Prediction of Mechanical, Thermal and Electrical Properties of Wool/Glass Fiber based Hybrid Composites

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ABSTRACT

The mechanical, thermal and electrical properties of wool and glass fiber-reinforced epoxy-based hybrid composites were investigated experimentally. Three different types of the composite material were manufactured. The first type was plain woven glass fiber reinforced epoxy with 50% volume fraction. The second type consisted of natural fiber (Wool) reinforced epoxy with 50% volume fraction. The third type was hybrid natural wool and plain woven glass fiber reinforced epoxy with 50% volume fraction (25% fiber + 25% wool).

The results showed that the hybrid composite specimens have higher values of the tensile strength, modulus of elasticity and flexural strength compared with the wool specimens, while these values are less than that for glass fiber specimens. The values of the thermal conductivity and electrical conductivity are arranged in an ascending order as follows: wool/epoxy, wool-glass/epoxy, and glass/epoxy composites.

KEYWORD: hybrid fiber; tensile test; electrical conductivity

1 INTRODUCTION

Natural materials can be considered as environmentally friendly as they are characterized by their renewable, biodegradable characteristics and low energy combustion. Wool, flax, kenaf, hemp, jute, banana, and sisal fibers are examples of the natural materials which are used in industries as alternative materials regarding to the manufacturing of composite. In addition, these materials are characterized by having a marketing appeal.

Recently, manufacturers in many fields of various industries are interested in using natural fibers and investigating new composites in order to substitute the fibers such as glass fiber-based polymers or composites.
Applications of natural fibers can be found in a variety of industries such as the industry of civil construction, automotive, and aerospace industries, etc. However, some drawbacks are available in natural fibers such as low mechanical properties compared with carbon or glass fiber-based composites. In addition, the absorption of water of natural fibers is extremely high compared with the synthetic fibers. Therefore, for the purpose of improving the properties of such materials and getting rid of the drawbacks mentioned above, hybrid bio composites made from two or more fibers having various physical or chemical properties in one matrix can be introduced.

In the industry, the usage of fiber composites which are based on glass fibers are common in the industry when good performances and low cost are needed. One of particular interest among the diverse applications, is that they can be used in pipe systems of chemical plants. Using composite pipes rather than metal pipes has many advantages including lower weight, increasing resistance to aggressive fluid, and easiness to build complicated shapes [1; 2].

The usefulness of the easy building of complicated shapes, at low numbers of production, is because of the potential to build on-demand utilizing cheap techniques like hand lay-up. Presently, glass fibers only can be utilized as reinforcement for such applications. Using the natural fibers to reinforce the composite for a wide domain of industries is attracting interest. As an example of using the natural fiber mats is that the interior and exterior components in the automotive sector [2; 3].

Among all natural fibers for composite materials, the best fibers which are extracted from the plants stems such as kenaf, jute, flax, hemp and ramie are widely accepted due to their extremely good mechanical properties. Hemp showed to have highly promising tensile properties where mechanical properties are substantial for applications [4; 5; 6].

The experimental study of Jayamani et al., 2014 [7] investigating the properties of dielectric such as dielectric loss factor, dissipation factor and dielectric constant of jute/bamboo fibers which are reinforced with unsaturated polyester and polypropylene hybrid composites was examined. In this study, various fiber loadings, chemical modifications, frequencies, and fiber ratios of natural fibers were considered.

Using a method of hand lay-up, an attempt was made by Teja et al., 2016 [8] to manufacture composites of sisal fiber polyester composite. They investigated SiC effect on mechanical and thermal properties of sisal fiber reinforced polymer. These authors showed that the composites with percentage of 10% SiC has a tensile strength greater than that for the composites without SiC by 2.53 times. The composite made of 10% SiC has an impact strength greater by 1.73 times than that of composites without SiC polyester as the same authors presented.

Chandramohan et al., 2017 [9] studied the mechanical properties (tensile strength, flexural strength, shear strength, and impact strength) for natural hybrid composites, once with moisture and once without moisture conditions. Samples were made from (coconut shell powder, walnut shells and rice husk) reinforced bio epoxy resin. The results of the properties of the hybrid composite are far better than that of single fiberglass reinforced composite subjected to mechanical loads as these authors concluded.
Fadhel et al., 2018 [10] examined mechanical and fatigue properties of natural fibers reinforced polymers (palm leaf, eggshell, and date seeds) with polyester. They also discussed the effect of ultraviolet rays. They found that increasing the volume fraction causes an increase in endurance stress for the natural composite materials. The authors concluded that palm leaf samples have better mechanical properties than eggshell samples and date seeds samples. They also observed that the tensile stress decreases with increasing the time of the UV exposure.

Nimanpure et al., 2019 [11] investigated mechanical, thermal, and electrical characteristics of the hybrid composites consisting of sisal fibril/kenaf fiber. They showed that the hybridization of kenaf fibers with sisal fibrils increases the mechanical strength of the hybrid polyester composite manufactured. They presented that the hybrid composite causes an increasing in the tensile strength by 24 and 18%, an increasing in the flexural strength by 30 and 36.4%, and an increasing in the impact strength by 196.3 and 196% compared with the composites which have the same loading of 40 weight% with the sisal fibrils and the kenaf fibers, respectively. They also showed that the hybrid composite has a high capability of electrical insulation. These authors found that the hybrid composites have a thermal stability, higher than that of kenaf fibers and sisal fibrils reinforced composites.

The current work aims at studying the hybridization of glass fiber with natural fiber (wool) to reinforce the matrix and investigate its mechanical, thermal and electrical properties.

2 MATERIALS

Figure 1 (a) and (b) shows the glass fiber and wool (natural fiber) respectively, which are used in the current work for experimental examinations. The range of wool fiber length is usually between 2 and 35 centimeters depending on the sheep breed.

In order to increase the quality of the composite materials reinforced by a natural fiber, chemical treatment operation was performed upon wool fiber as follows. Wool was washed repeatedly into clean running water. Having dried it, the wool was submerged for three hours in a solution consisting of 1% sodium hydroxide and 99% distilled water in order to be softened [11]. After that, the fibers were taken out and then washed in running water for two hours. The woven fiberglass of 200 gm/m weight (type E) used in this research was supplied by AMP Company. The epoxy resin used was EPL type.

Figure 1. The fiber used in this study (a) Glass fiber (b) Wool natural fiber.

3 EXPERIMENTAL WORK

This section explains experiments conducted to determine the tensile strength, Young’s modulus, flexural strength, flexural modulus, thermal conductivity, and electrical conductivity of the composites using the materials characterized in Section 2. This will involve the procedure details used to fabricate the specimens. It also characterizes the equipment used for tensile and
flexure testing. Details are given regarding the experiments, including tensile, flexural, electrical analysis, and thermal conductivity tests.

3.1 SAMPLES FABRICATING

Applying the hand lay-up technique, the laminated composite were fabricated in the polymer laboratory/College of Engineering/Mustansiriyah University using a metal mold made of aluminum (bare hand pressure is adequate for molding, and its internal surface can be dyed with releasing agent) with dimensions of (300×300×30) mm³.

The arrangement process of the fibers and placed inside the mold requires an accuracy and carefulness because of the interference between each fiber.

Before the manufacturing process begins, the mold sides and surface should be dyed with chemically treated paraffin for the purpose of closing the spaces and to take the sample easily from the mold. An isolated material (Tree-lack) which is a quick dry soap liquid is used for the purpose of isolating the mold from the sample.

Having prepared the mold, the mixture of the prescribed mass of the epoxy resin and the (Methyl Ethyl Ketone Peroxide, MEKP) as a hardener with 2% percentage is poured into the mold over the fibers [12]. Then the mold was pressed by a plate prepared previously in order to obtain a uniform thickness. The mold was left for 24 hours and the composite sheets were obtained. All composites were cured at ambient conditions for 5 days.

Three types of laminated composite materials were manufactured. The first laminate was fabricated from glass fiber mat. The second laminate was a net natural fiber (wool) used to reinforce the epoxy resin. The third laminate was fabricated from hybrid fiber consisting of natural fiber (wool) with woven fiberglass.

The volume fraction for all the types are of 50% ($V_f=50\%$). The densities of the E-glass fiber, wool fiber, and epoxy resin are (2.54 g/cm³, 1.314 g/cm³, and 1.1 g/cm³) [13]. The relationships used for the appropriate conversion are explained in equations 1 and 2 [14].

$$V_1 = \frac{W_1}{\frac{\rho_1}{V_1} + \frac{W_2}{\rho_2} + \frac{W_3}{\rho_3}} \quad \cdots \quad (1)$$

$$W_1 = \frac{\rho_1 V_1}{\rho_1 V_1 + \rho_2 V_2 + \rho_3 V_3} \quad \cdots \quad (2)$$

where $V_1$, $V_2$, and $V_3$ etc. are the volume fractions of the constituents, $W_1$, $W_2$, and $W_3$ etc. are the weight fractions of the constituents, $\rho_1$, $\rho_2$, and $\rho_3$ etc. are the densities of the constituents.

To produce the samples (Figure 2) for tensile test according to the ASTM D638 [15] and the samples (Figure 3) for flexural test according to ASTM D790 [16], the CNC machine was used. Table 1 lists the laminated composite specimens’ specification.
Figure 2. Sample dimension according to ASTM D 638 [15].

Figure 3. Sample dimension according to ASTM D 790 [16].

| Composite material symbol | Fiber type          | Matrix | Volume fraction (%) |
|---------------------------|---------------------|--------|---------------------|
| S1                        | Glass fiber         | Epoxy  | 50                  |
| S2                        | Wool fiber          | Epoxy  | 50                  |
| S3                        | Hybrid fiber (glass + wool) | Epoxy | 25+25               |

### 3.2 TENSILE TEST SPECIMENS AND APPARATUS

Figure 4 (a), (b), and (c) shows the photograph of the tensile test specimens for S1, S2, and S3 samples respectively. The apparatus used in this work is Universal Testing Machine, 5569A, Instron (Figure 5 (a)). The speed was set to 2 mm/min [17; 18].

Figure 5 (b) provides the photograph of the tensile test specimen during the test. The experiments were conducted at room temperature. More than five identical specimens were examined for each test, and the average results were taken into account.
3.3 FLEXURAL TEST

The Universal Testing Machine, 5569A, Instron (three-point bending apparatus) was used for flexure testing as shown in Figure 6 showing the sample during the test. The length of the span of the specimen was 50 mm and the speed was set to 2 mm/min [19; 20]. Many identical specimens, for each test were tested and the average results were accounted. All the tests were performed at room temperature. The flexure stress $\sigma_f$ and the flexural modulus of elasticity $E_f$ were calculated using Equations 3 and 4 [21].

$$\sigma_f = \frac{3PL}{2bd^2}$$  \hspace{1cm} \text{Equation (3)}

$$E_f = \frac{l^3m}{4bd^3}$$  \hspace{1cm} \text{Equation (4)}

where $P$ is the load applied at the fracture moment (N), $L$ is the span length (m), $b$ is the beam width (m), $d$ is the beam depth (m), and $m$ is the slope of the initial straight-line portion of the load deflection curve (N m$^{-1}$ of deflection).
3.4 ELECTRICAL ANALYSIS TEST

The electrical conductivity (σ) which is defined as the proportional permittivity of a particular material with vacuum permittivity is considered a significant electrical property of material. An HP Impedance analyzer E4980A was used in order to measure the dielectric properties of the composite specimens. Using the 16451B dielectric test fixture and the agilest E4980A precision LCR meter, the measurement program of dielectric constant assists to carry out the measurements. The measurement capability of LCR meter is up to 2MHz frequency. The diameter of the disc shaped samples is 50 mm and the thickness is about 3mm.

The contacting electrode method using a rigid metal electrode was performed to analyze the specimens shown in Figure 7. According to the ASTM D-150-10 standard [22], the values of the frequencies used during the measurements are generally in the 1kHz - 1MHz range.

Before the test begins, a vacuum-chamber was used to dry all the specimens at 70°C for 24 hours. The HP impedance analyzer was used for recording the average value of all the specimens tested 8 times at a given frequency.

3.5 THERMAL CONDUCTIVITY TEST

The Lee Disk device [23] shown in Figure 8 was used in this study to measure the thermal conductivity of the specimens. Lee disk is a glass flask including two disks. The first disk which is the source of heat was connected to the electricity source, while the second disk, which is a complicated heat transmitted from the first disk passing through the sample that is placed between both disks.
The sample being examined was placed in the space between both disks and discs were connected to devices (digital thermometer) in order to measure the temperature generated and transmitted, and calculating the thermal conductivity and then the data was recorded. The first reading was recorded by giving the first disk initial voltages. After that the voltages were gradually increased in order to record more than one reading.

Equations 5 and 6 [24] were used to calculate the transfer energy and thermal conductivity through the temperature differences between the heat generated and the heat transferred.

\[
h = \frac{H_t}{\pi r \left[ (T_c - T_m)r + 2 \left[ dm \cdot T_m + \frac{1}{2} ds(T_m + T_u) + du \cdot T_u + dc \cdot T_c \right] \right]} \quad \ldots (5)
\]

\[
K = \frac{T_u - T_m}{ds} = h \left[ T_m + \frac{2}{r} \left( dm + \frac{1}{4} \cdot ds \right) T_m + \frac{1}{2 \cdot r} \cdot ds \cdot T_u \right] \quad \ldots (6)
\]

The temperatures \((T_m, T_u, \text{and } T_c)\) were obtained to calculate \((K)\) the thermal conductivity \((\text{W/m}^*\text{K})\) given by Equation 6 using the Lee disk testing device, where \(T_m\) is the temperature of the disk M, \(T_u\) is the disk U temperature, \(T_c\) is the disc C temperature, \(ds\) is the disc S (sample) thickness, \(dm\) is the disc M thickness, \(r\) is the disc radius and \(h\) is the lose temperature \((\text{sec/cm}^2)\), and \(H_t\) is the power in Watt.

\section{RESULT AND DISCUSSION}

\subsection{RESULT OF TENSILE TEST}

Figure 9 representing the ultimate strength for all the composite groups shows that the highest value \((\approx 408\text{MPa})\) is for the fiberglass laminate, while the lowest values \((\approx 103\text{MPa})\) is for the wool laminate; the strength value for the hybrid laminate is \((\approx 227\text{MPa})\), which is in between the strength value of the fiberglass and the wool laminates.

These significant differences are due to the higher value of the tensile strength of the glass fiber than that of the wool fiber [25].

The values of the Young’s modulus are \((2.85\text{GPa})\), \((1.21\text{GPa})\), and \((1.89\text{GPa})\) for fiberglass laminate, wool laminate, and hybrid laminate, respectively, as shown in Figure 10. These values
show a similar trend as for the ultimate strength, which agrees with the results concluded by Portell et al., 2016 [26].

![Comparison of tensile strength of laminated composites reinforced by glass fiber, wool fiber, and hybrid fiber.](image)

**Figure 9.** Comparison of tensile strength of laminated composites reinforced by glass fiber, wool fiber, and hybrid fiber.

![Young’s modulus of S1, S2, and S3.](image)

**Figure 10.** Young’s modulus of S1, S2, and S3.

### 4.2 RESULT OF FLEXURAL TEST

The results of the flexural strength and modulus strength obtained from the three-point bending test are presented in Figure 11 and Figure 12. It is noteworthy that this test includes components of compressive, tensile, and shear and these components benefit from the existence of glass fibers.

The values of the flexural strength (≈142 MPa) and flexural modulus (10.35GPa) of the laminate including only glass fiber were much higher than that for the wool/epoxy specimens which were (≈42 MPa) and (2.36 GPa) respectively; this behavior is expected. Ahmed et al., 2008 [27] investigated laminates made from jute/glass and concluded that the arrangement of the glass fibers at the ends increases flexural strength, while the flexural strength decreases in the laminate including intercalated glass and jute layers. This is because the outer layers of the composite control the flexural strength and stiffness.
The values of both the flexural strength (≈80 MPa) and modulus strength (4.135 GPa) for the hybrid composite are in between that values for the glass and the wool composites which agrees with the results obtained by Ahmed et al., 2008 [27]

![Figure 11. Flexural strength of S1, S2, and S3.](image1)

![Figure 12. Flexural modulus of S1, S2 and S3.](image2)

### 4.3 RESULT OF ELECTRICAL TEST

Several samples fabricated from composite material were tested to investigate the electrical properties. The measurement of electrical conductivity (σ) which was performed as described previously in Section 3.4 is presented in Figure 13. It can be seen that the glass fiber samples have the highest electrical conductivity compared with the other types, while the lowest one is for the wool/epoxy.
Figure 13. Electrical conductivity of S1, S2, and S3.

4.4 RESULT OF THERMAL TEST

Using a guarded heat flow meter (Lee Disk), the thermal conductivity was measured experimentally along the longitudinal direction as explained in Section 3.5. The values of longitudinal thermal conductivities of the three laminated composite material (S1, S2, and S3) was estimated as a function of difference temperature for the disk \((T_u - T_m)\) as shown in the Figure 14. This figure shows that the thermal conductivity of (wool/epoxy) has the lowest values compared with the other two types, while the highest values were for the glass fiber. It can be also seen that the longitudinal thermal conductivities for all the composites types' increases with increasing of the temperature, this is because of that the moisture in the fibers begins to evaporate when the temperature increases. A similar trend of results was observed by Kalaprasad et al., 2000 [28].

Figure 14. Thermal conductivity of S1, S2, and S3.
5 CONCLUSION

1- The values of the tensile strengths are arranged in an ascending order as follows: wool/epoxy, wool-glass/epoxy, and glass/epoxy composite.

2- The flexural strength and the flexural modulus values of glass fiber/epoxy are higher than that of wool-glass/epoxy and wool/epoxy composite.

3- The value of the thermal conductivity for the wool/epoxy composite is lower than that for wool-glass/epoxy and glass/epoxy composite, while the glass/epoxy composite shows the highest thermal conductivity values.

4- The glass fiber samples have the highest value of the electrical conductivity compared with wool-glass/epoxy composite and wool/epoxy composite. The lowest value of the electrical conductivity is for the wool/epoxy composite.

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