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Transparency of chrysotile nanofiber-reinforced nanocomposite films: Effect of Rayleigh scattering

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ABSTRACT

Chrysotile nanofibers, which are derived from the natural mineral chrysotile, are a promising reinforcement material used to improve the mechanical properties of composite films, causing minimal reduction in visible transparency. The fabricated films were characterized through scanning electron microscopy, atomic force microscopy, and UV–Vis spectroscopy. Results showed that the composite films exhibited high luminous transmittance at fiber contents ranging from 10 wt.% to 40 wt.%, with an average transparency above 75%. Transparency showed low sensitivity to the nanofiber content of the composite films and was dependent on refractive index difference between the nanofiber and the resin. The refractive index distribution of the resins ranged from 1.496 to 1.619, the resin matched better with nanofiber the obtained composites got higher transparency. The composite film exhibited the highest transparency of approximately 85%, with transparency loss less than 5%, under equal refractive index between the chrysotile nanofiber and the resin. This study illustrates that the high transparency of the composite film mainly resulted from the reduction of Rayleigh scattering effect.

1. Introduction

The use of nanofiber-reinforced materials for the development of novel composite films has increased over the past years. The addition of small amounts of nanofiber can improve the mechanical property and thermostability of the composites while causing minimal reduction in light transparency. This treatment is vital for a wide range of applications, such as display devices, coatings, and lenses [1]. Through in-depth research, scholars have produced highly transparent composite films by using resins combined with natural and artificial fibers, such as plant fiber [2], aluminosilicate nanofiber [3], silver nanowire [4], carbon nanotube [5], chitin nanofiber [6], bacterial fiber [7], and glass fiber [8].

The size of fibers should be smaller than the wavelength of visible light to ensure that the fabricated composites will exhibit high transparency [9]. Moreover, the width of nanocomposite components should be less than one-tenth of the visible light wavelength to avoid light scattering [10]. For example, bacterial cellulose (BC), which are cellulosic nanofibers produced by bacteria, is used to obtain optical transparent materials because of its ribbon-shaped fiber size of 10 nm × 50 nm [11]. BC can also be used to reinforce transparent composites, while causing less than 10% loss of light transmittance, even at fiber contents as high as 70 wt.% [9]. In addition to BC, cellulose nanofibers can be isolated or fibrillated from plants by various routes and have received considerable attention because of their enhancement features in transparent composite films. Se et al. [12] used cellulose nanofiber as reinforcement to improve the mechanical properties of composite films and maintain high transparency; the fabricated composite film exhibited visible-light transmittance of 75% and increased mechanical strength and Young's modulus. Furthermore, several types of fiber can be used to produce flexible and transparent composite films. Chitin nanofibers, which are derived from shrimp shells or crab shells, are fabricated as nanofiber sheets; the sheets are then impregnated in resin and treated by UV curing to obtain flexible and transparent composite films [6,7,13]. Carbon nanotubes can also be introduced into the matrices of BC and electrospun nanofibers to prepare electrically conductive transparent films [5,14,15].

Chrysotile, with a nanotubular shape similar to carbon nanotubes, contains Si-centered tetrahedral sheets in a

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pseudohexagonal network combined with octahedral magnesium hydroxide sheets [16]. Chrysotile nanofibers exhibit external diameters of 20 nm–50 nm and internal channel diameters of 2 nm–10 nm, depending on the origin of mineral [17]. Chrysotile is in the main form of host or reinforced material and is applied to adsorption [18] and thermal insulation materials [19,20]. The preparation of transparent, flexible films from chrysotile nanofiber must be investigated, considering the mechanical properties of chrysotile; this mineral exhibits a Young's modulus of 261 GPa–323 GPa [21] and a tensile strength of 1.1 GPa–4.4 GPa [22]. Chrysotile can also be used as reinforcement in transparent organic materials because of its refractive index values of 1.517–1.562 (parallel to the fiber direction) and 1.493–1.560 (perpendicular to the fiber direction), which approximate those of common transparent resins and polymers [23]. Our preliminary work confirmed that chrysotile nanofiber/resin composite films exhibit optimal mechanical properties and high transparency [24].

In this study, we used chrysotile nanofibers to fabricate transparent and flexible composite films. This article focuses on exploring the effect of refractive index difference between chrysotile nanofiber and resin, as well as how this difference influences the light transmittance performance of the composite film.

2. Experimental

2.1. Materials

The raw material, chrysotile, with a length of less than 2.0 mm, was obtained from the Xiaobabao asbestos mine in China. The dispersant, *bis*(2-ethylhexyl) sulfosuccinate sodium, was purchased from Laxachem Organics Pvt. Ltd., India. A series of UV-curable acrylate resins with refractive indices from 1.496 to 1.619 and a uniform transmittance of 88% ± 2% at 590 nm (refractive indices and transmittances were measured from the cured resins) were purchased from the Royal DSM Company, Netherlands. A small amount of Darocur 1173 obtained from BASF was used as photoinitiator to cure the resins.

2.2. Preparation of nanofiber sheets

Raw material processing was discussed in our previous study [25]. Briefly, chrysotile was purified and dispersed to obtain high-purity chrysotile nanofibers. First, 10 g of the purified chrysotile and 2 g of the dispersant were added to 1 L of water and immersed for 24 h. Chrysotile was then dispersed by an emulsifying machine at 3000 r min^{-1} for 90 min and then centrifuged at 3500 r min^{-1} for 5 min to obtain the chrysotile nanofiber colloid solution. The nanofiber solution was then diluted by water and vacuum filtered using a polytetrafluoroethylene membrane filter with a pore size of 0.2 μm and a diameter of 50 mm to prepare nanofiber sheets. The fabricated sheets were dried at 55 °C for 30 min. The dried sheets were white, with thickness and diameter of about 50 μm and 40 mm, respectively. The refractive index of the chrysotile nanofiber sheets was 1.543, as determined by the liquid immersion method; this method is incorporated with optical microscopy and widely used to determine the refractive indices of various solid matters [26].

2.3. Preparation of composite films

According to our previous work [24], the composite films were prepared as follows. The obtained nanofiber sheets were first immersed in different UV-curable resins under a reduced pressure of −0.09 MPa for 24 h. After resin impregnation, the white sheets became transparent. Each impregnated film was trapped between two smooth, transparent disks. Various loads were then stacked on the disks for 10 min to obtain a smooth surface and composite films with different thicknesses and nanofiber contents. The as-obtained smooth sheets were cured by UV-light irradiation for 2 min to prepare transparent composite films. As a reference, pure resin sheets were also prepared in a similar manner.

2.4. Characterization

The nanofiber content of the composite films was calculated from the dry weights of the nanofiber sheets and the fabricated composite films [9]. A Shimadzu UV-2600 UV–visible spectrophotometer was applied to record the regular transmittance spectra of the nanocomposite film over the wavelength of 300 nm–800 nm, with air as the reference. A FEI Helios 600i scanning electron microscope (SEM) operating with 5 or 10 kV accelerating voltage was employed for morphological analysis. The surface topography of the composite films was examined with a NanoScope III atomic force microscope (AFM). Images were scanned in tapping mode under ambient conditions by using rectangular silicon cantilevers from Veeco-probes (MMP-12100-10) at resonance of about 110 kHz.

3. Results and discussion

3.1. Appearance of composite films

Fig. 1 shows the appearance of composite films with a thickness of approximately 70 μm and exhibiting outstanding transparency. The light yellow shown in transparent films originated from the resins. The transparency of the composite films is high and uniform. In certain aspects, the composite films appear smooth like ordinary hard plastic films and share similarities to paper in terms of bending, twisting, and folding. This phenomenon is the same as that reported in previous study on cellulose nanofiber/resin composite films [27,28]. As shown in Fig. 1, chrysotile nanofiber/resin composite films show high transparency, and both distant and close objects are clearly observed through the films.

3.2. Microstructure analysis of composite films

To gain an overview of the morphology of the nanocomposite films, we analyzed the film surface by SEM and AFM. The smooth morphology shown in Fig. 2 suggests that the nanofiber sheet is well covered by resin after UV curing. The magnification in Fig. 2(a) is 200×, whereas that in Fig. 2(b) is 10000×. Several raised points are found in Fig. 2(a). These points resulted from air dust deposition on the composite film surface. Fig. 2(a) and (b) indicate that the surface is extremely smooth, thereby reducing the diffuse reflection of incident light on the surface and ensuring the high transparency of the composite films [29,30].

Fig. 3 shows the micro-area surface roughness of the composite film, as determined through AFM. The analyzed microzone covers an area of 5.36 μm × 5.36 μm. The bright areas in the AFM images correspond to the high height region. The image shows that the maximum height of fluctuation is 36.2 nm, which is derived from three tiny dust particles dropped on the surface. The composite film surface is extremely smooth and flat. At the same time, the values of average roughness (Ra) and average square root roughness (R_q) of the composite films are 0.604 and 1.162 nm, respectively. Composite films with low roughness possess significantly reduced surface reflection.

Fig. 4 shows the SEM images of the cross-section of the composite film. Fig. 4(a) presents a typical sandwich structure, in which nanofiber sheets filled with pure resin is trapped between two