Preparation of monodisperse silica-polyacrylamide hybrid particles with snowman or core-shell morphologies using a microfluidic device

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ABSTRACT

Hybrid particles composed of organic and inorganic parts offer unique properties owing to their physical and chemical constitution and are desirable in different applications, such as drug delivery, cosmetics, sensors, optics, and electronics. In this study, microfluidics-based preparation of monodisperse silica-polyacrylamide (PAAM) hydrogel hybrid particles with snowman or core-shell morphologies is reported. Monodisperse droplets of sodium silicate solution (water glass) were prepared using a microfluidic device, and an aqueous solution of sodium hydrogen carbonate (NaHCO₃) and acrylamide (AAM) was transferred to the droplets. The reaction between sodium silicate and NaHCO₃ created separate silica-rich and AAM-rich phases, forming snowman or core-shell structures, depending on the AAM concentration. These morphologies were fixed via photopolymerization of AAM. Moreover, when dispersed into an aqueous ethanol solution, the size of the PAAM hydrogel part could be easily tuned by varying the ethanol concentration.

1. Introduction

Organic-inorganic hybrid particles share the advantages of both materials, complement each other, and produce synergistic effects of the components. They exhibit unique properties owing to their morphology and the combination of constituents. For instance, snowman-shaped hybrid particles consisting of hydrophilic silica and hydrophobic polystyrene particles have anisotropic properties and function as solid surfactants that offer more effective stabilization compared to traditional surfactants [1–4]. Core-shell particles, in which the solid core is coated or encapsulated with shell material, exhibit enhanced stability, dispersibility, and controlled release of the core material [5–8]. When smart materials [9,10], which change their behavior systematically as a response to a specific stimulus, are used as the components, hybrid particles with on-demand tunable properties can be obtained. In particular, smart hydrogels are the most promising because their chemical and physical properties and release mechanisms can be controlled through volume change using an external stimulus, such as pH, temperature, and solvent [11–14]. So far, organic-inorganic hybrid particles with different morphologies have been prepared using different methods. Particularly, snowman-shaped particles have been prepared via seeded emulsion [15,16], phase separation [17,18], and self-assembly [19]. Core-shell particles can be prepared via graft polymerization [14,20], sol-gel [21,22], layer-by-layer assembly [23,24], and phase separation [25]. Recently, some excellent methods have been reported to prepare silica-poly styrene hybrid particles with different morphologies in the same system [26,27]. However, to the best of our knowledge, there have been no reports on the preparation of monodisperse organic-inorganic hybrid particles consisting of smart hydrogel particles in the same system. Such particles could be highly valuable in various fields, including pharmaceuticals, cosmetics, and materials science and engineering.

In this study, we report a microfluidic device-based method to prepare monodisperse snowman-shaped or core-shell hybrid particles consisting of silica and polyacrylamide (PAAM) hydrogel particles in the same system. The microfluidic device, which consists of micron-scale flow channels, can produce monodisperse droplets with a controlled size by adjusting the flow rates and dimensions of the flow channels [28–30]. Monodisperse droplets of sodium silicate solution (water glass) were prepared using the device, and an aqueous solution of sodium hydrogen carbonate (NaHCO₃) and acrylamide (AAM) was transferred to the droplets through the reverse micelle mechanism. It was found that after the reaction of sodium silicate with NaHCO₃, separate silica-rich and AAM-rich phases were generated and the morphology changed to snowman or core-shell shapes, depending on the concentration of AAM added in the middle of the process. The AAM was further photopolymerized to yield monodisperse silica-PAAM hydrogel hybrid particles.
with snowman or core-shell morphologies. Moreover, the size of the PAAM hydrogel part could be controlled by varying the ethanol concentration. The proposed method potentially contributes to the progress in drug delivery, cosmetics, and materials science and engineering.

2. Materials and methods

2.1. Fabrication of the microfluidic device

To fabricate the flow-focusing microfluidic device (39-42) (Figure 1), a round glass capillary tube (outer diameter: 0.9 mm, inner diameter: 0.5 mm, Sanaryo Co. Ltd.) was tapered using a micropipette puller (P-1001VF, Sutter Instrument Co.), and the tip inner diameter was adjusted to 200 µm using a microforge (MF-900, Narishige) and abrasive paper (#2000, Sankyo Rikagaku Co. Ltd.). To prevent the wetting of the inner wall of the capillary by the water phase, water repellent treatment was applied by passing a fluorinated silane coupling agent (triethoxy-1H,1H,2H,2H-tridecafluoro-n-octylsilane, Tokyo Chemical Industry Co. Ltd.) through the capillary and heating at 60°C on a hot plate for 6 h. The round capillary tube was then inserted into a square glass capillary (inner diameter: 1.0 mm, wall thickness: 0.20 mm, VitroCom), and adhered to a glass slide using epoxy resin. Plastic needles, which served as inlets of the water and oil phases, were placed on both ends of the square capillary and glued.

2.2. Preparation of monodisperse silica-PAAM hybrid particles

An aqueous solution of water glass (3 M, sodium silicate solution (No. 3), Kishida Chemical Co. Ltd.) was used as the water phase. Silicone oil (KF-96-50CS, Shin-Etsu Chemical Co. Ltd.) containing surfactant (2 wt.%, DOWSIL RSN-0749, Dow Inc.) was used as the oil phase. Both phases were filled into separate syringes and infused into the device via polyethylene tubing using syringe pumps (KDS-100, KD Scientific Inc.). The formation of monodisperse droplets of sodium silicate solution was monitored using a charge-coupled device (CCD) camera (XCD-V60CR, Sony) attached to an inverted optical microscope (CKX41, Olympus Corporation).

An aqueous solution (3 mL) of NaHCO₃ (1 M), AAM (2–9 M, Sigma-Aldrich), and N,N'-methylenebis(acrylamide) (BIS, 0.1 M, Sigma-Aldrich) was placed in a glass tube bottle. Silicone oil (1 mL) containing surfactant (2 wt.%) and photoinitiator (0.2 wt.%, DAROCUR 1173, BASF) was placed on top of the aqueous solution in the bottle. The obtained monodisperse droplets of sodium silicate solution accompanying silicone oil were directed to the oil phase in the bottle. The aqueous solution containing NaHCO₃, AAM, and BIS diffused across the oil phase to the droplets via the reverse micelle mechanism [43] forming reverse micelles with the aqueous solution entraped in the cores. After the chemical reaction of sodium silicate with NaHCO₃, changes in the morphology of droplets were observed. Afterward, the droplets along with the oil phase were transferred to a glass container with a quartz glass cover and irradiated with ultraviolet (UV) light (SUV-16, AS ONE) for 2 h to photopolymerize. The obtained particles were washed with silicone oil (KF-96L-0.65CS, Shin–Etsu Chemical Co. Ltd.) three times, dried, and then immersed in aqueous ethanol solutions with different ethanol concentrations. At all stages, the changes in the morphology and size were observed using the inverted optical microscope.

3. Results and discussion

The microscopy image in Figure 2(a) shows the formation of monodisperse droplets of sodium silicate solution in the microfluidic device when the water and oil phases were infused at flow rates of 1.0 mL/h and 3.2 mL/h, respectively. The outer oil phase flow hydrodynamically focused the inner water phase flow, causing its breakup at the orifice of the inner capillary and generating the droplets periodically. Highly

![Figure 1. Schematic diagram of the process for the preparation of monodisperse silica-PAAM hydrogel hybrid particles with snowman or core-shell morphologies.](image-url)
monodisperse droplets had an average diameter of 167 µm and a coefficient of variation (CV) value of 1.4%, as shown in Figure 2(b).

After transferring the aqueous solution containing \( \text{NaHCO}_3 \), AAM, and BIS to the droplets via the reverse micelles, sodium silicate reacted with \( \text{NaHCO}_3 \) to form two types of phase separation on the basis of the AAM concentration. The snowman and core-cell structures were formed at low and high AAM concentrations, respectively (Figure 3). At an AAM concentration of 2 M, the AAM-rich droplet protruded from the silica-rich droplet at an elapsed time of 15 min, resulting in a snowman structure (Figure 3(a)). The average diameter of the AAM-rich droplets was 131 µm, which increased to 186 µm after 48 h. The average diameter of silica-rich droplets was 150 µm after 15 min and remained constant even after 48 h. This indicates that the chemical reaction between sodium silicate and \( \text{NaHCO}_3 \) was almost complete after 15 min, although the aqueous solution continued to diffuse into the droplet. The snowman structure formed up to an AAM concentration of 4 M. With increasing AAM concentration, the AAM-rich and silica-rich droplets became closer, and the sizes of AAM-rich and silica-rich droplets increased and slightly decreased, respectively (Figure S1). At an AAM concentration of 4 M, the diameter of AAM-rich droplets increased from 150 to 199 µm when the elapsed time increased from 15 min to 48 h, whereas that of silica-rich droplets remained constant at 146 µm (Figure 3(b)). At AAM concentrations between 5 and 7 M, a mixture of snowman and core-shell structures was obtained (Figure 3(c) and Figure S1). While the snowman structures formed after 15 min, core-shell structures, wherein a silica-rich droplet was formed inside an AAM-rich droplet, were observed after 30 min. In both structures, the average diameters of the AAM-rich droplets increased with elapsed time, whereas those of the silica-rich droplets remained constant. When the AAM concentration further increased, the sizes of the AAM-rich and silica-rich droplets tended to increase and decrease, respectively. At AAM concentrations of 8 M and 9 M, only core-shell structures were generated after 30 min, as shown in Figure 3(d) and (e), respectively. At an AAM concentration of 9 M, the average diameters of the outer AAM-rich and inner silica-rich droplets were 160 µm and 128 µm, respectively. The diameter of the AAM-rich droplets increased to 208 µm after 48 h, whereas that of silica-rich droplets remained constant. At lower AAM concentrations (≤ 4 M), the interfacial tension between the AAM-rich and silica-rich droplets was very high causing the AAM-rich droplet to have low wettability to the silica-rich droplet. This resulted in partial wetting and the formation of a snowman.
Figure 3. Microscopy images and diameters of droplets with different AAM concentrations as a function of elapsed time ((a) 2 M, (b) 4 M, (c) 6 M, (d) 8 M, (e) 9 M).
structure. However, as the concentration increased, the interfacial tension decreased and the wettability of the AAM-rich droplet to the silica-rich droplet increased, leading to a complete wetting and a core-shell structure.

Monodisperse silica-PAAM hydrogel hybrid particles with snowman or core-shell structures were prepared by polymerizing the AAM in the droplets under UV light (Figure 4 and Figure S2). At very low AAM concentrations (< 2 M), deformed PAAM particles were obtained. At higher concentrations (≥ 2 M), both morphologies were almost retained. However, the sizes of the AAM-rich droplets in the snowman and core-shell structures decreased by 10% and 2%, respectively, because of the evaporation of water.

The size of the PAAM hydrogel part could be altered by changing the concentration of the swelling solvent, i.e. ethanol. For instance, the snowman-shaped hybrid particles prepared at an AAM concentration of 2 M exhibited significant shrinkage of the PAAM particles with increasing ethanol concentration (Figure 5(a)). The diameter decreased from 149 to 108 μm with increasing ethanol concentration from 0 to 100 wt.%.

The diameter of the silica particles, however, remained almost constant (127 μm). As a result, the head and body of the snowman structure switched to each other above 60 wt.% ethanol concentration. For the snowman-shaped hybrid particles with an AAM concentration of 4 M, a small change in the size of the silica particles was observed, in addition to the significant change in the size of the PAAM particles (Figure 5(b)). This could be due to the migration of a certain amount of AAM and its polymerization in the silica-rich droplets. The core-shell hybrid particles prepared at an AAM concentration of 8 M exhibited significant and slight shrinkages of the PAAM shell and silica core, respectively, with increasing ethanol concentration (Figure 5(c)). For the hybrid particles prepared at an AAM concentration of 9 M, the shell thickness shrank significantly without any change in the size of the silica core (Figure 5(d)).
Figure 5. Microscopy images and diameters of silica-PAAM hybrid particles with different AAM concentrations as a function of ethanol concentration: (a) 2 M, (b) 4 M, (c) 8 M, (d) 9 M.
4. Conclusion

Monodisperse silica-PAAM hybrid particles with snowman or core-shell morphologies were successfully prepared in the same system. Monodisperse droplets of sodium silicate solution were generated using a flow-focusing microfluidic device, and aqueous solutions of NaHCO$_3$ and AAM were transferred to the droplets via the reverse micelle mechanism. The ensuing reaction between sodium silicate and NaHCO$_3$ generated well-separated silica-rich and AAM-rich phases in snowman or core-shell morphologies, depending on the AAM concentration. At AAM concentrations between 2 and 4 M, the AAM-rich droplet protruded from the silica-rich droplet to form a snowman structure. A mixture of snowman and core-shell structures was obtained at AAM concentrations between 5 and 7 M. Only core-shell structures, wherein a silica-rich droplet was formed inside an AAM-rich droplet, were generated at AAM concentrations of 8 M and 9 M. The morphological change from snowman to core-shell was attributed to the decrease in the interfacial tension between AAM-rich droplets and silica-rich droplets when the AAM concentration was increased. Finally, photopolymerization of AAM was performed to obtain monodisperse silica-PAAM hydrogel hybrid particles with snowman or core-shell morphologies. Due to its sensitivity to ethanol, the size of the PAAM hydrogel part in the particle could be easily altered by changing the ethanol concentration. In particular, for the particle with an AAM concentration of 2 M, the head (PAAM) and body (silica) of the snowman structure switched to each other above 60 wt.% ethanol concentration. The proposed method for the preparation of silica-PAAM hydrogel hybrid particles would be applicable for silica-hydrogel hybrid particles that respond to other stimuli. These smart particles are useful in drug delivery, cosmetics, and materials science and engineering.

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Disclosure statement

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