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ARTICLE

The Optical Properties of Unsaturated Polyester Reinforcement by Glass Fibers

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Abstract: The effects of laminates chopped strand mat fibers with various weight percentages (0.1, 0.5, 1.1, and 1.7 wt.%) on the optical characteristics of unsaturated polyester prepared by casting technique are examined by the measurement of changes in the visible light and ultraviolet wavelength regions. Due to direct transitions permitted for pure and various polymer composites, polymer composites display a novel UV-visible absorption band in a wavelength range of 320-580 nm. The optical transmission technique is effectively used to determine the optical absorption, transmittance, optical energy gap, extinction coefficient, and reflectance of produced composites. The results reveal that the optical band gap (Eg) for authorized direct transition increases as the concentration of glass fibers increases. Increased fiber content correlates with elevated optical absorption, extinction coefficient, and reflectance. Moreover, transmittance curves showed significant variation with increasing weight percentages of glass fibers.

Keywords: Unsaturated polyester, Glass fibers, Optical properties, Glass fibers composite, Optical band gap.

Introduction

Technology today requires materials with a combination of properties that traditional materials such as metals, ceramics, and polymers cannot provide. As a result, engineers are being forced to seek out alternative materials to meet the complex service requirements of modern applications. These materials should possess good process ability along with excellent mechanical characteristics [1]. Polymers have become important in fabrication due to their ease of processing, acceptable chemical and volumetric stability, high electrical insulation, lightweight nature, good resistance to acids and alkalis, excellent rigidity, cost-effectiveness, and wide range of functionalities [2]. Polymer resin, such as unsaturated polyester, is a thermosetting polymer that cannot be reformed by heat once converted into a solid. It is also famous for its many advantages, such as high transparency, which makes it an alternative to glass in applications like aircraft, factories, greenhouses, and laboratories, as well as in complex optical technologies such as lenses and prisms [3, 4]. Polymer composites have been produced to fulfill a variety of industrial needs, including the need for simpler processing and a broader range of qualities, by altering the type, relative composition, or shape of each component.

For many years, researchers have been interested in the effects of UV radiation on polymers. Spectroscopy plays a crucial role in studying these effects. When electromagnetic radiation falls on the surface of a material, several optical phenomena can occur, including transmittance, absorption, reflection, and refraction. The occurrence of these phenomena depends on the nature of the material and the wavelength of the rays used.

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Assuming that ultraviolet-visible absorbance is zero above 700 nm, the average sample absorbance between 700 and 800 nm was removed from the spectra to adjust for offsets owing to instrument baseline drift, temperature, scattering, and refractive effects. Under irradiation, polymers with dangling aromatic ring groups, such as polyester, are known to exhibit a novel fluorescence band at a longer wavelength. This is due to the interaction between excited and ground-state aromatic groups, i.e. the production of intermolecular excimers. This phenomenon is frequently employed as a valuable tool in the study of polymer structure [5].

The absorption coefficient (α) is related to the absorbance (A) based on the Lambert-Beer law [6]:

$$Ln(I_o/I) = 2.303A = \alpha d \quad (1)$$

$$\alpha = 2.303\ A / t \quad (2)$$

where α (m^{-1}) is the absorption coefficient of the material, (A) is the absorbance of the material, and t (mm) is the thickness of samples.

The energy of the incident photon (E (ev)) as a function of wavelength (λ(nm)) is given by the relationship [7]:

$$E(ev) = 1240 / \lambda_{nm} \quad (3)$$

The energy of the direct optical gap (E_g (ev)) can be calculated by plotting the relationship $(\alpha h)^n$ as a function of the energy of the photon (E(ev)) and then plotting the tangent to the curve to cross the x-axis at the point equal to the direct energy gap [8]:

$$\alpha h\upsilon = A(h\upsilon - E_g)^n \quad (4)$$

where h is Planck's constant, A is a constant, υ is the frequency of the incident ray, and n is a relative number that depends on the nature of the transitions, taking values ½ and 2 for allowed transitions (direct and indirect, respectively), and 3/2 and 3 for forbidden transitions (direct and indirect, respectively) [9, 10].

As for the extinction factor, it can be calculated from the following relationship [11]:

$$K = \alpha\lambda / 4\pi \quad (5)$$

One approach for obtaining the refractive index (n) is to use the reflectance (R) and the extinction coefficient (k), where $k=\alpha\lambda/4\pi$ [12]:

$$n = (1+R/1-R) + \{(4R/(1-R)^2) - k^2\}^{1/2} \quad (6)$$

Here, n represents the real component of the complex refractive index, denoted as ṅ = n + i. R is the reflectance computed from the absorbance (A) and transmission (T) spectra using the following relation [13]:

$$R = 1- \{T*\exp(A)\}^{1/2} \quad (7)$$

This paper reviews the fundamental emission and optical properties, such as absorption, reflection, transmission, and refraction effects, of unsaturated polyester resin reinforced with different weight percentages of E-type glass fiber. These aspects are important for applications in many fields such as optoelectronic devices, aircraft glass, greenhouses, as well as lenses and prisms in complex optical technologies.

Experimental Methods

Materials and Procedures

Unsaturated polyester (UP), manufactured by Saudi Industrial Resins Limited (SIR), was employed as the matrix material. This UP had a yellow appearance and a density of 1.3 g/cm^3 [14].

Methyl ethyl ketone peroxide (MEKP) was used as a hardener, applied to the matrix material at room temperature at 2%. Cobalt octoate was added at 0.5% to accelerate the process and promote matrix solidification. The laminates chopped strand mat glass fibers type (E-Glass) were used for strengthening the unsaturated polyester matrix, with different weight percentages (0.1, 0.5, 1.1, and 1.7 wt.%) and a fiber diameter of about 4μm.

The manual molding method (hand lay-up) was used in the preparation of the glass fibers composite. A mold made of glass was prepared in the form of rectangular cubicles measuring 1 × 10 × 60 mm.

The weight percentage of the reinforcement materials added to the resin was calculated based on the following equation [15]:

$$Wt._f\% = \frac{w_f}{w_c} \times 100\% = \frac{w_f}{w_f + w_m} \times 100\% \quad (8)$$

where w_c is the weight of the composite material, w_m is the weight of the base material, and w_f is the weight of the reinforcing material.

The resin was mixed with the accelerator (cobalt octoate) at 0.4 wt.%. A hardener (methyl ethyl ketone peroxide) at 2 wt.% was added and mixed for 5 minutes. The glass fibers, with different weight percentages (0.1, 0.5, 1.1, and 1.7 wt.%) were impregnated with resin by pouring the resin onto the fibers from one corner of the mold after putting fibers into the mold. This method helps avoid bubble formation, which causes cast damage. Then the mixture was left to solidify for 24 hours at room temperature. Subsequently, the samples were placed in an oven at 55^{o}C for an hour to complete the hardening process. The samples were removed from the oven and left in the air for 7 days to be ready for testing operations.

Characterization and Properties

UV-visible spectroscopy of the prepared samples was performed in absorption mode using a UV - VIS Spectrophotometer-2550 in the wavelength range of 200 to 1000 nm at room temperature. The device was calibrated by placing two strips of glass in front of the window of the first source and the other in front of the reference.

Surface Topography

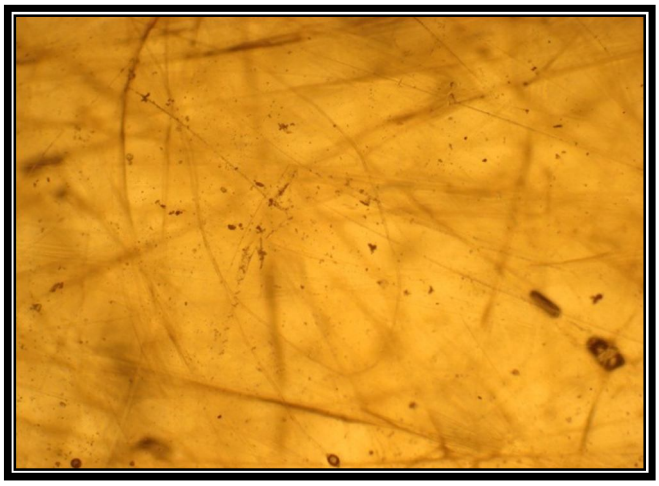
Surface morphology was examined using an optical microscope (OM) and a field emission scanning electron microscope (FESEM), which is a type of microscope that scans a focused beam of high-energy electrons across the surface to generate various signals at the surface of solid specimens, resulting in images of the sample. Electrons in the beam interact with atoms in the solid specimens, generating a range of signals that may be detected and give information about the surface topography and composition of the sample. Zeiss Sigma VP was used for the FESEM study.

Results and Discussion

Surface Topography

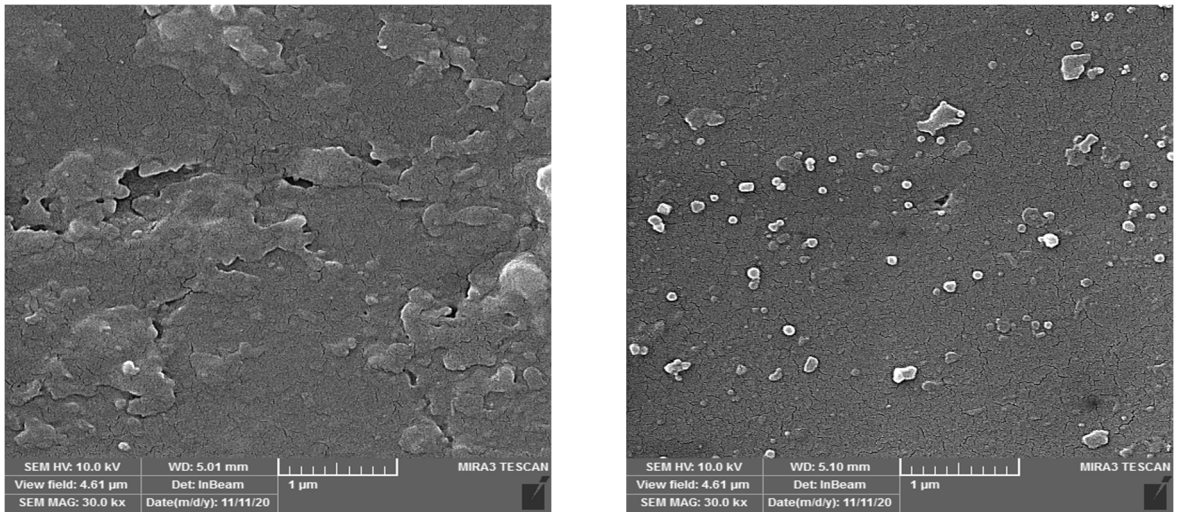
Figure 1 shows the microscopic imaging of the composite sample reinforced with E-glass fibers randomly woven in the form of laminate fibers. The image illustrates the regular distribution of the random fibers within the prepared samples.

The samples' morphology was examined using FESEM. Figure 2 shows images of unsaturated polyester resin reinforced with 0.1 and 1.7 wt.% glass fibers.



1.7 wt.%, 120X

FIG. 1. Microscopic imaging of the glass fiber composite.



0.1 wt.% **1.7 wt.%**

FIG. 2. Microstructure of the glass fiber filled with unsaturated polyester composite.

The composite samples exhibited both smooth and rough morphology with occasional voids and micro fractures, indicating that the composites utilized in the study were brittle. Some blisters were also found on the surface of the sample, likely caused by the air bubbles that did not burst during the sample preparation process [16]. With the increase in the weight percent to 1.7 wt.% of the glass fibers, the surface of composites seemed to become wavy and rougher, which indicates the brittle property of composites used in the study. It was also noted that the surface was porous as a result of the formation of voids on the surface, which is clearly visible in the microscopic imaging shown in the figure above. This porosity could result in the formation of plates or flakes, which could be caused by the random growth of three-dimensional polymers [17]. Additionally, some micro cracks were noted on the surface.

Optical Properties

1. Optical Absorption

Typical UV-Vis spectra of unsaturated polyester–glass fiber composites are shown in Fig. 3. The figure illustrates the normalized UV-Vis spectra of polyester with glass fiber content of 0.1, 0.5, 1.1, and 1.7 wt.%.

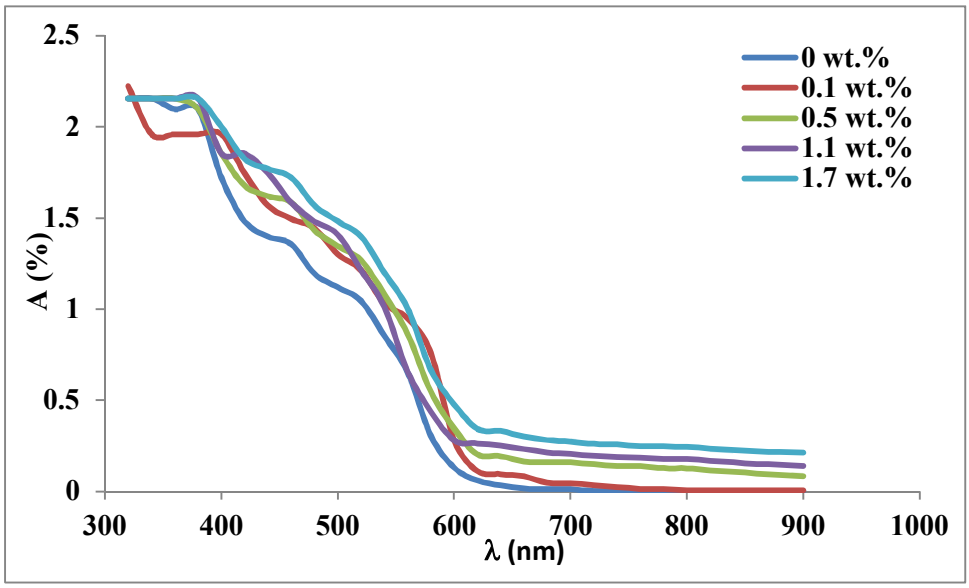


FIG. 3. Variation of absorbance values as a function of wavelength for glass fiber composites.

It has been demonstrated that adding a filler to a polymer increases the intensity of the peak. A critical examination of the UV-Vis spectra of polyester-glass fiber composites reveals that the absorption wavelength shifts are in the region of 320-600 nm. An increase in conjugation duration

might explain the change in the absorption edge from UV to visible. The absorption of light energy by polymeric materials in the UV and visible ranges requires the transfer of electrons from the ground state to higher energy levels in the (n) to (π*) orbital. This is due to the fact that the absorption peaks for these transitions are located in an experimentally useful area of the spectrum (200-700). To give the (π) electron, these transitions need an unsaturated group in the molecule [18].

From the discussion above, we can infer that the composite has the maximum absorption value at short wavelengths. Because the energy of the incident photons is lower than the energy of the optical energy gap, absorption decreases as wavelength increases.

Optical Transmittance

A comparison was made between the transmittance values as a function of the wavelengths of the unreinforced and reinforced unsaturated polyester with different weight percent of glass fibers. It was found that the base material has very little transmittance at wavelengths less than 400 nm, i.e., within the ultraviolet (UV) irradiation region. This is due to the high absorption of samples in that region (see Fig. 4).

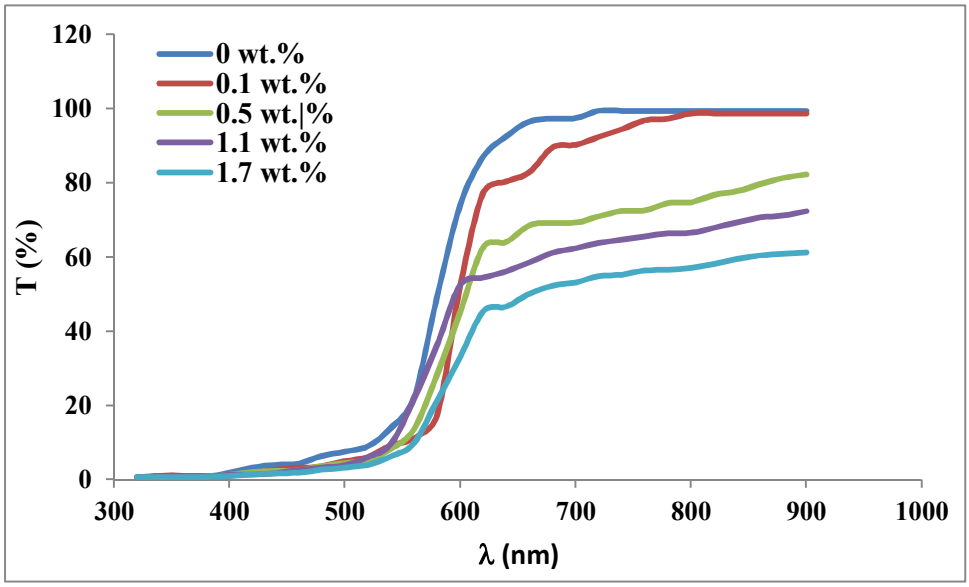


FIG. 4. Variation of transmittance values as a function of wavelength for glass fiber-filled unsaturated polyester composite.

It can be seen that the transmittance curves tend to remain almost constant at wavelengths less than 380 nm, then increase with increasing wavelengths (400-900 nm) for nearly all concentrations of glass fiber composites. This change is attributed to direct electronic transitions from the orbital (n) in the ground state to (π) in the agitated state within the region of visible wavelengths compared to the unsupported substrate [19].

A significant variation in the decreasing transmittance curves was noticed with increasing weight concentrations of glass fibers. The transmittance decrease ranged from 10% to 50% as the weight concentration of glass fibers changed between 0.1 wt.% and 1.7 wt.% in the composites compared to the unsupported substrate.

In general, this decrease in the transmittance values of these composites can be explained by the increasing weight percent of the glass fibers in the unsaturated polyester leading to the formation of donor or amenable levels within the energy gap, displacing the Fermi level and resulting in the absorption of low-energy photons. This occurs due to the increase in the density of carriers, which is inversely proportional to transmittance [20].

2. Optical Energy Gap

Figure 5 depicts the relationships between $(\alpha h\upsilon)^2$ and photon energy E_g (eV) for unsaturated polyester samples, both unreinforced and reinforced with different weight percentages of laminates chopped strand mat glass fibers, for allowed transition at room temperature (25°C). The extension point of the straight line

tangentially intersecting the absorption curve with the photon energy axis represents E_g. A tangent is drawn from the best straight line that most points pass through after the absorption edge, where the photon energy axis crosses at $(\alpha h\upsilon)^2=0$), representing the value of the permissible optical gap energy gap for direct transmission.

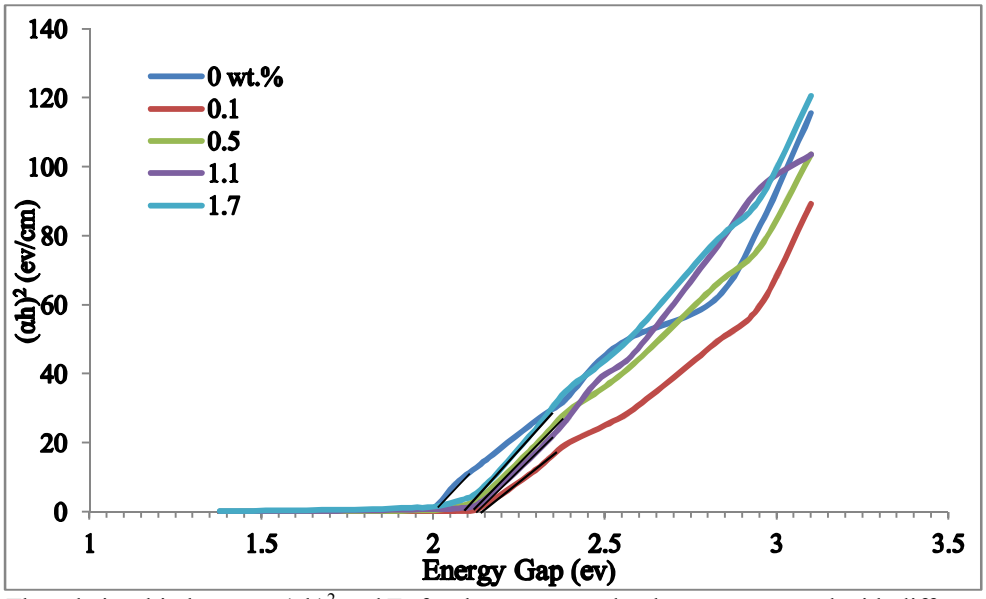


FIG. 5. The relationship between $(\alpha h)^2$ and E_g for the unsaturated polyester supported with different weight percentages of glass fibers.

Figure 6 shows that the gap energy of the matrix sample is equal to 2 eV. This value begins to increase with increasing the weight percent to 0.1 wt.% of glass fibers, then decreases as the weight percent of the glass fibers continues to grow. This behavior is attributed to the formation of local levels between the valence band and the conduction band. Despite these fluctuations, the energy gap remains higher compared to the unsupported base material.

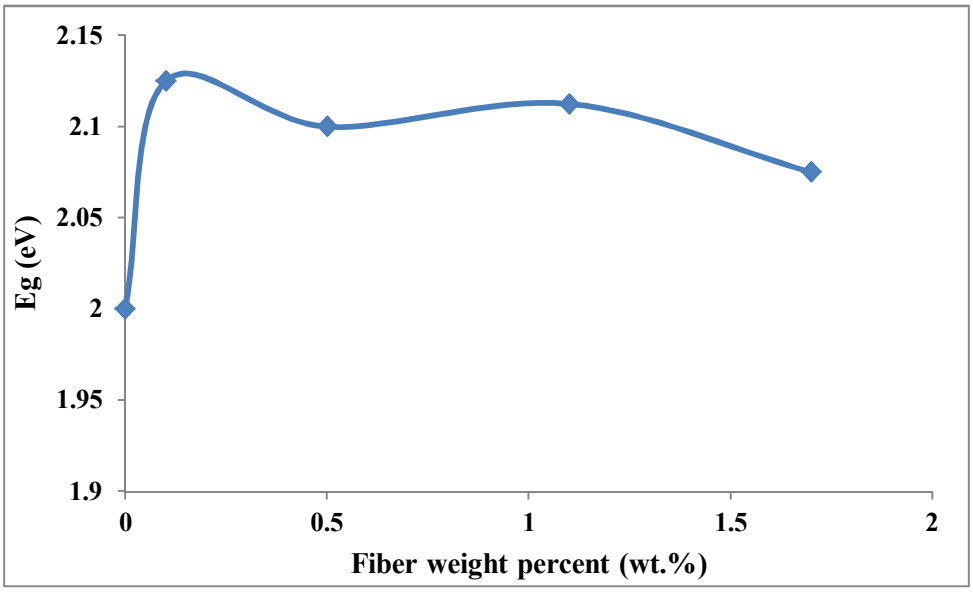


FIG. 6. The change in the light energy gap at different weight percent of the glass fibers.

3. Extinction Coefficient

The change in the values of the extinction coefficient (K) as a function of the wavelength for the glass fiber composites is depicted in Fig. 7.

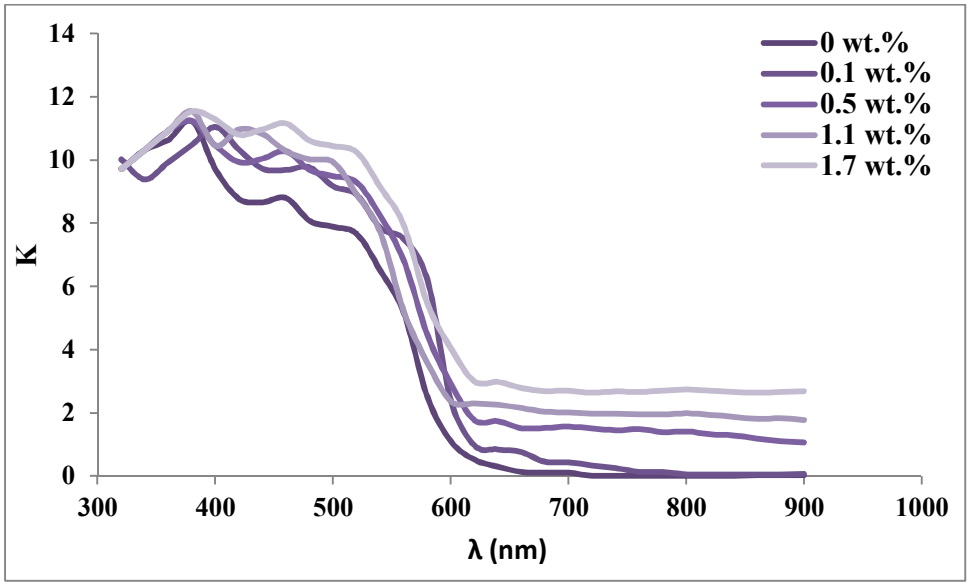


FIG. 7. Variation of extinction coefficient values as a function of wavelength for glass fiber composite.

We can see that the extinction coefficient steadily reduces as the wavelength increases in the range of 320-900 nm. Large extinction coefficient values at short wavelengths arise due to the loss of incident wave energy caused by the fundamental absorption process. The low extinction coefficient values at long wavelengths can be attributed to an increase in the quantity of layer permeability of the tested substances. Due to the fundamental absorption process, the extinction coefficient has an impact on the loss factors of the incident wave energy. This behavior is comparable to that of the absorption coefficient (α), as indicated by the relationship in Eq. (5) [21], which shows a clear dependency between the two parameters. The extinction coefficient increases with the increase in the weight percentages of the reinforcing materials.

4. Reflectance

Reflectance is described as the proportion of energy that is reflected when radiation falls on the surface of a material compared to the amount of the incident radiation energy. The reflectivity was calculated from the absorbance spectrum (A) and the transmittance spectrum (T) according to the law of conservation of energy using Eq. (7). Figure 8 represents the reflectivity of the prepared samples.

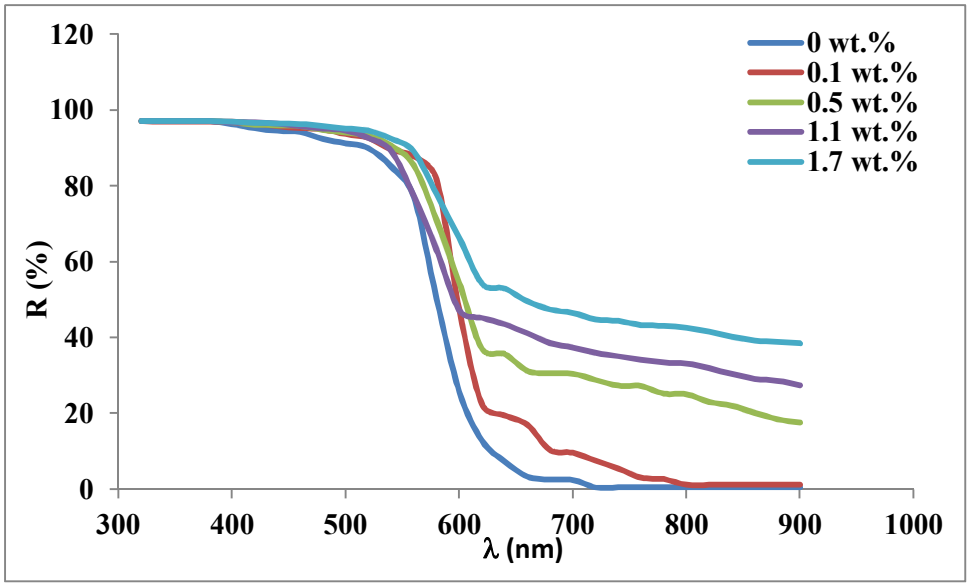


FIG. 8: Variation of reflectivity values as a function of wavelength for glass fiber composites.

We find that the reflectivity decreases gradually with increasing wavelengths of the rays used for glass fiber composite. This change can be explained by the occurrence of refraction in bonds, causing changes in the crystal lattice and surfaces of the composites, which leads to the generation of localized levels and a decrease in the value of the energy gap. We also note from the figure, that there is an increase in reflectivity with the increasing weight percent of glass fibers. It was also observed that the reflectivity was greater for the weight percent of fibers around 1.7 wt.% compared to that of the unfilled matrix [22].

Conclusions

1. Microscopic surface imaging of the prepared glass fiber composite samples revealed smooth and rough morphology with some blisters, voids, and micro-cracks. As the weight percent of fibers increased, the composite surface became wavier, rougher, and porous, with a propensity to develop micro-cracks and flakes.
2. Optical absorption decreased as the wavelength increased in the prepared composites, while it showed an increase with the higher weight percent of glass fibers.
3. It was found that transmittance is directly proportional to the wavelength in each glass fiber and inversely proportional to the increase in the weight percent of these fibers.
4. An increase in the local levels between the valence band and the conduction band for the glass fiber composite resulted in a visible shift in the value of the optical energy gap (Eg) as the weight percent of glass fibers increased. The Eg initially increased with a weight percent of 0.1 wt.%, then decreased with further increases in fiber weight percent, but it remained superior compared to the unreinforced base material.
5. The data also showed that increasing the weight percent of glass fibers resulted in higher coefficients of extinction, refraction, and reflectivity. Furthermore, it was observed that longer wavelengths corresponded to lower values of these coefficients.

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