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ORIGINAL CONTRIBUTION

Preparation and characterization of core-shell polystyrene/polychloromethylstyrene and hollow polychloromethylstyrene micrometer-sized particles of narrow-size distribution

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Abstract Polystyrene core microspheres of narrow-size distribution were prepared by dispersion polymerization of styrene in a mixture of ethanol and 2-methoxy ethanol. Polystyrene/polychloromethylstyrene and polystyrene/poly(chloromethylstyrene-divinylbenzene) core-shell microspheres of narrow-size distribution were prepared by seeded emulsion polymerization of chloromethylstyrene or chloromethylstyrene and divinylbenzene in the presence of the polystyrene core microspheres at 71 °C. Core-shell particles with different properties (size, surface morphology, and composition) have been prepared by changing various parameters belonging to the emulsion polymerization process, e.g., volume of the chloromethylstyrene and the volume ratio of chloromethylstyrene to divinylbenzene. Dissolution of the polystyrene core of the polystyrene/poly(chloromethylstyrene-divinylbenzene) core-shell particles resulted in the formation of crosslinked hollow polychloromethylstyrene microspheres, broken crosslinked polychloromethylstyrene shells, or particles containing voids, depending on the composition of the polystyrene/poly(chloromethylstyrene-divinylbenzene) particles.

Keywords Polystyrene microspheres · Polychloromethylstyrene microspheres · Core-shell particles · Hollow microspheres · Emulsion polymerization

Introduction

Micrometer-sized particles of narrow-size distribution have attracted much attention in many applications such as adsorbents for high-pressure liquid chromatography, calibration standards, spacers for liquid crystals, inks, catalysis, etc. [1–7], of particular interest are micrometer-sized particles containing functional groups such as aldehydes, chloromethyls, oxiranes, hydroxyls, etc. These functional groups have been used for the covalent binding, via various activation methods, of bioactive reagents such as proteins, enzymes, antibodies, oligonucleotides, etc. [1, 2, 7]. The bioactive-conjugated particles were then used for various biomedical applications such as specific cell labeling and separation, diagnostics, enzyme immobilization, chromatography, etc. [1, 2, 7].

Dispersion polymerization is the common method for preparing uniform non-porous micrometer-sized particles in a single step [8–13]. However, the particles formed by this method possess specific properties, e.g., surface morphology and functionality, which can barely be manipulated [8, 9]. Furthermore, uniform particles of a diameter larger than 5 μm usually cannot be prepared by dispersion polymerization. These limitations have been overcome by several swelling methods of micrometer-sized polystyrene (PS) particles with appropriate hydrophobic vinylic monomers and initiators, e.g., multi-step swelling [14–20], dynamic swelling [21, 22], and a single-step swelling [23–27].

Core-shell materials consist of a core structural domain covered by a shell domain. The core and shell domains may be composed of a variety of materials, including polymers, inorganic solids, and metals. Core-shell materials are typically spherical in shape, although other shapes are also possible. Core-shell nano- and micrometer-sized particles

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with different interesting morphologies have been the subject of numerous investigations, largely due to the applicability of such materials in the areas of coating, catalysis, and diagnostics [28–32]. Techniques for the preparation of core-shell materials on both nanometer and micrometer scales include intramicellar polymerization [33, 34], template-directed living polymerization [35, 36], and one- [37, 38] or two-step [38–40] emulsion polymerization processes. Core-shell particles serve as the precursors to hollow structures, lowering particle density, or to save the use of precious materials by protecting them with inexpensive cores [41]. In recent years, there has been intense interest in the preparation and applications of nano- and micrometer-sized hollow spheres. The hollow particles are exceptionally promising materials in diverse fields of technology, including catalysis, drug delivery, photonics, biotechnology, and electrochemical cells [42–50]. The most studied procedure for the preparation of the hollow particles involved the synthesis of core/shell composite particles and the subsequent removal of the template core by selective dissolution in an appropriate solvent or by calcination at an elevated temperature.

The present manuscript describes in details the preparation of polystyrene/polychloromethylstyrene, PS/PCMS, and polystyrene/poly(chloromethylstyrene-divinylbenzene), PS/P(CMS–DVB), and core-shell micrometer-sized particles of narrow-size distribution. These core-shell particles have been prepared by seeded emulsion polymerization of chloromethylstyrene (CMS) or CMS and divinylbenzene (DVB) in the presence of uniform PS microspheres at 71 °C. During the synthesis of these particles, various parameters such as the volume of the CMS and the volume ratio of CMS to DVB was varied. Dissolution of the PS core of the optimized PS/P(CMS–DVB) core-shell particles resulted in the formation of crosslinked hollow PCMS microspheres.

Experimental

Chemicals

The following analytical-grade chemicals were purchased from Aldrich and used without further purification: benzoyl peroxide (BP, 98%), potassium persulphate (PPS, 99%), sodium dodecyl sulfate (SDS), polyvinylpyrrolidone (PVP, m.w. 360,000), 2-methoxy ethanol (HPLC), ethanol (HPLC), dry toluene (HPLC), dry tetrahydrofuran (THF, 99.9%), CMS (97%), and DVB (80%). Styrene (99%) was passed through activated alumina (ICN) to remove inhibitors before use. Water was purified by passing deionized water through an Elgastat Spectrum reverse osmosis system (Elga, High Wycombe, UK).

Synthesis of uniform PS core microspheres

PS core microspheres of narrow-size distribution were prepared according to the literature [9, 10]. Briefly, in a typical experiment, PS microspheres of 3.1±0.1 μm hydrodynamic diameter were formed by introducing into the reaction flask (a three-neck 1-L round-bottom flask is equipped with a condenser and a mechanical stirrer and immersed in a constant temperature silicone oil bath at a preset temperature) a solution containing PVP (3.75 g) dissolved in a mixture of ethanol (150 mL) and 2-methoxy ethanol (62.5 mL). The temperature of the mechanically stirred solution (200 rpm) was then preset to 73 °C. Nitrogen was bubbled through the solution for ca. 15 min to exclude air, after which a blanket of nitrogen was maintained over the solution during the polymerization period. A deaerated solution containing the initiator BP (1.5 g, 6.2 mmol) and styrene (37.5 mL, 327.3 mmol) was then added to the reaction flask. The polymerization reaction continued for 24 h and was then stopped by cooling to room temperature. The microspheres formed were washed from excess reagents by extensive centrifugation cycles with ethanol and water and then dried by lyophilization.

Synthesis of uniform PS/PCMS core-shell microspheres

In a typical experiment, PS/PCMS microspheres of 4.9±0.2 μm hydrodynamic diameter were prepared by adding 0.6 mL of CMS, 12 mg of PPS, and 0.2 g of SDS in 8 mL of water to 2 mL of an aqueous dispersion of the PS microspheres (150 mg) of 3.1±0.1 μm. The mixture was then shaken under N_2 atmosphere at room temperature for 5 min and then at 71 °C for 80 min. The resulting core-shell particles were washed of the excess reagents (e.g., CMS, PPS, SDS, and non-grafted PCMS nanoparticles of 28±4 nm hydrodynamic diameter produced in the aqueous continuous phase) by extensive centrifugation cycles with water and ethanol and then dried by lyophilization. PS/PCMS core-shell microspheres of various properties were prepared by changing the CMS volume. Table 1 summarizes the various recipes used for the preparation of the PS/PCMS core-shell microspheres.

Synthesis of uniform PS/P(CMS–DVB) core-shell microspheres

Uniform PS/P(CMS–DVB) core-shell microspheres were prepared by a procedure similar to that described in the previous paragraph, substituting the CMS for a mixture of CMS and DVB. In a typical experiment, PS/P(CMS–DVB) core-shell microspheres of 4.4±0.2 μm hydrodynamic diameter were prepared by polymerization of 0.59 mL of

Table 1 Recipes used for the synthesis of the uniform PS/PCMS core-shell microshperes

Ingredients		No. 1	No. 2	No. 3	No. 4	No. 5
PS microspheres	mg	150	150	150	150	150
PPS	mg	12	12	12	12	12
SDS	mg	200	200	200	200	200
H_2O	mL	10	10	10	10	10
CMS	mL	0.1	0.2	0.4	0.6	0.8

PS/PCMS core-shell microshperes were prepared by seeded emulsion polymerization of different volumes of CMS in the presence of PS microshperes of 3.1±0.1 µm hydrodynamic diameter dispersed in aqueous continuous phase, according to the description in the "Experimental" section

CMS and 0.01 mL of the crosslinker monomer DVB (total monomer volume of 0.6 mL) in the presence of the PS microspheres (150 mg) of 3.1±0.1 µm, according to the former procedure. The core-shell microspheres formed were washed by extensive centrifugation cycles with water and ethanol and then dried by lyophilization. PS/P(CMS–DVB) core-shell microspheres of various properties were prepared by changing the monomers' (CMS and DVB) volume ratio while maintaining the total monomer volume constant, e.g., 0.6 or 0.2 or 0.1 mL. Table 2 summarizes the various recipes used for the preparation of the PS/P(CMS–DVB) core-shell microspheres.

Preparation of uniform crosslinked PCMS hollow microspheres

Uniform P(CMS–DVB) hollow microspheres were prepared by the dissolution of the PS core of the PS/P(CMS–DVB) core-shell microspheres prepared by the polymerization of 0.16 mL CMS and 0.04 mL DVB (total monomer volume of 0.2 mL) in the presence of the PS core microspheres, according to the description in the former paragraph. In a typical experiment, 50 mg of the dried PS/P(CMS–DVB) core-shell microspheres was dispersed in 20 mL of dry toluene. The mixture was then shaken at room temperature for a few hours. The obtained soluble PS toluene solution was then removed from the remaining hollow crosslinked PCMS microspheres by centrifugation. These microspheres were then redispersed in toluene, and the former procedure was repeated. This process, related to the extraction of the soluble PS from the crosslinked PCMS hollow microspheres, was repeated several times, until the extracted toluene solution was free of residual PS. This was confirmed by obtaining a transparent solution after transferring 1 mL of the toluene solution to 20 mL of ethanol. The remaining crosslinked hollow PCMS particles were then washed several times by centrifugation cycles with dry THF, ethanol, and water and then dried by lyophilization. Table 3 summarizes the various recipes used for the preparation of the P(CMS–DVB) hollow microspheres.

Characterization of the microspheres

Optical microscope pictures were used for measuring the hydrodynamic size and size distribution of the microspheres dispersed in aqueous continuous phase. This was obtained with an Olympus microscope, model BX51, by measuring the hydrodynamic diameter of more than 100 particles on optical micrographs with image analysis software from AnalySIS Auto (Soft Imaging System GmbH, Germany).

Fourier transform infrared (FTIR) analysis was used for obtaining information on the composition of the particles. The FTIR was performed with a Bomem FTIR spectrophotometer, model MB100, Hartman & Braun. The analysis was performed with 13 mm KBr pellets that contained 2 mg of the detected material and 198 mg of KBr. The pellets were scanned over 200 scans at a 4 cm^{-1} resolution.

Surface morphology and dry size and size distribution of the dry microspheres were characterized with a FEI scanning electron microscope (SEM) Model Inspect S. For this purpose, a drop of dilute microsphere dispersion in water was spread on a glass surface and then dried at room temperature. The dried sample was coated with gold in vacuum before viewing under SEM. The dry particles' average size and size distribution were determined by measuring the diameter of more than 100 particles with image analysis software from AnalySIS Auto (Soft Imaging System GmbH, Germany).

Transmission electron microscope (TEM) pictures were also used for particle morphology investigation. This was obtained with a JEOL-JEM 100SX electron microscope with 80–100 kV accelerating voltage. Samples for TEM

Table 2 Recipes used for the synthesis of uniform PS/P(CMS–DVB) core-shell microshperes

Ingredients		No. 1	No. 2	No. 3
		[CMS]/[DVB] (mL/mL)		
		49.0	15.6	4.0
PS microspheres	mg	150	150	150
PPS	mg	12	12	12
SDS	mg	200	200	200
H_2O	mL	10	10	10
CMS	mL	0.59	0.564	0.48
DVB	mL	0.012	0.036	0.12

The PS/P(CMS–DVB) core-shell microspheres were prepared by seeded emulsion polymerization of 0.6 mL monomers (CMS and DVB) in the presence of PS microshperes of 3.1±0.1 µm hydrodynamic diameter at different volume ratios of [CMS]/[DVB], according to the description in the "Experimental" section

Table 3 Recipes applied for the synthesis of the uniform PS/P(CMS–DVB) particles used for the preparation of the hollow crosslinked PCMS microspheres

Ingredients		No. 1	No. 2	No. 3
		[CMS]+[DVB] (mL)		
		0.6	0.2	0.1
PS/P(CMS–DVB) microspheres	mg	50	50	50
PPS	mg	12	12	12
SDS	mg	200	200	200
H_2O	mL	10	10	10
CMS	mL	0.48	0.16	0.08
DVB	mL	0.12	0.04	0.02

The uniform crosslinked PS/P(CMS–DVB) microspheres used for the preparation of the crosslinked hollow PCMS microspheres were formed by seeded emulsion polymerization of CMS and DVB in the presence of PS microspheres of 3.1±0.1 μm hydrodynamic diameter at volume ratio [CMS]/[DVB] of 4.0 and total monomers volumes of 0.6, 0.2, and 0.1 mL, according to the description in the "Experimental" section. Hollow crosslinked PCMS microspheres were then prepared by dissolution of the PS part of the PS/P(CMS–DVB), according to the description in the "Experimental" section

were prepared by placing a drop of the diluted sample on a 400-mesh carbon-coated copper grid.

Electrokinetic properties (ξ-potential) as a function of pH were determined by Zetasizer (3000HSa, Malvern Instruments, UK). The measurements were performed by determining the ξ-potential in 15 different pH points via decreasing the pH from 11.5 to 1.5 by adding HCl 1 M gradually to the microparticles aqueous dispersion.

Elemental analysis of the various particles was performed using an elemental analysis instrument, model EA1110, CE Instruments.

Surface elemental analysis was obtained by X-ray photoelectron spectroscopy (XPS), model AXIS-HS, Kratos Analytical, England, using Al K_α lines, at 10^{-9} Torr, with a take-off angle of 90°. The reported Cl values of the XPS are an average of measurements performed at least

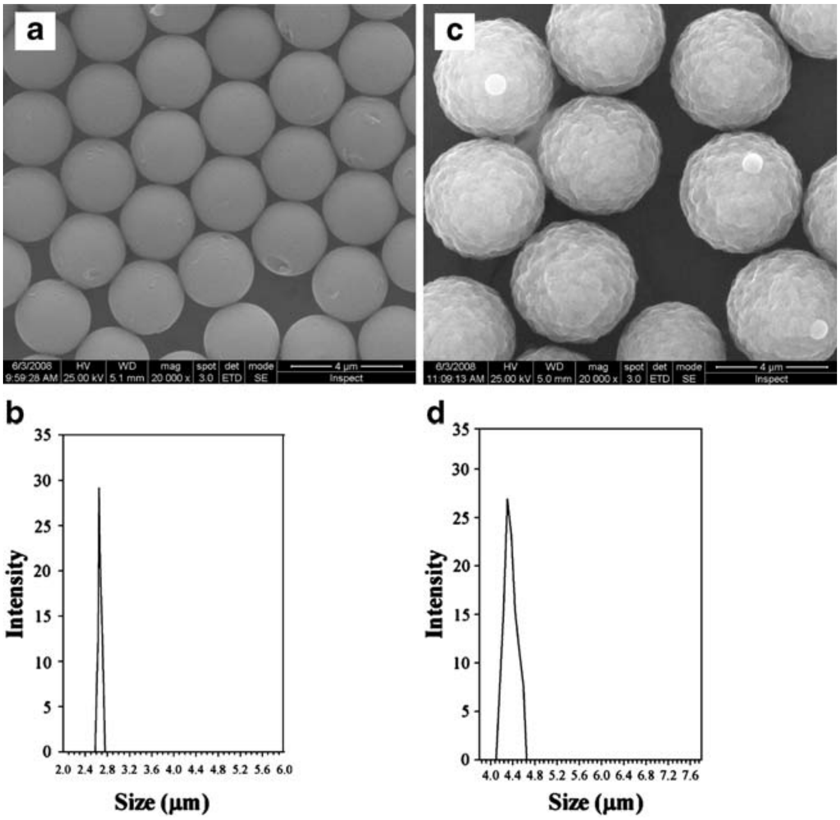

Fig. 1 SEM and size histograms pictures of the PS core microspheres (a and **b**) and the PS/PCMS core-shell microspheres (**c** and **d**). The PS/PCMS core-shell microspheres were prepared by emulsion polymerization of 0.6 mL of CMS in the presence of PS microspheres of 3.1±0.1 μm hydrodynamic diameter dispersed in an aqueous continuous phase, according to the description in the "Experimental" section

four times for each of the tested particles and have a maximum error of about 5%.

Results and discussion

PS/PCMS core-shell microspheres

Figure 1 shows SEM and size histogram pictures of the PS microspheres dispersed in an aqueous continuous phase before (a and b) and after (c and d) the seeded emulsion polymerization of 0.6 mL of CMS, according to the description in the "Experimental" section. Figure 1a and b shows that the measured dry diameter and size distribution of these microspheres are 2.7±0.1 µm. Figure 1c and d demonstrates the increase in the dry particles' diameter from 2.7±0.1 to 4.3±0.2 µm due to the seeded emulsion polymerization of 0.6 mL of CMS in the presence of the PS core particles. The hydrodynamic size and size distribution of the PS and the PS/PCMS microspheres, as measured by the optical microscope, are 3.1±0.1 and 4.9±0.2 µm, respectively. Both measuring methods, SEM and the optical microscope, illustrate good correlation. However, the diameters measured by the optical microscope are always slightly larger than that measured by the SEM. The reason for this difference is due to the fact that the optical microscope measures the diameter of the particles dispersed in the aqueous continuous phase, which takes into account all the "structured" water adsorbed around each particle, while the SEM measures the size of the particles in the dry state. It should be noted that henceforth in order to prevent confusion, only hydrodynamic sizes will be written.

The smooth surface morphology and perfect spherical shape of the PS microspheres are illustrated in Fig. 1a. In contrast to the PS microspheres, the PS/PCMS core-shell microspheres possess "bumpy" surfaces, as shown in Fig. 1b. This bumpy morphology is probably due to the PCMS coating on the smooth surface of the PS microspheres as a consequence of the interaction between surface PCMS oligoradicals and CMS in the aqueous continuous phase. The non-coated PCMS nanoparticles of approximately 28±4 nm, probably produced via emulsion polymerization mechanism, were washed off by centrifugation, as described in the "Experimental" section.

Figure 2 shows the FTIR spectra of the PS microspheres (a) and the PS/PCMS core-shell microspheres (b). The FTIR spectrum of the PS microspheres demonstrates absorption peaks at 1,492 and at 3,000–3,100 cm^{-1} corresponding to the aromatic CH stretching bands, peaks at 2,849 and 2,922 cm^{-1} corresponding to the CH_2 stretching bands, and a peak at 700 cm^{-1} corresponding to the C–C vibration band. The FTIR spectrum of the PS/PCMS core-shell microspheres is similar to that of PS, except for an additional peak at 1,266 cm^{-1} corresponding to the C–Cl stretching band of the PCMS.

Figure 3 illustrates the kinetics of the formation of the PS/PCMS core-shell microspheres formed by seeded emulsion polymerization of 0.6 mL of CMS, as described in the "Experimental" section. Figure 3a illustrates this kinetics by following the hydrodynamic diameter increase of the core-shell particles as a function of time, while Fig. 3b does this by following the increase in the weight percent of the PCMS belonging to the produced PS/PCMS microspheres. The weight percent PCMS belonging to these core-shell microspheres was calculated from the weight percent Cl obtained by elemental analysis. Since PS does not contain Cl, the % Cl was used for calculating the % PCMS of the PS/PCMS core-shell microspheres, according to the following equation: % PCMS=(% Cl×100)/23.3, where % Cl is obtained from the elemental Cl analysis, and 23.3 is the % Cl in pure PCMS.

Figure 3a and b shows that under experimental conditions, most of the CMS seeded emulsion polymerization

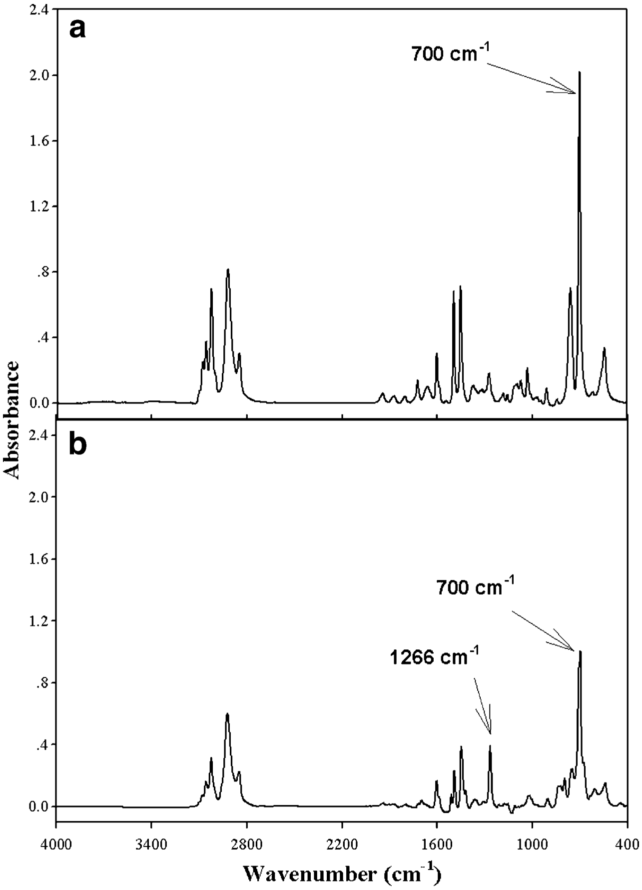

Fig. 2 FTIR spectra of the PS core microspheres (**a**) and the PS/PCMS core-shell microspheres (**b**). The PS/PCMS core-shell microspheres were prepared by emulsion polymerization of 0.6 mL of CMS in the presence of PS microspheres of 3.1±0.1 µm hydrodynamic diameter dispersed in an aqueous continuous phase, according to the description in the "Experimental" section

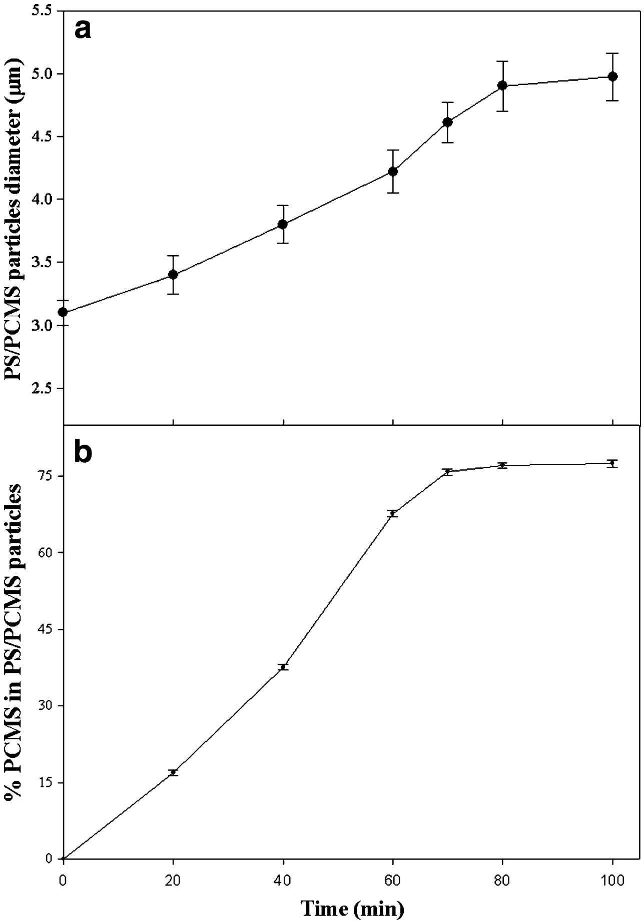

Fig. 3 Kinetics of the CMS (0.6 mL) grafted polymerization, by following the PS/PCMS particles' diameter (**a**) and the weight percent of PCMS in the PS/PCMS particles (**b**), as a function of time. The PS/PCMS core-shell microspheres were prepared by seeded emulsion polymerization of 0.6 mL of CMS in the presence of PS microspheres of 3.1±0.1 μm hydrodynamic diameter dispersed in an aqueous continuous phase, according to the description in the "Experimental" section

was completed within 70–80 min. Figure 3a also illustrates that the core-shell particles more or less preserve their size distribution during the growing process of the particles.

Figure 4 illustrates the ζ-potential as a function of the pH of the PS (A) and the PS/PCMS core-shell microspheres formed by seeded emulsion polymerization of 0.6 mL of CMS, as described in the "Experimental" section (B). This figure illustrates, for both types of particles, an increase in the ζ-potential as the pH of the aqueous dispersions of the particles decreases. This increase in the ζ-potential as the pH rises is mild for the PS microspheres and prominent for the PS/PCMS microspheres. For example, Fig. 4 A shows for the PS core particles an increase of the ζ-potential from −8 to +2.5 eV while changing the pH from 11.0 to 2.5. This change in the surface potential is probably attributed to the PVP coating on the PS surface that was used as a steric stabilizer in the formation of these particles. In an acid environment, the positive surface charge is excepted due to the protonation of the coated PVP, as reported in the literature [51, 52]. Figure 4 B shows for the PS/PCMS microspheres an increase of the ζ-potential from −76.4 to −0.7 eV while changing the pH from 11.0 to 2.5. This change in the surface potential is probably attributed to the negative particles' surface charge over the entire pH range due to the surface sulfate group belonging to the adsorbed SDS. This negative charge of the PS/PCMS particles through the whole pH range from 11.0 to 2.5 is thus indicative of their good electrostatic stability under these conditions [53].

Figures 5 and 1c show SEM photomicrographs of the PS/PCMS core-shell micrometer-sized particles prepared by seeded emulsion polymerization of increasing volumes of CMS (0.1, 0.2, 0.4, 0.6, and 0.8 mL), as described in the "Experimental" section. Figure 5a demonstrates that in the presence of 0.1 mL of CMS, PS/PCMS core-shell microspheres of "raspberry-like" morphology were produced [43]. This morphology can be explained by heterocoagulation of the PCMS nanoparticles formed in the aqueous continuous phase with the PS core particles. In addition to the heterocoagulation process, the rough surface texture may also be explained by the reaction of CMS free molecules grafted onto the PS surface, forming a polymer during the early steps of the polymerization [54]. This polymer will continue to grow until it reaches a critical size and becomes a nucleus. Due to the presence of the surfactant, these nuclei can become steady polymer particles. Some aggregated polymer particles can be observed on the PS particles, as shown in Fig. 5b and c.

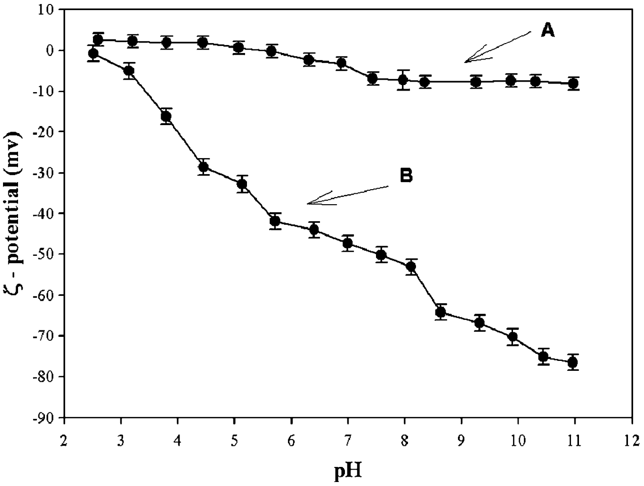

Fig. 4 ζ-Potential of the PS core (*A*) and the PS/PCMS core-shell (*B*) microspheres as a function of pH. The PS/PCMS core-shell microspheres were prepared by seeded emulsion polymerization of 0.6 mL of CMS in the presence of PS microspheres of 3.1±0.1 μm hydrodynamic diameter dispersed in an aqueous continuous phase, according to the description in the "Experimental" section

This aggregation occurs with increasing volumes of the CMS (0.2 and 0.4 mL). As a result of this, the global morphology of the PS/PCMS core-shell microspheres was changed. Figure 1c shows that in the presence of 0.6 mL CMS, the PCMS coating onto the PS core microspheres is rough and bumpy, and the spherical shape was lost, probably due to the significant aggregation of the coated PCMS particles. On the other hand, Fig. 5d shows that in the presence of the highest volume of CMS (0.8 mL), the PS/PCMS core-shell microspheres have a smooth surface morphology. This morphology can be explained by the preference of oligomer formation over the formation of polymeric particles [55]. It is also possible that the smooth surface arises because the PS core particles in the presence of 0.8 mL CMS are significantly more swollen with CMS than in the lower amount of CMS, as will be shown later. Partial agglomeration of the core-shell microspheres was observed in the presence of CMS volumes above 0.8 mL.

Figure 6 illustrates the influence of the CMS volume on the PS/PCMS core-shell microspheres' hydrodynamic diameter (a) and the weight percent of PCMS in the PS/PCMS core-shell microspheres (b). The weight percent of the PCMS belonging to the core-shell microspheres was calculated from the % Cl obtained by elemental analysis, as described previously. Figure 6a clearly demonstrates the increase in the diameter while preserving, more or less, the size distribution of the produced core-shell particles as the CMS volume increases. For example, in the presence of 0.1, 0.2, 0.4, and 0.8 mL CMS, the hydrodynamic diameter of the core PS particles increases from 3.1±0.1 μm to 3.7±0.1, 4.3±0.2, 4.6±0.2, and 5.1±0.2 μm, respectively. Figure 6b indicates a gradual increase in the weight percent of PCMS in the PS/PCMS particles as the CMS volume increases. For example, increasing the volume of CMS from 0.1 to 0.2, 0.4, 0.6, and 0.8 mL resulted in an increase in the weight percent of PCMS in the PS/PCMS core-shell microspheres from 33.1±1.5% to 52.5±1.0%, 69.8±1.4%, 77.7±1.7%, and 81.0±2.1%, respectively.

Table 4 summarizes the surface composition of the PS/PCMS microspheres, i.e., the % surface PCMS and PS fractions, prepared in the presence of increasing volumes of CMS, as calculated from the Cl XPS measurements. The % surface fraction of the PCMS in the PS/PCMS core-shell microspheres was calculated by the following equation:

$$\%\,\text{surface PCMS} = [(\%\,\text{surface Cl}_{\text{PCMS}}) \times 100]/23.3,$$

where % surface Cl was obtained from the XPS data, and as shown in Table 1, 23.3 is the % chlorine in pure PCMS. The % surface PS was calculated by reducing from 100 the % surface PCMS.

Table 4 shows that the % surface PCMS of the PS/PCMS core-shell microspheres prepared by increasing the

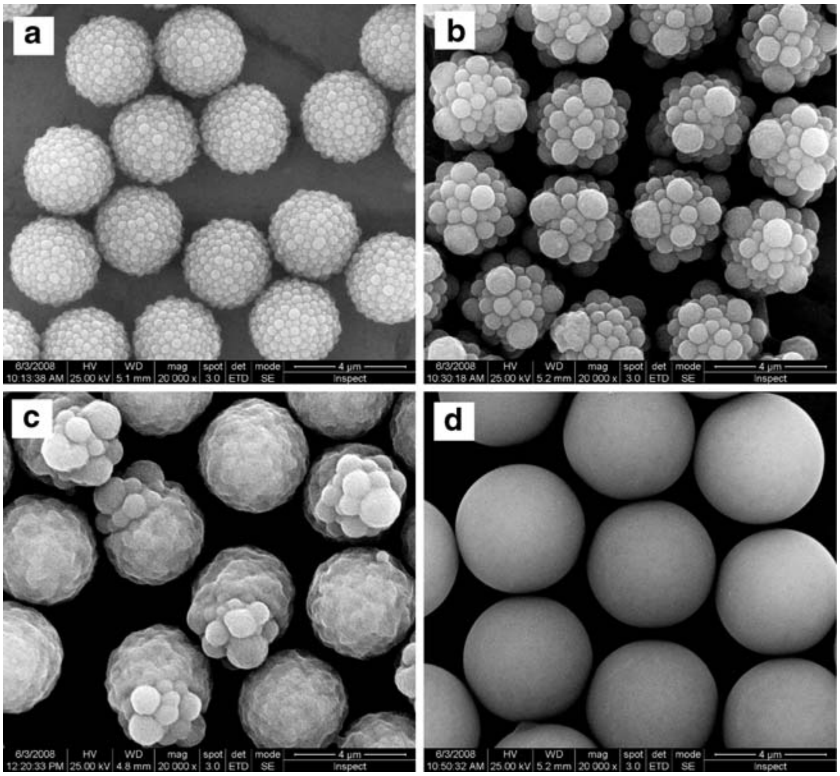

Fig. 5 SEM photomicrographs of the PS/PCMS core-shell microspheres prepared by seeded emulsion polymerization of increasing volumes of CMS, 0.1 (**a**), 0.2 (**b**), 0.4 (**c**), and 0.8 mL (**d**) in the presence of PS microspheres of 3.1±0.1 μm hydrodynamic diameter dispersed in an aqueous continuous phase, according to the description in the "Experimental" section

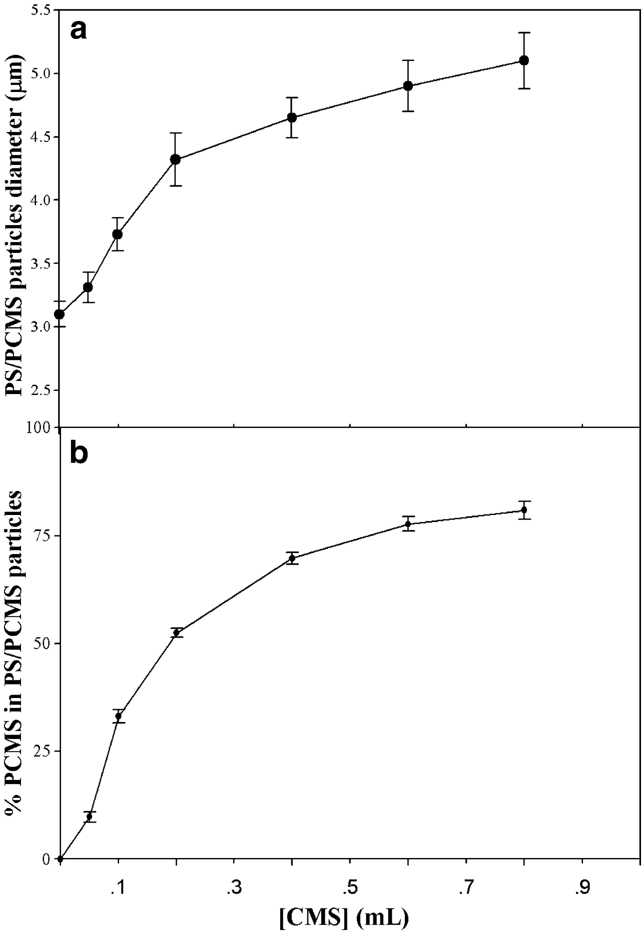

Fig. 6 Effect of the CMS volume on the PS/PCMS particles' diameter (**a**) and the weight percent of PCMS in the PS/PCMS particles (**b**). The PS/PCMS core-shell microspheres were prepared by the seeded emulsion polymerization of various volumes of CMS in the presence of PS microspheres of 3.1±0.1 µm hydrodynamic diameter dispersed in an aqueous continuous phase, according to the description in the "Experimental" section

CMS volume, 0.1, 0.2, 0.4, 0.6, and 0.8 mL, increased, as expected, from 38.6 to 44.1, 46.6, 49.1, and 50.7, respectively.

XPS measurements provide information on the most outer surface composition of the PS/PCMS microspheres, while elemental analysis provides similar information on the bulk composition of these particles. For these core-shell microspheres, we should expect that the surface % of the PCMS should be significantly higher than that of the bulk. Indeed, in the presence of 0.1 mL of CMS, the measured % surface PCMS of the PS/PCMS particles was 38.6% (Table 4) while that of the bulk was 33.1% (Fig. 6). On the other hand, in the presence of CMS volumes higher than 0.1 mL, the measured % surface PCMS of the PS/PCMS particles was lower than that of the bulk. Furthermore, the higher the CMS volume, the higher was the difference between the % surface PCMS and the bulk, e.g., in the presence of 0.2, 0.4, 0.6, and 0.8 mL CMS, the measured surface % PCMS fraction was 44.1%, 46.6%, 49.1%, and 50.7%, respectively (Table 4), while that of the bulk was 52.9%, 69.8%, 77.7%, and 81.1%, respectively (Fig. 6). These results indicate that as the CMS initial volume increases, the content of the PCMS within the PS/PCMS particles also increases. This behavior may be explained by the ability of CMS to swell the PS core microspheres, prior to polymerization, as depicted in Table 5 by following the diameter of the PS core microspheres as the CMS volume increased. Indeed, in the presence of 0.1 mL of CMS, no significant change in the hydrodynamic diameter of the core microspheres was observed, while in the presence of 0.2, 0.4, 0.6, and 0.8 mL of CMS, the diameter of the PS core microspheres increased gradually from 3.1±0.1 to 3.2±0.1, 3.6±0.1, 3.9±0.1, and 4.2±0.1 µm, respectively. We assume that under these conditions the PCMS content of the PS/PCMS particles is due to the polymerization of both the CMS in the aqueous continuous phase and the CMS in the swollen PS core particles.

PS/P(CMS–DVB) core-shell microspheres

Figure 7 shows SEM photomicrographs of the PS/P(CMS–DVB) core-shell microspheres, produced by seeded emulsion copolymerization of CMS and the crosslinker monomer, DVB, in the presence of the PS core microspheres. The total monomer (CMS+DVB) volume was set up to be 0.6 mL, while the volume ratio [CMS]/[DVB] was altered to be 49.0, 15.6, and 4.0, as described in the "Experimental" section. Figure 7 shows that the hydrodynamic diameter and size distribution of the produced PS/P(CMS–DVB) core-shell microspheres were not significantly affected by the change in the volume ratio [CMS]/[DVB] so long as the total monomer volume

Table 4 XPS Cl data illustrating the influence of CMS volume on the surface composition of the PS/PCMS core-shell microspheres

[CMS] (mL)	Surface weight percent		
	Cl	PCMS	PS
PS only	0	0	100
0.1	8.0	38.6	61.4
0.2	10.3	44.1	55.9
0.4	10.7	46.6	53.4
0.6	11.4	49.1	50.9
0.8	11.8	50.7	49.3

The PS/PCMS core-shell microspheres were prepared by seeded emulsion polymerization of different volumes of CMS in the presence of PS microspheres of 3.1±0.1 µm hydrodynamic diameter dispersed in aqueous continuous phase, according to the description in the "Experimental" section

Table 5 Effect of CMS volume on the swelling of the PS core microspheres

[CMS] (mL)	Swollen PS particles diameter (μm)
PS only	3.1±0.1
0.1	3.1±0.1
0.2	3.2±0.1
0.4	3.6±0.1
0.6	3.9±0.2
0.8	4.2±0.2

PS core microspheres of 3.1±0.1 μm hydrodynamic diameter dispersed in aqueous continuous phase containing SDS, PPS, and different volumes (0.1, 0.2, 0.4, 0.6, and 0.8 mL) of CMS were shaken at room temperature for 5 min. The temperature was then raised to 71 °C for the polymerization of the CMS, according to the description in the "Experimental" section

remained constant (0.6 mL). Furthermore, a comparison between Figs. 1b and 7 illustrates a similar diameter and size distribution for the particles formed in the presence 0.6 mL of CMS only or in the presence of 0.6 mL of CMS and DVB. Figures 7a and 1b also demonstrate a similar morphology for the microspheres formed in the presence of 0.6 mL of CMS only and those formed in the presence of 0.6 mL of CMS+DVB at a volume ratio [CMS]/[DVB] of 49.0. On the other hand, a clear morphology change was observed while altering the volume ratio [CMS]/[DVB] from 49.0 to 15.6 and 4.0. The surface of the PS/P(CMS–DVB) microspheres formed at a volume ratio [CMS]/[DVB] of 15.6 (Fig. 7b) is significantly more bumpy than that produced at volume ratio [CMS]/[DVB] of 49.0 (Fig. 7b). The bumps may be due to heterocoagulation of the P(CMS–DVB) nanoparticles produced in the aqueous continuous phase and the PS core particles and to graft polymerization initiated by surface oligoradicals (produced by polymerization of the monomers swollen within the PS core) with CMS and DVB dissolved in the aqueous continuous phase. Moreover, the PS/P(CMS–DVB) microspheres formed at the highest crosslinker monomer concentration, i.e., at a volume ratio [CMS]/[DVB] of 4.0, lost their perfect spherical shape, and their surface morphology became much less bumpy than those formed in the volume ratio [CMS]/[DVB] of 15.6. The loss of the spherical shape may be due to the relatively higher concentration of the crosslinker monomer, which restricts the growth of the core-shell microspheres

Dissolution of the PS part of the PS/P(CMS–DVB) core-shell microspheres

The main aim for dissolving the PS core part of the PS/P(CMS–DVB) core-shell microspheres was in order to produce hollow crosslinked PCMS microspheres. For this purpose, PS/P(CMS–DVB) microspheres were prepared in the presence of 0.1, 0.2, and 0.6 mL of CMS and DVB while maintaining the volume ratio [CMS]/[DVB] at 4.0. The PS part of the PS/P(CMS–DVB) microspheres was then extracted by intensive washing of the various PS/P(CMS–DVB) microspheres with toluene, according to the description in the "Experimental" section. TEM photomicrographs of the obtained crosslinked particles are shown in Fig. 8. It is interesting to realize that the structure and morphology of the formed materials are dependent on the total volume of the monomers, CMS and DVB. In the presence of 0.6 mL of the total monomer volume, P(CMS–DVB) particles containing voids were observed (Fig. 8a), instead of the expected hollow particles. This is probably because the crosslinked P(CMS–DVB) part belonging to the PS/P(CMS–DVB) particles exists both on the surface and within the PS core particles. The P(CMS–DVB) part within the PS particles was probably produced due to the swelling of the inner part of the PS core with CMS and

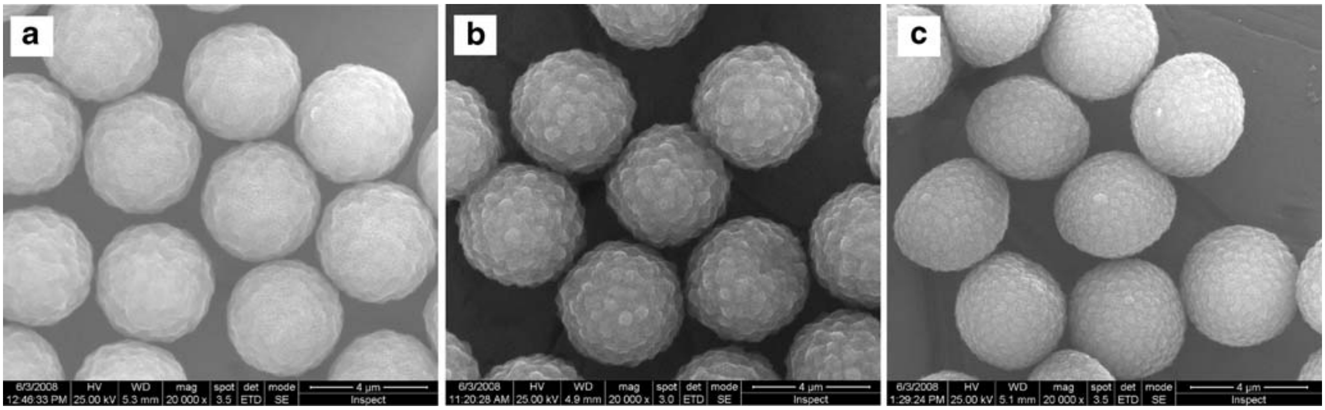

Fig. 7 SEM photomicrographs of the PS/P(CMS–DVB) core-shell microspheres formed by seeded emulsion polymerization of 0.6 mL monomers (CMS and DVB) in the presence of PS microspheres of 3.1±0.1 μm hydrodynamic diameter at different volume ratios of [CMS]/[DVB]: 49.0 (**a**), 15.6 (**b**), and 4.0 (**c**), according to the description in the "Experimental" section

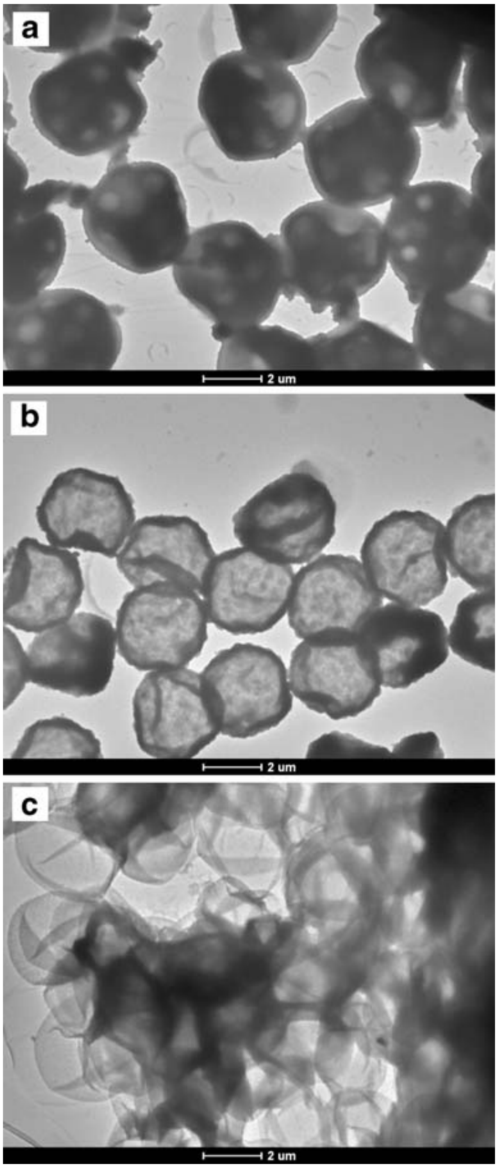

Fig. 8 TEM photomicrographs of the crosslinked P(CMS–DVB) particles formed by dissolution of the PS part of the PS/P(CMS–DVB) microspheres prepared by seeded emulsion polymerization of CMS and DVB in the presence of PS microspheres of 3.1±0.1 µm hydrodynamic diameter at volume ratio [CMS]/[DVB] of 4.0 and total monomers volumes of 0.6 (**a**), 0.2 (**b**), and 0.1 mL (**c**), according to the description in the "Experimental" section

DVB. The dissolution of the PS part of the PS/P(CMS–DVB) particles therefore resulted in a void formation belonging to the extracted PS. These voids can be distinguished from the remaining homogeneous particles, as observed by the TEM picture (Fig. 8a) due to density contrast. On the other hand, Fig. 8b illustrates that when the total volume of the monomers was lower, e.g., 0.2 instead of 0.6 mL, hollow P(CMS–DVB) particles were produced after dissolution of the PS part of the PS/P(CMS–DVB) particles. This indicates that under these conditions the swelling of the inner part of the PS core particles by CMS and DVB was neglected, so that the polymerization of these monomers occurs mainly on the surface of the PS core particles. The folding, creasing, and flattening of these hollow particles, as shown in Fig. 8b, are probably due to the drying procedure prior to the measurements [56, 57]. Figure 8c illustrates that in the presence of a total monomer volume of 0.1 mL, after the dissolution of the PS part of the PS/P(CMS–DVB) particles, broken P(CMS–DVB) shells, instead of the expected hollow particles, were observed. This can be explained by the thinner P(CMS–DVB) shell obtained in the presence of 0.1 mL of the total monomer volume relative to that obtained in the presence of 0.2 mL (0.2±0.05 and 0.5±0.05 µm hydrodynamic shell thickness, respectively). It should be noted that observation by light microscopy indeed indicated the formation of hollow P(CMS–DVB) particles of 3.5±0.2 µm hydrodynamic diameter after the dissolution of the PS part. However, the relatively thin shell P(CMS–DVB) hollow particles probably could not withstand the conditions required for the TEM picture, e.g., the high vacuum, and collapse to pieces as illustrated in Fig. 8c.

Summary and future plans

The present article describes a new method for preparing micrometer-sized PS/PCMS and PS/P(CMS–DVB) core-shell particles of narrow-size distribution, by seeded emulsion polymerization of CMS or CMS and DVB in the presence of uniform PS core microspheres. The properties of these core-shell microspheres, e.g., size, size distribution, surface morphology, and composition, were controlled by changing various parameters belonging to the polymerization process, e.g., volume of the CMS and the volume ratio of CMS to DVB. This manuscript also illustrates that, in addition to the shell formation by the seeded emulsion polymerization process, a swelling process of the core PS microspheres with the CMS and DVB may also occur, followed by the polymerization of these monomers within the swollen particles. The content of the polymerization within the PS core particles is dependent on conditions such as swelling time and CMS and DVB volumes. The present manuscript also illustrates that the composition of the PS/P(CMS–DVB) core-shell particles needs to be optimized in order to obtain hollow particles, by dissolution of the polystyrene core of these optimized particles.

In future studies, we wish to continue this work, particularly to improve our understanding of how to control the formation of crosslinked hollow PCMS microspheres. In addition, efforts to study the conversion of the chloromethyl groups of these particles to other functional groups such as hydroxyls, primary amines, and aldehydes and for the covalent immobilization of bioactive reagents such as proteins, enzymes, antigens, antibodies, and drugs to the surface of these particles will be accomplished. The bioactive-conjugated micrometer-size particles will then be studied for various biomedical uses such as specific cell labeling and separation, diagnostic, and drug targeting.

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