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Switchable transparency of dual-controlled smart glass prepared with hydrogel-containing graphene oxide for energy efficiency

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ABSTRACT

In this study, smart glass with the property of auto-adjust transparency was constructed to economize the consumption of energy by screening sunlight irradiation entering a building. Graphene oxide (GO), a photothermal conversion material, when intercalated within a thermotropic hydrogel can effectively convert the photoenergy of sunlight into thermal energy and cause the smart glass to reach an opaque state owing to the increased temperature of the hydrogel heated by solar light, as a result, reducing the incident intensity of solar energy and room temperature. In addition, GO embedded within the thermotropic hydrogel absorbs the colored organic solvent, which provides the smart glass with arbitrary color.

1. Introduction

Energy conservation is crucial for overcoming global warming and reducing the emission of oxocarbon generated by the usage of fossil fuel. To optimize energy consumption in the operation of space cooling and heating systems, building materials with heat insulation and sunlight shielding have received much attention recently [1,2]. Glass with adjustable transparency can effectively shield incident light and lower room temperature, as a result, enhance energy usage efficiency [3]. Several materials have been adopted to modulate the optical transparency of glass in response to external stimuli such as electric field-controlled liquid crystal glazing and electrochromic glass which are based on the use of electrical energy during the “active” switching process [4]. On the other hand, the temperature-driven system was also used to adjust optical transparency by relying on the phase transition of thermotropic materials such as hydrogel [5–7]; thus energy supply from external can be minimized because of the “passive” switching process. In this regard, it would be desirable to have high performance dual-mode stimulating thermotropic materials to replace the monotonous switching system. Therefore, hybrid system, consisting of thermotropic materials and electron-conducting indium–tin oxide glass has been developed, which can be heated by Joule heating through applying a voltage [8,9].

The transparent/opaque transition could be performed both by applying an electric field as well as by controlling temperature; however, if the switching behavior depends on temperature only regardless of the intensity of sunlight, it may cause the system to fail if the temperature is below the switching threshold, in spite of intense of solar irradiation. Thermotropic poly(N-isopropylacrylamide) (PNIPAM) hydrogels, generally be used for thermotropic smart window, are prepared by copolymerization of the monomer N-isopropylacrylamide (NIPAM) and a chemical organic cross-linker such as N, N-methylenebisacrylamide. However, the applications of conventional, chemically cross-linked hydrogels are limited due to their poor mechanical properties and low response rate [10]. Graphene oxide (GO) with photothermal properties has the potential to overcome these drawbacks [11]. Hydrophobic graphene has poor dispersibility in water and carbon nanotubes have negative effect on the polymerization of NIPAM monomer because of their long and narrow structure [12]. Amphiphilic GO, containing oxygenated groups including hydroxyl, carbonyl, carboxyl, and epoxide groups on its surface, is an important building block for synthesizing various functional materials. Recently, in order to improve the mechanical property of temperature responsive PNIPAM hydrogels, GOs were utilized as a filler to manufacture GO/PNIPAM nanocomposite hydrogels by a simple free-radical polymerization method. They demonstrated reversible switching of phase transition upon exposure to near infrared light [13,14].

In this study, GO used as a bridge to crosslink the polymer by grafting PNIPAM chain onto the GO surfaces directly via in situ free-radical polymerization [15]. The hybrid materials loaded in the interspace between two glasses demonstrated reversible phase transition upon exposure to sunlight irradiation, providing a switchable trans-

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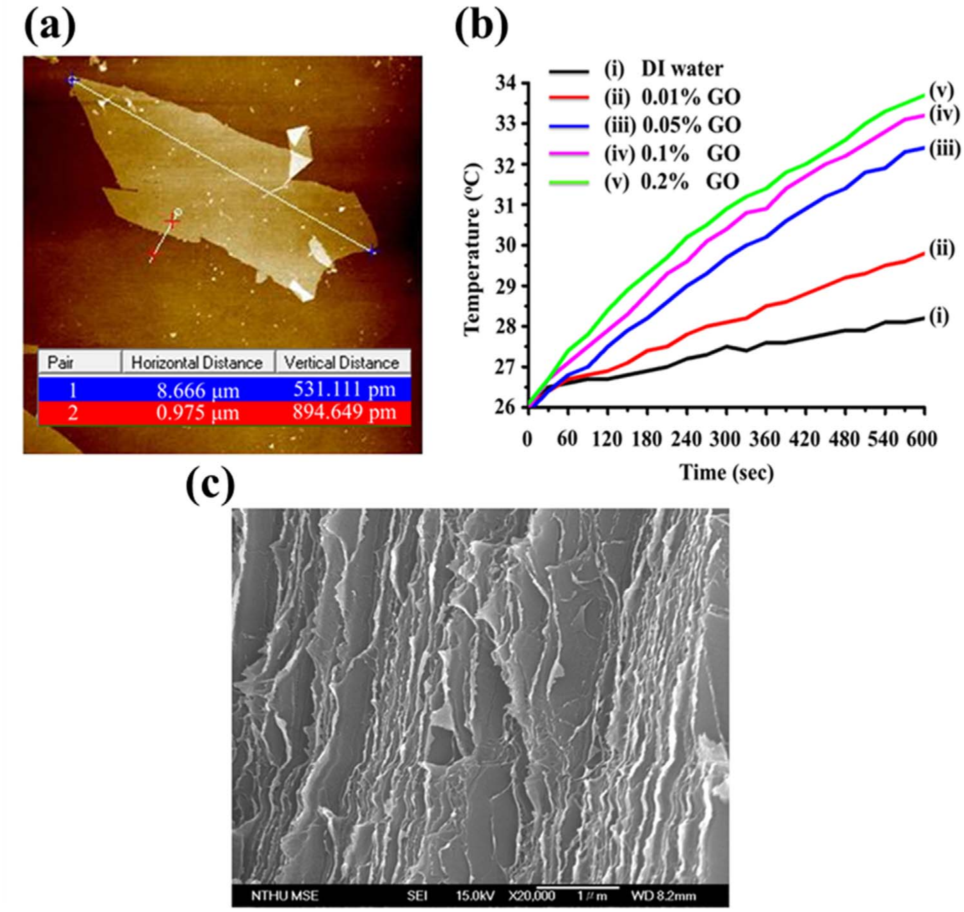

Fig. 1. Characterization of nanomaterials used in this study. (a) AFM image of GO for height and topology measurement. (b) Temperature changes of pure water and different concentrations of aqueous GO under irradiation (c) FESEM images of GO/PNIPAM.

parent/opaque property of the glass. Glass with adjustable transparency can moderate sunlight irradiation and indoor temperature. This material can be used in windows for green buildings, greenhouses, and large displays, especially located in low temperature environment but with high sunlight irradiation. Besides, to the best of our knowledge, very few article deals with colored hydrogel, however, our study could be the first work for incorporating GO, hydrogel and dye to prepare colored hydrogel with excellent sunlight shielding effects.

2. Experimental

2.1. Reagents and materials

Graphene oxide was prepared by the modified Hummers method. N-isopropylacrylamide (NIPAm), potassium persulfate (KPS), and sodium sulfite (Na_2SO_3) were purchased from TCI (Nihonbashihoncho, Chuo-ku, Japan), J.T. Baker (Philipsburg, USA), and SHOWA Chemical Industry CO. (Tokyo, Japan), respectively.

2.2. Preparation of colored GO/PNIPAM hydrogel

The thermotropic hydrogel possessing photothermal phenomenon was prepared by entrapping the GO sheet within the PNIPAM hydrogel after polymerization. Briefly, a specific amount of KPS was mixed and stirred with 20 mL of aqueous GO solution for 30 min. This was followed by the addition of NIPAM monomer to the mixed solution and subsequent degassing the reaction system. Free-radical polymerization was initiated by adding Na_2SO_3 solution to the reaction system, and the gel-like product was collected after 24 h. The final product was washed with water and centrifuged three times. The topology of GO and GO-PNIPAM was examined using an atomic force microscope (AFM, Veeco Nanoscope 3100, Japan) and a field-emission scanning electron microscope (SEM, JSM-6500, JEOL, Japan). To investigate the temperature raising of the aqueous GO when subjected to sunlight, a test relating to photothermal phenomenon was conducted after the temperature of aqueous GO reached equilibrium with the environment temperature of 26 °C.

Since GO is a promising material for absorbing dye, colored GO/PNIPAM hydrogels were prepared [16,17]. In short, an adequate amount of GO was mixed and stirred with colored organic solvent, such as bromocresol green, Congo red, and methylene blue. To remove unbinding dye, colored GO was washed and collected for later use.

2.3. Construction of smart glass and analysis of its optical property

Smart glass was fabricated by arranging two paralleled glass panels, separated by spacers made of polydimethylsiloxane (PDMS) with a thickness of 200 µm [8]. The space between two glass panels was loaded with thermotropic hydrogels through an opening with the assistance of an insulin syringe. Finally, the open edge was sealed with PDMS and silicone to prevent water evaporation. The transmittance of the smart glass as a function of temperature was measured using a UV–vis spectrometer (Hitachi U-3010, Japan).

2.4. Cooling capability of the hydrogel glass

To compare the cooling capability and sunlight shielding ability of a hydrogel glass, polystyrene foam incorporating with PNIPAM glass, GO-PNIPAM glass, or commercial glass to construct model houses. During the test, the glass was placed under a halogen lamp