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A Study on Thermal Diffusivity and Dielectric Properties of Epoxy Matrix Reinforced by Fibers Material

دراسة الأنتشار الحراري وخواص العزل الكهربائي لنسيج الايبوكسي المدعم بالألياف

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Abstract

The study of thermal diffusivity, dielectric properties and fabrication of fabric composite materials such as carbon fiber-epoxy, glass fiber-epoxy and hybrid fiber-epoxy composite materials are identified and reported in this paper. Hand layup method was used for the samples preparation. Thermal diffusivity of these samples was measured using photoflash method. The thermal diffusivity values of these materials were compared with the thermal diffusivity of several materials including ceramics ($SrTiO_3$). The results show that carbon and glass fibers have lowest thermal diffusivity values compared with other materials. Dielectric constant, dielectric loss and conductivity were measured at room temperature using impedance analyzer technique. It was found that although hybrid material has the same behavior of glass fiber but the value of the dielectric constant was significantly increased.

Keywords: carbon fiber (CF), hybrid fiber (HF), thermal diffusivity, dielectric, photoflash

الخلاصة:

في هذا البحث تم دراسة الانتشار الحراري و خصائص العزل الكهربائي لمواد نسيجية محضرة تحتوي على مادة راتنج الايبوكسي مثل نسيج ألياف الكاربون- الايبوكسي، الياف الزجاج- الايبوكسي والمواد المركبة الهجينة من ألالياف و الايبوكسي. استخدمت طريقة الصب اليدوي (Hand layup) لتحضير العينات. لقد تمت مقارنة قيم الانتشار الحراري للمواد المحضره مع الانتشار الحراري لمجموعة من المواد بما في ذلك سيراميك التيتانات السترونتيوم ($SrTiO_3$). وقد أظهرت النتائج إن ألياف الكاربون والزجاج لها أدنى قيم للانتشار الحراري مقارنة مع المواد الأخرى. أيضا تم قياس ثابت العزل الكهربائي، و فقدان العزل الكهربائي والموصلية الكهربائية في درجة حرارة الغرفة باستخدام تقنية محلل المعاوقه. لقد تبين أنه على الرغم من أن المواد الهجينة لديها نفس سلوك الألياف الزجاجية ولكن قيمة ثابت العزل الكهربائي قد زادت بشكل ملحوظ.

مفاتيح دالة: ألياف الكاربون، ألياف الزجاج، ألياف هجينه، الانتشار الحراري، خصائص العزل الكهربائي

1. Introduction

Carbon fiber (CF) has special characteristics and features such as corrosion resistant, high hardness, light-weight material, high strength, low thermal expansion and high temperature; these features make this type of fiber useful in several applications and fields such as mechanical, aerospace, and civil engineering, as well as in military and motorsports applications [1-4]. On the other hand CF is quite costly if compare with other fibers such as the glass fibers. Although glass fiber (GF) is a brittle material but it is a cheap as well as good thermal and electrical insulator.

Composites materials such as CF and glass fibers when mixed with epoxy resin offer very good potential for thermal insulation as well as several commercial and aeronautics applications. Epoxy resin is one type of polymers that it is non-compliant by heat, and it can convert from complex liquid to solid by physical and chemical methods [5, 6]. Glass and carbon fiber epoxy resin has been used in many applications starting from small housing products to automotive and aerospace applications due to low weight, high strength and non-corrosive materials [7]. Composite material has been used for several thermal applications because it has a good electrical properties and thermal insulation [8].

Effective thermal conductivity (ETC) of advance composites materials using local fractal model dimensions was studied and explained experimentally by Rajpal and his group; they showed and reported that the effective thermal conductivity depends on the volume fraction and the ratio of thermal conductivity of its constituents [9] . There are many approaches and methods that have been used to measure thermal, mechanical and electrical properties of composite materials [10]. In this paper, thermal diffusivity was studied using photo flash method while impedance analyzer was used to determine the dielectric properties of the prepared samples.

2.Experimental part

2.1 Materials

Epoxy resin was manufactured by LECO Corporation Company (USA), and used as a basis material. The glass fiber (GF) woven mat with density of 2.5 gm/cm^3 and the carbon fiber (CF) woven mat with density of 1.78 gm/ cm^3 were used in this study. More details about the raw materials that used to develop composites through hand layup method in this study were listed in Table 1.

2.2 Preparation of CF/Epoxy and GF/Epoxy

Carbon fiber/epoxy resin (CF) and glass fiber/epoxy resin (GF) samples were prepared by using hand layup method. It is considered as a simplest and cheapest method used for samples preparation of composite materials in many applications. There are distinct steps, in the beginning, adding a few amount of released gel on the surface of mold to avoid any adhering of composite constituents on the surface. To get samples with smooth surface, thin plastic sheets are used and covered the top and bottom of the mold. Reinforcement carbon fiber (CF) or glass fiber (GF) in the form of woven fibers fabric are cut as the same size of the mold and placed at the top surface of the mold. Then the resin in liquid form is mixed completely with a hardener (liquid form also) in a suitable ratio according to standards ratio of mixing to get a new liquid called epoxy resin or matrix, then placed on the surface of the first layer of the fibers that was already placed in the mold. The brush was directly used to spread the epoxy resin uniformly inside the mold. Then, second layer of fiber was placed on the first layer of the composite surface and a roller tool was used and moved with a suitable pressure by hand on the composite layers to eliminate any gaps or air trapped inside the composite as well as the extra composite present. Then repeat the procedure for each layer of fiber and epoxy resin till the required layers are stacked in good form. This step was repeated for each layer by overlapping the layers with the mixture until the last layer to become as composite laminates. After that, the treatments step by reunion the composite together with the mold was take place at room temperature.

Then mold was opened as usual and the composite sample was extracted and taken out for further processed. The schematic of composite hand layup method is shown in Figure 1.

Stacking sequences of the carbon and GF that has been used in this current investigations is (0/90/-45/+45) (for covering all the gaps in fiber layers) is shown in Figure 2. Photographs were taken by normal camera thorough the procedure of the composite materials as shown in Figure 3.

The curing time depends on the type of polymer that is used for composite processing. Epoxy resin was used for current study; the normal curing time at room temperature was 24 hours. This method always is used and suitable for the fabrication of composite samples if the polymer or epoxy resin used from thermosetting types. In the last step, samples cutting were done by using CNC cutting machine and finishing machine to get the required dimension of the sample as shown in Figure 4.

2.3 Thermal Diffusivity

Photoflash technique was used to determine the thermal diffusivity. The photo flash system shown in Figure 5 consists of an electronic photo flash (Minolta flash 5400HS) with pulse time duration 5 ms as pulse light source, sample holder, K-type thermocouple, Low-noise preamplifier (SR-560) and Digital oscilloscope (Tektronix TDS220) [11].

The thermal diffusivity is given by

$$\alpha = \frac{0.1388 L^2}{t_{1/2}} \qquad (1)$$

Where α is the thermal diffusivity , $t_{1/2}$ is the half rise time of temperature profile of the sample and L is the thickness of the sample [12].

2.4 Dielectric properties

The dielectric properties were measured using impedance analyzer technique. The impedance analyzer consists of three parts; Chelsea Dielectric Interface (CDI), Frequency Response Analyzer (FRA) and Computer Processor Unit (CPU). The measurements were carried out at room temperature and in frequency range (10 - 10^6) Hz with alternating current power. Briefly, it consists of two conducting surfaces sandwich the samples in-between thus it works as capacitance to store the charges. The impedance analyzer was used to measure the capacitance (C´) and conductance (G) as a function of frequency (f). The other parameters such as dielectric constant (ε´), loss factor (ε´´), imaginary part of capacitance (C´´), conductivity (σ), dielectric loss (tan δ) and quality factor (Q) can be calculated using the following equations (2-7) [13-15].
The dielectric constant can be written as the following equation:

$$\varepsilon' = \frac{C' d}{A\, \varepsilon_\circ} \qquad (2)$$

where, $\varepsilon_\circ$ is the permittivity of free space, d and A are the thickness (cm) and the area (cm^2) of the sample respectively. The imaginary part of dielectric constant (ε'') is called the dielectric loss factor which is the electrical energy lost through conduction when a voltage is applied across the dielectric materials. ε'' can be given by below equation:

$$\varepsilon'' = \frac{C'' d}{A\, \varepsilon_\circ} \qquad (3)$$

where (C″) is the imaginary part of capacitance. It can be described by the following equation:

$$C'' = \frac{G}{2\pi f} \qquad (4)$$

where (G) is the conductance which is the ability of material to pass or conduct electrons. The conductivity of the materials can be written as:

$$\sigma = \frac{Gd}{A} \qquad (5)$$

The energy dissipation in the dielectric system is called dielectric loss tangent ($\tan\delta$), which is directly proportion to the imaginary part of dielectric constant ε'' and negatively with the real part ε'. It can be written as the following equation:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (6)$$

The quality factor (Q) is the reciprocal of the loss tangent. Thus it can be defined as:

$$Q = \frac{1}{\tan\delta} \qquad (7)$$

3. Results and Discussion

Thermo-gram of the samples using photoflash technique is shown in Figure (6). The data reported in Table 2 shows that the thermal diffusivity and the density of CF is 3.652×10^{-3} cm^2/s and 1.002 gm/cm^3 respectively, while it was 2.330×10^{-3} cm^2/s and 1.034 gm/cm^3 for GF.

These results indicate that the higher the density the lower the thermal diffusivity which follows the relation ($k=\alpha\rho c$), where (ρ) is the density, (k) is the thermal conductivity and (c) is the specific heat capacity. For the hybrid fiber (HF) the thermal diffusivity is $3.500 \times 10^{-3}$$cm^2/s$ and the density is 1.071gm/cm^3. It's clear that although the thermal diffusivity of the hybrid is higher than the fiber glass but its density is also higher, this may due to the density of epoxy resin matrix. Toward better understanding of these results, the thermal diffusivity of some chosen materials values were listed in Table 3. Among several materials such as $SrTiO_3$ dielectric ceramics, it is clear from the results that our samples are standing as good thermal insulators.

The collected data from the impedance analyzer were analyzed and plotted using origin program. The dielectric constant (ε') of the samples is calculated using equation (2) and plotted versus the logarithm of frequency as shown in Figure 7. It is clear that the dielectric constant of CF higher than the GF while for the hybrid is as an intermediate value. Thus the hybrid fiber is highly affected by the GF where both of them have the same behavior but the effect of CF on hybrid is to raise the dielectric constant of hybrid. The dielectric constant at low frequency has a high value and it is strongly dispersed. It could be caused by the electrode blocking layers which is the prevailed phenomenon at low frequencies [16]. As the frequency increased the dielectric constant of all samples decreased which is a probable behavior of all dielectric materials. This can be attributed to the fact that the orientation polarization is caused by the dielectric relaxation [17]. The orientation polarization is depending on the configurations of molecule which made the material act as a dielectric material [18]. The decrement in dielectric constant continued until it reached steady rate and became almost independent at frequency higher than 400 Hz owing to the interfacial polarization. This explained by, at high frequencies the rotational motion of the polar molecules of dielectric materials is not fast enough to reduce the dielectric constant [19].

Figure 8 shows the dielectric loss factor as a function of log frequency. The dielectric loss factor of all samples shows attenuation versus increasing frequency. The reduction of (ε'') by increasing frequency can be ascribed to Debye relaxation [20].

Figure 9 shows log conductivity against log frequency. This figure indicates that the CF exhibited the higher conductivity among these samples while the GF is the lowest. It can observe that the conductivity of carbon is stable along all the frequencies range. This behavior indicated that the conductivity of CF is high and frequency independent. The conductivity growing of GF and HF by rising the frequency is a regular behavior of polymeric and semiconductor materials. At high frequencies the conductivity increased linearly with frequency. This could be caused by the movement of ions and the transportation close to or at the interstitial surface between fiber and epoxy composite. The conduction mechanism of these samples could be described by the hopping of the charge carriers [21]. Every layer of the fiber represents a capacitance which participates in conduction procedure and the dipole is formed inside it. It's well known that when the external electric field is applied, dielectric polarization occurs. Thus the polarization of the formed dipoles is responsible for the charge density (conductivity) elevating with increasing frequency.

Figure 10 shows the dielectric loss ($tan\delta$) depends upon frequency. At low frequencies the CF shows high tangent loss and reduces at higher frequency. This peaking behavior of CF occurs due to the existence of relaxing dipoles. The featured properties of dipolar relaxation may control the strength and frequency of relaxation. The glass and HFs show very small loss; which suggest that both are frequency independent. Since the preferable insulating materials have high quality factor (low $tan\ \delta$) therefore the HF is suitable for dielectric application. The dielectric measurements were summarized in Table 4.

4. Conclusion

In this work the thermal diffusivity and dielectric properties of fiber glass as hybrid composite with CF were studied. The thermal diffusivity results revealed that these samples have good thermal insulators. The general observation of the results showed increasing the thermal diffusivity values with increasing density. Enhancement of dielectric properties was observed after reinforcement the CF by glass fibers. Generally the dielectric properties values decrease with the increase of frequency. The results show that the presence of GF in the composite modifies the behavior of the HF as well as improves the dielectric properties. It was observed that the dielectric constant of the hybrid was higher than both glass and carbon fibers. Also it was found that the conductivity of hybrid and glass fibers increased with the increment of the frequency, while it was remain constant for carbon fiber. These results indicated that the hybrid sample is good candidate in dielectric applications.

5. References

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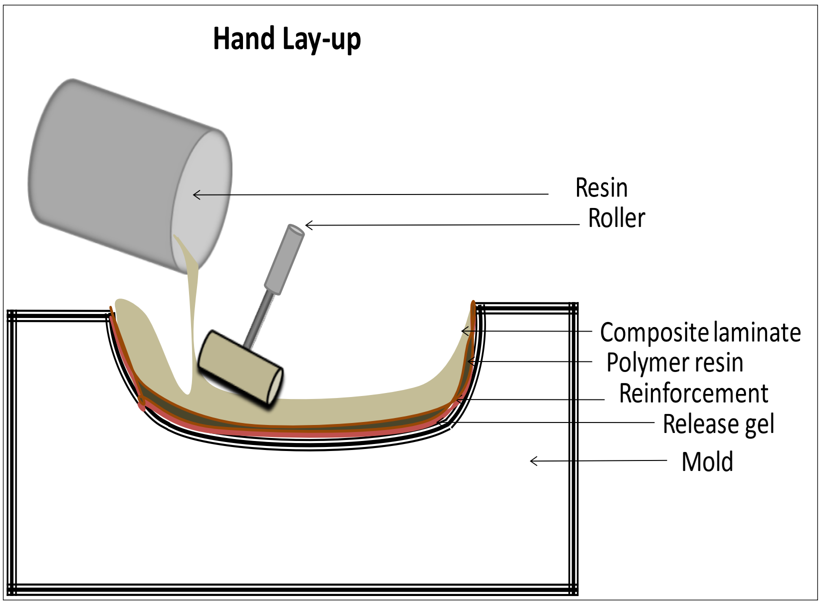

Figure 1: Schematic diagram of Composite Hand Layup Method.

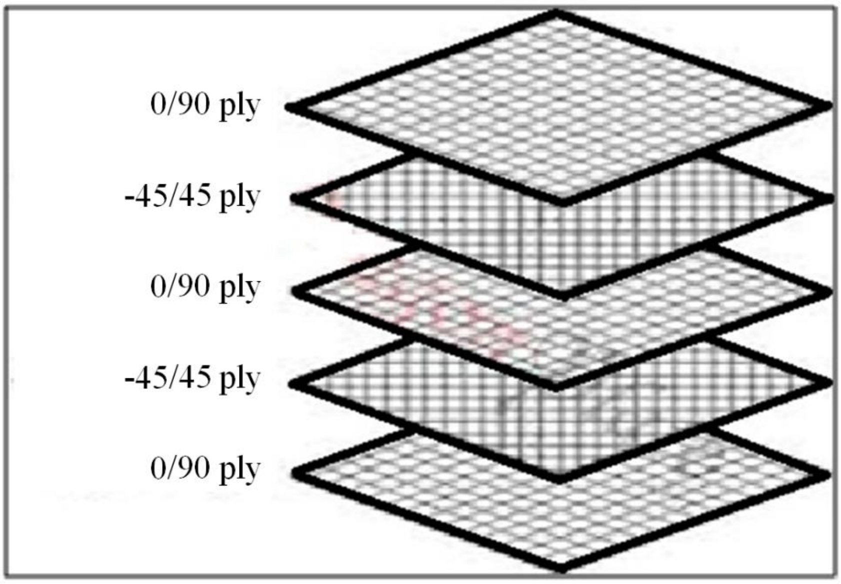

Figure 2: Stacking Sequences form of the Carbon (CF) or Glass Fiber (GF).

Figure 3: Typical Photographs of Composite through the Hand Layup Process.

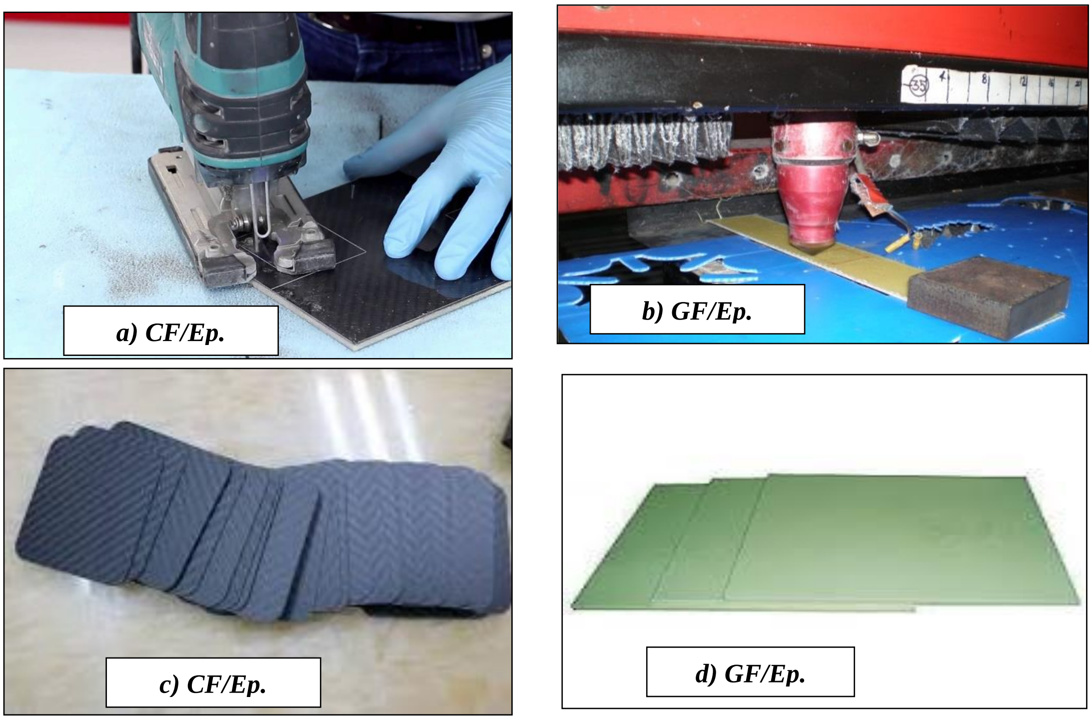

Figure 4: ***a)*** **Cutting process of Carbon Fiber** ***b*****) Cutting process of Glass Fiber, (*c)* and *(d*) Carbon Fiber and Glass Fiber Samples after Cutting and Finishing.**

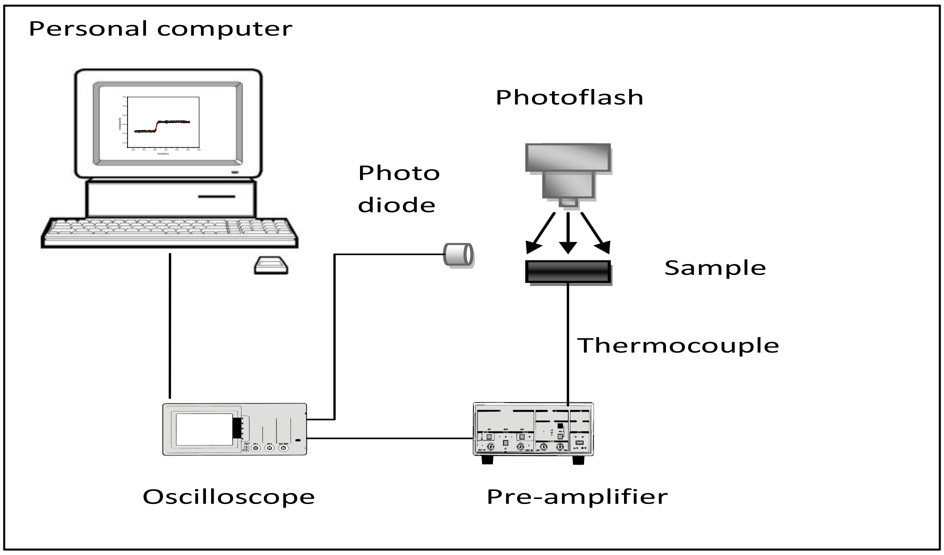

Figure 5: Experimental System of Photo Flash Technique [11].

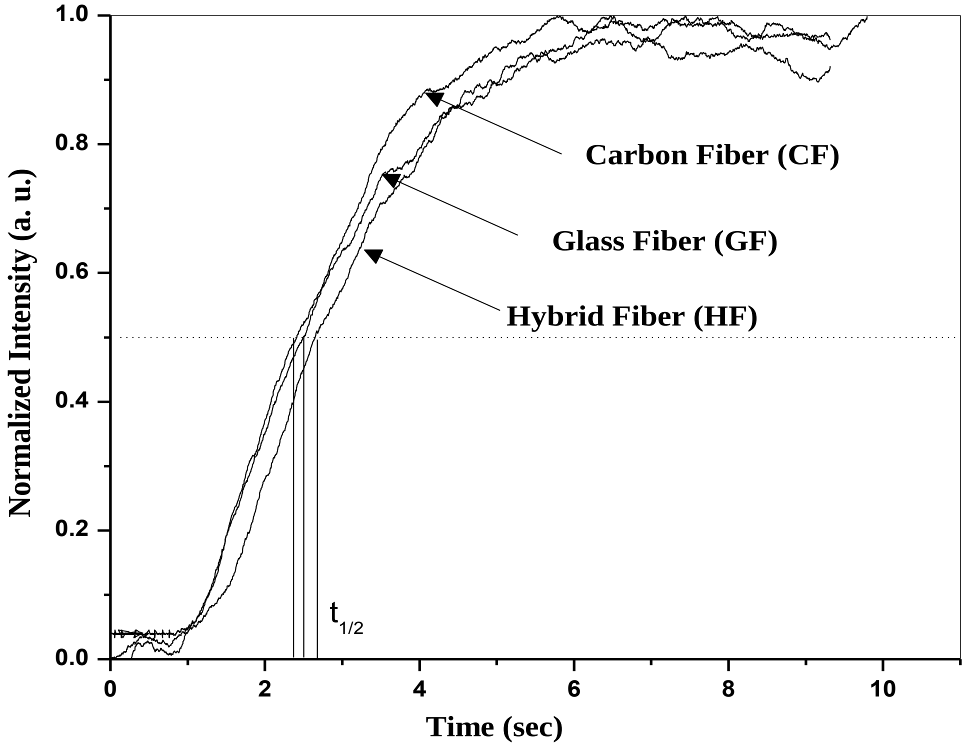

Figure 6: Thermo-gram of the samples using photoflash technique.

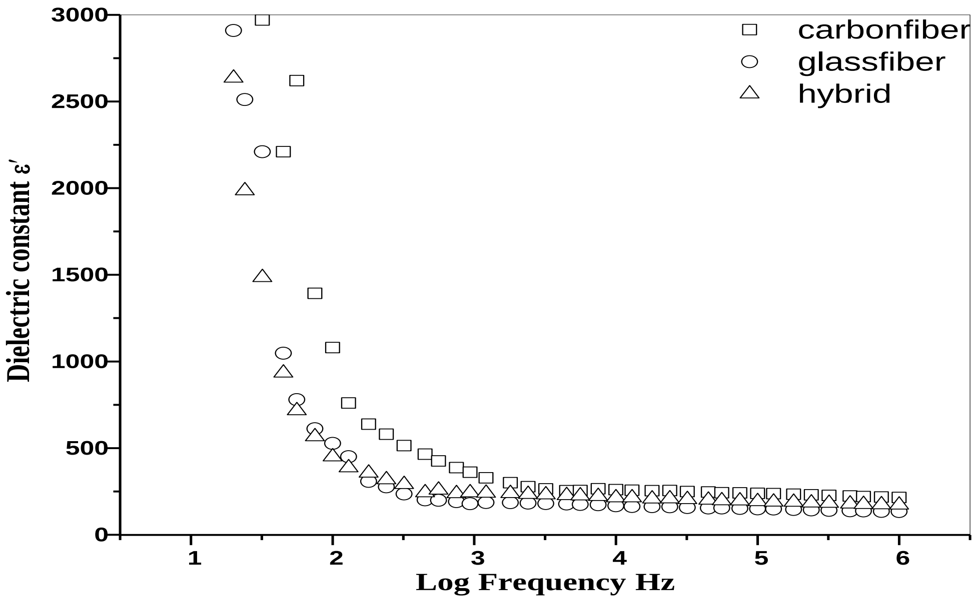

Figure 7: Dielectric constant versus log frequency.

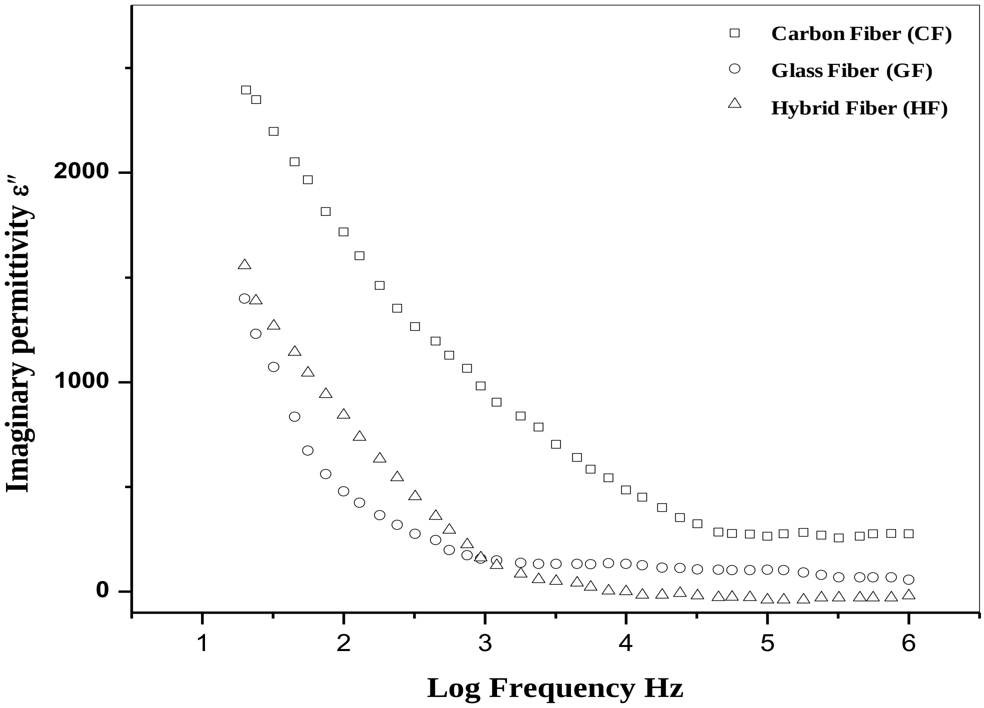

Figure 8: Dielectric loss factor versus log frequency.

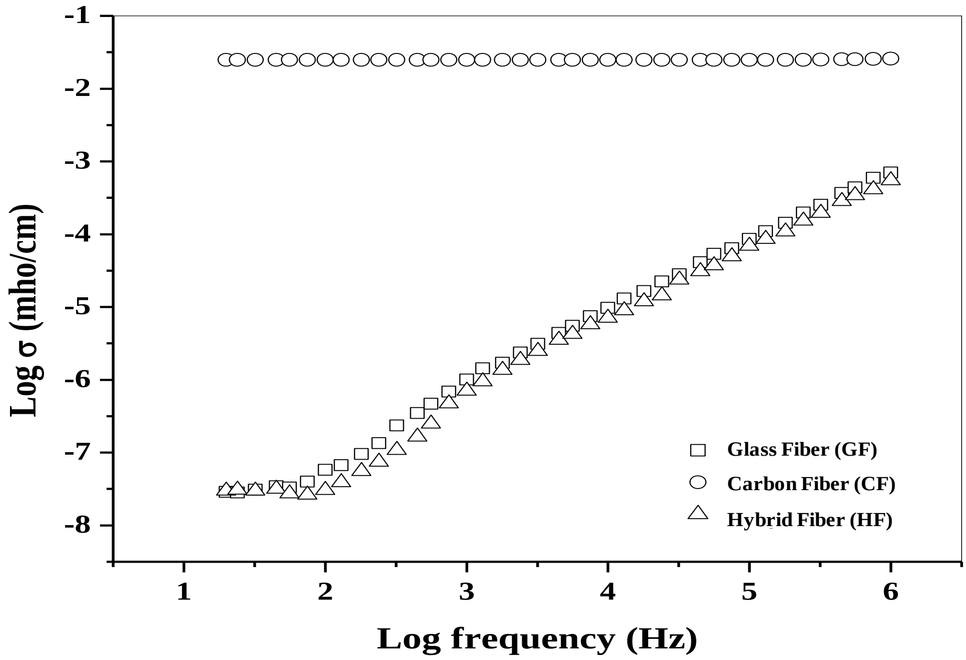

Figure 9: Log conductivity versus log frequency.

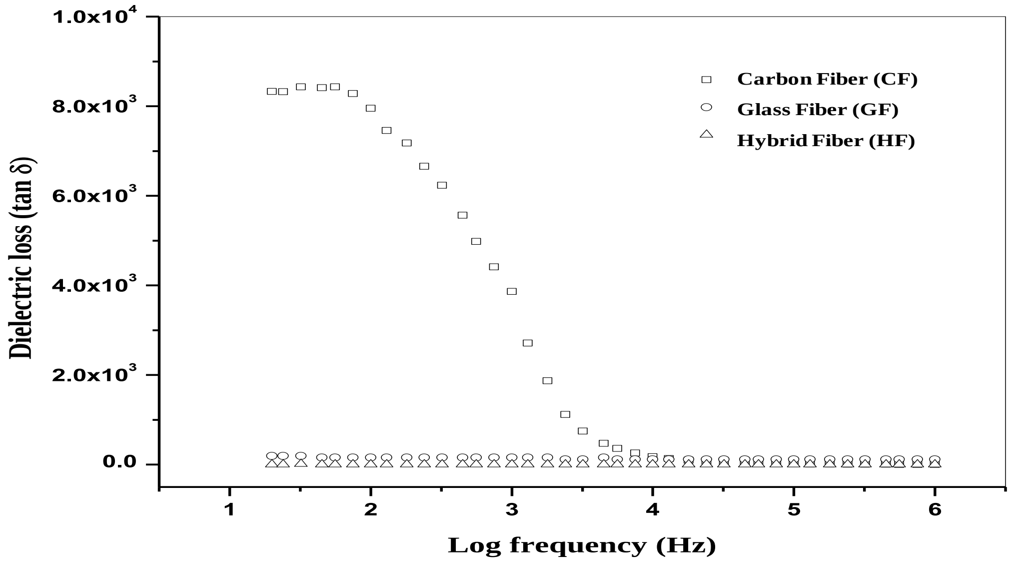

Figure 10: Dielectric loss (*tanδ*) versus log frequency.

Table 1: Materials used in hand layup technique.

Material	Specifications (Type/ source)
Epoxy resin	LECO 811-563-103 (USA)
Hardener	LECO 811-563-104 (USA)
Reinforcement 1: Woven roving glass fiber (GF)	S-Glass- No. 400 Thick fiber (China) Diameter (Each filament): 20 μm Tensile strength: 660,000 Ib/in^2 (PSI) Modulus of Elasticity: 12.5 Mpa Elongation: 5%
Reinforcement 2: Woven roving carbon fiber (CF)	Woven roving, Thick (China) Diameter (Each filament): 18 μm Tensile strength: 477,000 Ib/in^2 (PSI) Modulus of Elasticity: 35 Mpa Elongation: 1.5%

Table 2: Thermal diffusivity of the samples which measured by photo flash technique at room temperature.

Sample	Thickness (cm)	Density gm/cm^3	Thermal diffusivity $\alpha \times 10^{-3}$ (cm^2 / sec)
Glass Fiber	0.2008	1.034	2.330
Carbon Fiber	0.2565	1.002	3.652
Hybrid Fiber	0.2586	1.071	3.500

Table 3: Thermal diffusivity of several selected materials which measured by photo flash technique at room temperature.

Material	Thermal diffusivity $\times 10^{-3}$ cm^2/sec	Reference
$SrTiO_3$	6.46	[11]
Alumina	79.6	[22]
Aluminum	988	[23]
Carbon/carbon composite	2165	[24]

Table 4: Dielectric properties measured at room temperature at 1 KHz.

Sample	ε'	ε''	tan δ	σ	*Q*
Glass Fiber	1.790×10^{2}	1.27×10^{1}	7.09×10^{-2}	7.05×10^{-7}	1.41×10^{1}
Hybrid Fiber	2.430×10^{2}	1.81×10^{1}	7.45×10^{-2}	10.1×10^{-7}	1.34×10^{1}
Carbon Fiber	0.116×10^{2}	4.46×10^{5}	3.84×10^{4}	2.48×10^{-2}	2.60×10^{-5}