots when loads are bent [22].

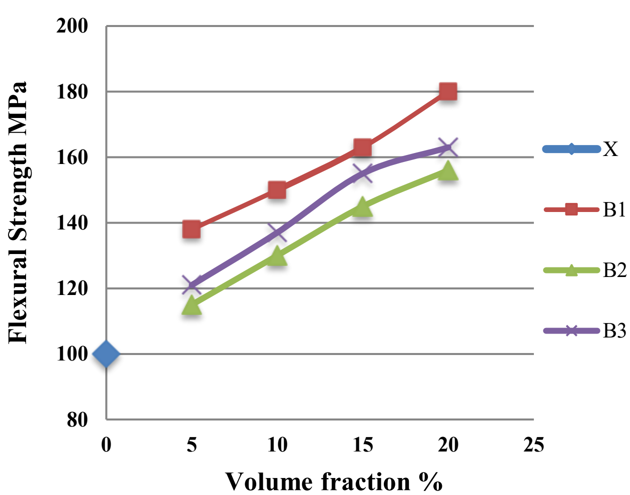

Figure 5. Flexural strength of composites.

5.2. Impact Strength

The results of the impact strength test on the polymer blend resin with metal mesh and filler particles (hybrid composites) are exhibited in Fig. 6. Generally, the impact strength is considered low due to (UPs/PU) this material's brittleness. When the material is reinforced with Al metal mesh and particles, impact strength increases because the metal mesh and the particles carry the upper part of the impact energy, which is transferred to the composite material. When the composite material is subjected to impact stress perpendicular to the reinforcing metal mesh, the crack extends through the resin to the Al metal mesh [23]. The increase in impact strength can be observed from the results. The maximum values of impact strength were found to be B1 9 kJ/m² at (20vol% Al alloy mesh) for the hybrid material is B3 (8 kJ/m²). The higher SF concentration increases the matrix's ability to absorb energy and, in this way, reinforces its toughness, so that the impact strength is increased, but the values of the impact strength (SF/Al wire mesh) are lower than those of the impact strength of Al wire mesh. Because aluminum wire mesh provides a continuous path for crack deflection, enhancing toughness, SF particles may disrupt the metal mesh-matrix interface, leading to poor adhesion between the metal mesh and the matrix [10].

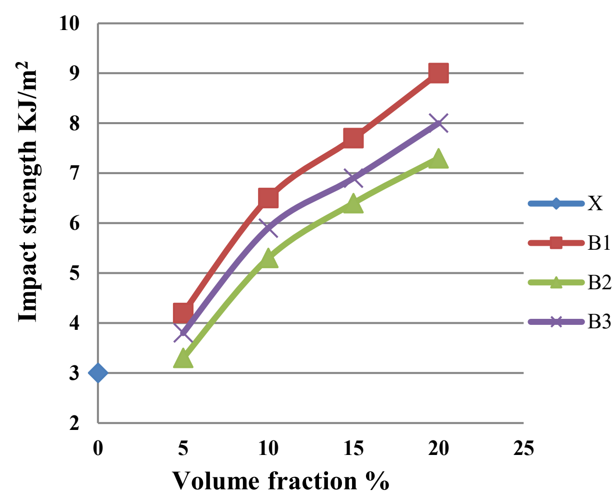

Figure 6. Impact strength of the specimen.

5.3. Hardness

Plastic materials typically have a low hardness value. Fig. 7. shows the lowest value for the polymer blend prior to reinforcement. However, when the matrix is supplemented with a hybrid filler that combines metal mesh and particles, this hardness value significantly rises. This increase could be linked to reduced defects and voids, as well as good adhesion (interface) between the metal mesh-particle filler and the matrix. The higher hardness values are also due to the retardation of the end chains' movement and the increase in the cross-linking force [24]. The maximum values of hardness (Shore D) were found to be B1 (83 at 20vol% Al alloy mesh) for hybrid materials and B3 (89 at 20vol% Al alloy mesh and 16 vol% SF).

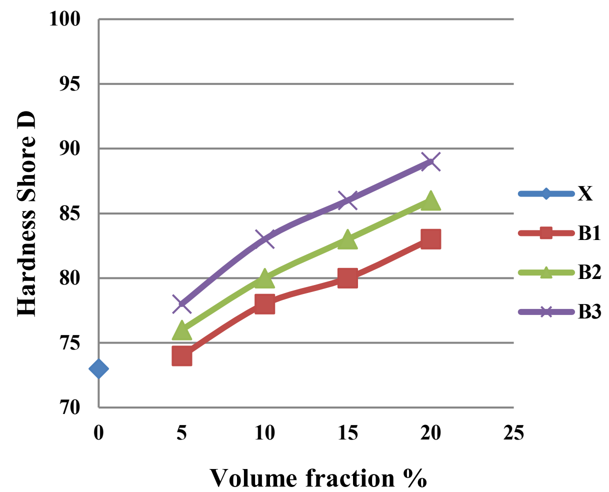

Figure 7. Shore hardness of specimen.

5.4. Thermal Conductivity

It is evident that when the volume percentage of the metal wire mesh grows, thermal conductivity rises as well due to the higher values of metals' thermal properties compared to those of polymers. The values are slightly lower when filler particles with Al alloy mesh are added to the polymer blend matrix but still higher than the values of thermal conductivity for the polymer blend in hybrid composites as shown in Fig 8. The chain of conductivity is created when the average interparticle distance is shorter than that in other parts, leading to an increase in thermal conductivity (K) along these chains [25]. The maximum values of thermal conductivity were found to be B1 (0.9 W/m x °C at 20vol% Al alloy mesh) for hybrid materials and B2 (0.82 W/m x °C at 20vol% Al alloy mesh and 16 vol% SF).

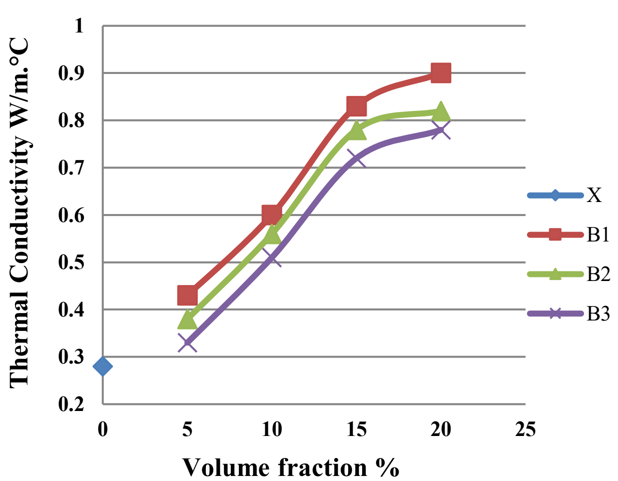

Figure 8. Thermal conductivity of specimen.

6. Conclusions

This study's principal objective was to examine the effect of Al alloy mesh and SF on polymer blends. The data analysis indicates that the addition of SF and Al alloy mesh to UPs/PU blend improves its impact strength, flexural strength, and hardness value. The impact strength is low, but is enhanced with reinforcements. The hardness value also increases significantly. Thermal conductivity increases with the higher volume fraction of Al alloy mesh but decreases with SF addition.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Akram Q. Moften, Zainab Y. Hussien, Marwa A. Anber, and Mohammed Ali Abdulrehman.

Akram Q. Moften wrote the first draft of the manuscript, and all authors provided comments on the previous versions. The final manuscript was read and approved by all authors.

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