



Fabrication of carbon foams with high mechanical properties derived from sucrose/polyacrylamide hydrogel



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ABSTRACT

The physical foaming and gel casting techniques are combined to fabricate carbon foams with high mechanical properties, which is based on the interaction of the three-dimensional polymer networks by using sucrose/polyacrylamide hydrogel as the carbon precursor. After the thermal polymerization and carbonization, a high carbon yield (94.96% of the theoretical value) of carbon foams is attributed to the high cross-linking degree of sucrose/polyacrylamide hydrogel. Besides, anionic surfactant sodium dodecyl sulfate (SDS) is utilized to enhance the foaming ability. The well-defined cell structures of carbon foams are easily controlled by adjusting the contents of sucrose and SDS. The density of carbon foams is regulated in the range of 0.17–0.93 g/cm³, whereas the compressive strength is in the range of 3.0–108.0 MPa. Carbon foams prepared by this method showed a fracture-dominated mechanical behavior and are purely brittle. Furthermore, energy as high as 23.52 MJ·m⁻³ can be absorbed when compressed.

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1. Introduction

Carbon foams have excellent properties such as low density, adjustable thermal properties, tunable pore structure and good electronic conductivity [1–7]. Thus, they are attractive candidates for industrial adsorption, capacitors and electrodes, thermal insulation and heat management systems. The structure and properties of carbon foams are mainly controlled by selecting the suitable raw materials and foaming methods [7].

Nowadays, the preparation of carbon foams from renewable organic molecule attracts more attention for the depletion of the fossil fuel based carbon precursors [8–17]. As a representative water-solubility carbohydrate, sucrose has been identified as one of the most suitable carbon precursors due to its availability and high carbon content [11]. Prepared by the carbonization of sucrose, carbon foams show a low density and well-defined pore structure [11–17]. Recently, more works have been carried out to enhance the properties of carbon foams by optimizing foaming method or using additives [11–16]. The template method has been applied to synthesize sucrose-based carbon foams with ultralow density (0.04–0.075 g/cm³) [12]. But, these carbon foams were provided with low carbon yield, leading to low compressive strength (0.11–0.23 MPa). On the other hand, the team of R. Narasimman and K. Prabhakaran used boric acid to increase the carbon yield (24–39 wt.%) by the formation of the B–O–C cross-links [15]. Even

with the similar carbon yield, the compressive strength (1.1 MPa) was much lower than that of lignin-based carbon foams (12 MPa) [9]. It is indicated that the high cross-linking degree among the polymer chains is beneficial for improving the mechanical properties. Additionally, H. Ji et al. expected to improve the mechanical properties of carbon foams by adding Kaolinite [16]. But the cracks surrounding the voids, induced by the large shrinkage during carbonization, result in an unsatisfactory mechanical strength (0.08–0.21 MPa). Obviously, the application of sucrose-based carbon foams is greatly limited by the low mechanical strength due to the cracks, the low carbon yield and cross-linking degree. Consequently, it is necessary to explore a production method to overcome the disadvantages of the known techniques.

As known in gel-casting technique, polyacrylamide hydrogel has been widely applied for manufacturing high-quality materials with homogeneous microstructure [18–21]. In our process, polyacrylamide hydrogel was used as a structure-directing agent to absorb sucrose solution into the three-dimensional polymer structure. After the dehydration and thermal polymerization, this firm sucrose/polyacrylamide hydrogel matrix was polymerized into a high cross-linking degree and reacted without destroying the three-dimensional polymer network, resulting in higher carbon yield and less cracks. Besides, if we immobilized uniform bubbles into the three-dimensional polymer network, an interesting product with large porosity would be obtained. Herein, uniform bubbles were introduced by stirring the solution before the controlled catalytic polymerization of polyacrylamide hydrogel, the so-called physical foaming process. To enhance the foaming ability of this physical foaming process, the anionic surfactant sodium dodecyl sulfate (SDS) was also added for its low critical micelle concentration (CMC) (8.3×10^{-3} mol/l at 25 °C) [22,23].

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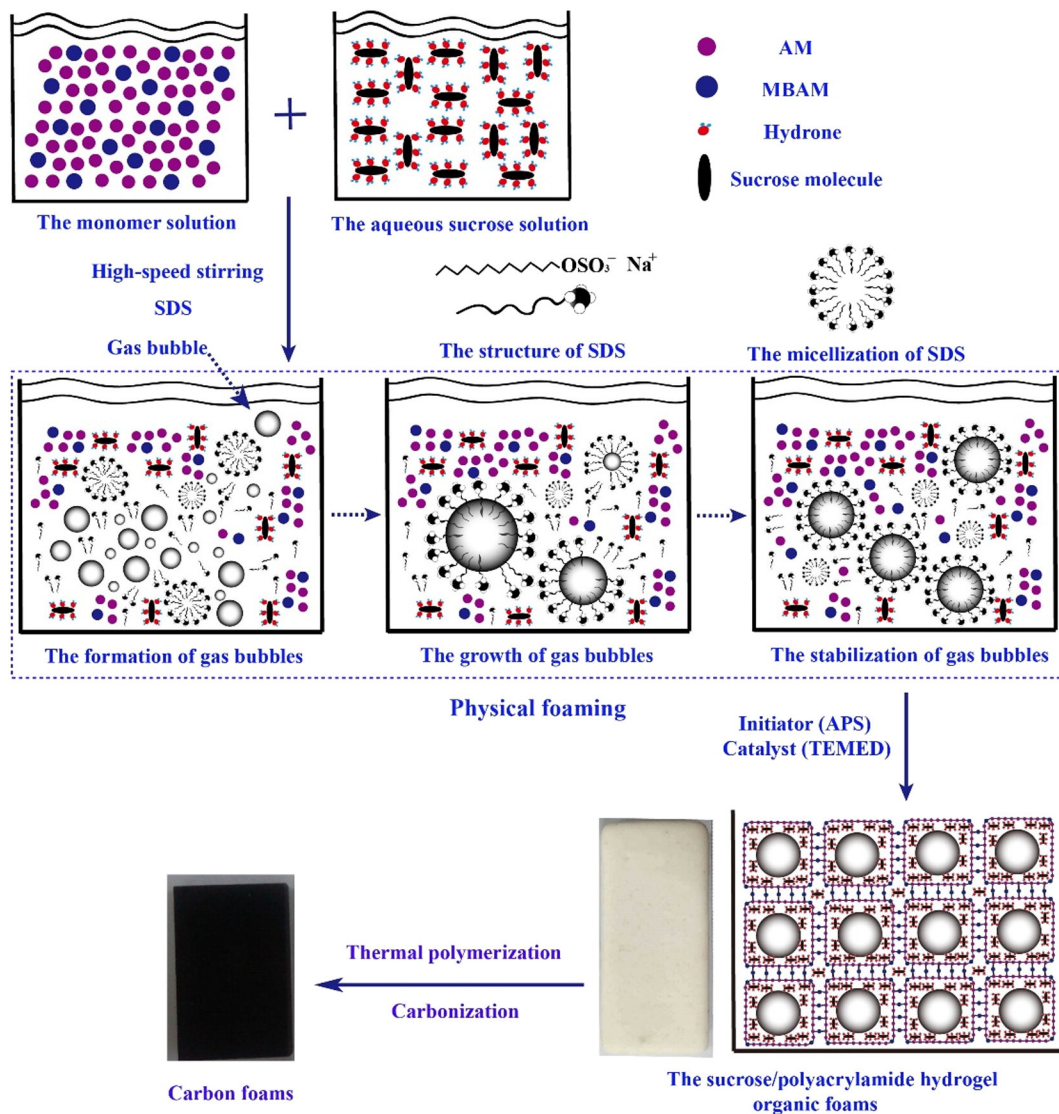


Fig. 1. Schematic representation of the procedure to prepare carbon foams.

This paper aims to synthesize low-density carbon foams with high mechanical properties by using sucrose/polyacrylamide hydrogel as carbon precursor. By adding SDS as foaming agent, carbon foams with uniform cell structure can be obtained. To our knowledge, this is the first example to show that carbon foams with controlled properties can be derived directly from sucrose/polyacrylamide hydrogel and modified by SDS.

2. Experimental

2.1. Foam preparation

2.1.1. Materials

As the carbon precursor, sucrose (Sinopharm Chemical Reagent Co., Ltd) was chemically pure. Acrylamide (AM), *N,N'*-methylene bisacrylamide (NMBA), *N,N,N',N'*-tetramethyl ethylenediamine (TEMED) and ammonium persulfate (APS) were obtained from Sinopharm Chemical Reagent company to prepare polyacrylamide hydrogel, which was also already described in several papers using the gel-casting technique [20]. The anionic surfactant sodium dodecyl sulfate (SDS, Sinopharm Chemical Reagent Co., Ltd) was added to

enhance the foaming ability, resulting in a well-defined cell structure of carbon foams.

2.1.2. Organic foams

Different contents of sucrose were dissolved in deionized water (15 ml) to form a pre-solution. In the meanwhile, the monomer solution was prepared by mixing AM and NMBA of which the ratio is 9:1 in deionized water. Then, they were mixed under an ultrasonic dispersion for 20 min. After that, different contents of SDS were added into the solution with high-speed. Until the stabilization of foams in the solution, the initiator (APS) and catalyst (TEMED) were added slowly into the foaming solution with low-speed continuous stirring. This foaming solution was casted into molds for the initial gelation. The monomers in the system were polymerized and cross-linked to form the firm sucrose/polyacrylamide hydrogel organic foams.

2.1.3. Carbon foams

In order to prevent the deformation and cracks during the heat treatment, the organic foams were dried in air atmosphere in the draught drying cabinet at 30 °C for 24 h. After that, all samples were annealed by the thermal polymerization and carbonization process: the sucrose/polyacrylamide hydrogel was thermal polymerized in air atmosphere

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