

Synthesis of Sugar-Containing Amphiphiles for Liquid and Supercritical Carbon Dioxide

Weijun Ye[†] and Joseph M. DeSimone*

Department of Chemistry, CB# 3290, Venable Hall University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3290

Liquid and/or supercritical carbon dioxide as a useful processing fluid is limited by its inability to solubilize highly polar compounds. This problem can be alleviated by the addition of CO₂-philic amphiphiles. Our primary objective herein is to design and synthesize novel materials that have both strong polar moieties and highly CO₂-philic segments. Sugar-containing hydrophobic/hydrophilic fluorinated copolymers were synthesized by free-radical polymerization. The degree of solubility of the amphiphiles in CO₂ was found to be heavily influenced by the amphiphilic structure, including the polarity of the sugar head (acetal protected and deprotected), and the fraction of CO₂-philic groups. We also found that the presence of water in the CO₂ phase could decrease the solubility of the hydrophilic copolymer. The dispersion polymerization of 2-hydroxyethyl methacrylate in CO₂ was tested by using the hydrophilic amphiphile as a stabilizer. Spherical particles in the submicron size range were obtained.

Introduction

Carbon dioxide is the most widely preferred supercritical fluid (SCF) because of its environmental acceptability and its easily accessible supercritical parameters (critical temperature and pressure are 31 °C and 73.8 bar, respectively). It is readily available, inexpensive, nontoxic, and nonflammable. These properties allow CO₂ to be a useful replacement for organic solvents to minimize current organic wastes. In practice, CO₂ has been used for the extraction of caffeine from coffee. Micell Technologies¹ has developed CO₂ as a solvent in the dry cleaning industry. Homogeneous and heterogeneous dispersion polymerizations in liquid and supercritical CO₂ were first reported by DeSimone's group.^{2,3} In April 1999, Du Pont announced plans to build a \$40 million development facility to use supercritical CO₂ as a reaction solvent for the production of Teflon.⁴ It is apparent that CO₂ is becoming an increasingly important solvent in science, engineering, and manufacturing and service industries.

CO₂ is a nonpolar molecule with a low dielectric constant and low polarizability per unit volume, which limits its ability to dissolve many compounds. Many polar molecules, such as water, ureas, amides, ionic species, proteins, sugars, etc., exhibit very poor solubility in CO₂.⁵ CO₂ is also reported as a poor solvent for most macromolecules. There are only two classes of polymeric materials that show appreciable solubility in CO₂, and we designate them as CO₂-philic: amorphous fluoropolymer and silicone.⁶ The solubility problem of CO₂ can be overcome by the addition of certain stabilizers to help emulsify insoluble hydrophilic or lipophilic substances in CO₂. Consani and Smith⁷ have examined the solubility of more than 130 commercially available surfactants. They found that all of them are insoluble or only slightly soluble in CO₂. Recently, several types of CO₂ amphiphiles were reported, such as perfluoro-

polyether (PFPE) with different terminating polar groups,⁸ copolymers with a CO₂-philic segment,⁹ and a dendritic surfactant with a CO₂-philic shell.¹⁰ Our approach is to design sugar-containing fluorinated copolymers by free-radical polymerization. The dispersion polymerization of 2-hydroxyethyl methacrylate in CO₂ was also studied using the hydrophilic copolymer as the stabilizer.

Experimental Section

Materials. 1,1-Dihydroperfluorooctyl methacrylate (FOMA; 3M, St. Paul, MN) and 2-hydroxyethyl methacrylate (HEMA; Aldrich, Milwaukee, WI) were purified by passing through an alumina column. 2,2'-Azobis(isobutyronitrile) (AIBN; Aldrich, Milwaukee, WI) was recrystallized twice from methanol. Pyridine (Aldrich, Milwaukee, WI) was distilled and dried over potassium hydroxide. 1,2:5,6-Di-*O*-isopropylidene- β -D-glucopyranose, methacrylic anhydride, trifluoroacetic acid, α,α,α -trifluorotoluene, and tetrachlorohydroquinone were from Aldrich (Milwaukee, WI) and were used as received. Carbon dioxide (SFE/SFC grade) was provided by Air Products (Allentown, PA) and was used as received.

Synthesis of 3-*O*-Methacryloyl-1,2:5,6-di-*O*-isopropylidene- β -D-glucopyranose (MAIpGlc; Figure 1a). This synthesis followed the method reported by Ohno et al.¹¹ To a stirred solution of 1,2:5,6-di-*O*-isopropylidene- β -D-glucopyranose (10 g, 38.4 mmol) in 50 mL of dry pyridine was added dropwise at room temperature 10 mL of methacrylic anhydride. Then the mixture was heated at 65 °C for 4 h and for a further 1 h with water (35 mL) added. Stirred magnetically overnight at room temperature, the reaction mixture was extracted three times with light petroleum (bp 30–70 °C, 3 \times 50 mL). The combined extracts were washed with a 5% aqueous sodium hydroxide solution (2 \times 100 mL) and water (3 \times 60 mL) and dried over anhydrous sodium sulfate. Tetrachlorohydroquinone (~0.02 g) was added before the extract was concentrated to a syrup. The crude product was purified twice by vacuum distillation to give a colorless oil (~60%). ¹H NMR (CDCl₃): δ 1.25 (s, 6 H,

* To whom correspondence should be addressed. E-mail: desimone@email.unc.edu. Fax: 919-962-5467.

[†] E-mail: wye@email.unc.edu.

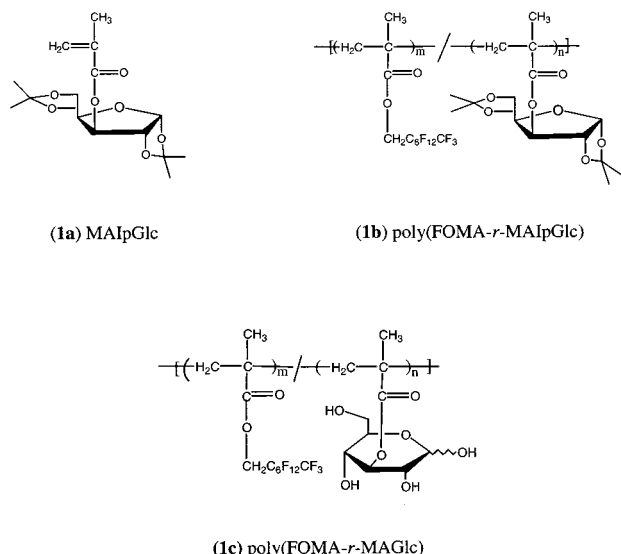


Figure 1. Chemical structure of the MAIpGlc monomer (**1a**), poly(FOMA-*r*-MAIpGlc) (**1b**), and poly(FOMA-*r*-MAGlc) (**1c**).

2CH₃), 1.35 (s, 3 H, CH₃), 1.5 (s, 3 H, CH₃), 1.9 (s, 3 H, CH₃), 3.95, 4.05, 4.20, 4.50, 5.25, 5.85 (7H, sugar moiety), 5.60, 6.10 (s, 2H, CH₂=C<).

Preparation of Poly(1,1-dihydroperfluorooctyl methacrylate)-*r*-poly(3-*O*-methacryloyl-1,2:5,6-di-*O*-isopropylidene- α -D-glucopyranose) Random Copolymer [poly(FOMA-*r*-MAIpGlc); Figure 1b]. To a round-bottomed flask with a stir bar equipped with dry argon flow were dissolved monomer MAIpGlc and FOMA (3 g, in determined mole fractions) in α,α,α -trifluorotoluene (35 wt % based on the monomer weight). AIBN (1 wt %, based on the monomer weight) was added, and the mixture was stirred under argon flow for 20 min. Then the flask was heated in a 65 °C oil bath for 20 h. The polymer solution was diluted with α,α,α -trifluorotoluene and precipitated into methanol. White polymer powder was filtered and dried under vacuum. ¹H NMR (C₆F₆/C₆D₆): δ 0.8–2.3 (br, 5H, FOMA; 17H, MAIpGlc), 3.5–4.8 (br, 2H, CH₂C₇F₁₅, FOMA; 6H, sugar moiety), 5.6 (s, 1H, sugar moiety).

Preparation of Poly(1,1-dihydroperfluorooctyl methacrylate)-*r*-poly(3-*O*-methacryloyl- α -D-glucopyranose) Random Copolymer [poly(FOMA-*r*-MAGlc); Figure 1c] by Deprotection of 1b. Copolymer **1b** (1 g) was dissolved in 3 mL of α,α,α -trifluorotoluene. A total of 15 mL of a trifluoroacetic acid/water solution (CF₃COOH:water = 9:1) was added, and the mixture was stirred overnight at room temperature. The deprotected copolymer **1c** was precipitated from the concentrated solution into methanol and dried in vacuo. The final product was analyzed by FT-IR and ¹H NMR.

Solubility of Poly(FOMA-*r*-MAIpGlc) and Poly(FOMA-*r*-MAGlc) in CO₂. A 2.5 mL stainless steel, cylindrical, high-pressure view cell was used for solubility investigation. Each end of the cell was equipped with a sapphire window, which permits visual observation. The cell was charged with 0.025 g of dry copolymer followed by the addition of liquid CO₂ to approximately 4000 psi via an automatic syringe pump (ISCO model 260D). The temperature of the cell was kept at room temperature (25 °C). The mixture was agitated by a small egg-shaped stir bar.

Instrumentation. ¹H NMR spectra were obtained in CDCl₃ or C₆F₆/C₆D₆ with a Bruker Avance 400 Hz spectrometer. FT-IR spectra were taken on a Bio-Rad

FTS-7 IR spectrometer. Scanning electron microscopy (SEM) images were obtained at North Carolina State University on a JEOL 6400 FE SEM.

Results and Discussion

Copolymer Synthesis. Previous work^{2,9,12} has shown that poly(FOMA) and its random, block, and graft copolymers are soluble in CO₂. Here, we used poly(FOMA) as the CO₂-philic group and the sugar monomer (MAIpGlc) as the CO₂-phobic group. A series of random copolymers of poly(FOMA-*r*-MAIpGlc) (monomer feed mole ratio from 10:1 to 0.1:1; Table 1) were prepared by free-radical copolymerization. The reaction medium remained homogeneous throughout the reaction time. After precipitation and vacuum-drying, the monomer conversion (based on the weight) was about 90%. The copolymer composition was calculated from the ¹H NMR integral intensity of the signal at 5.6 ppm (1H, sugar moiety) and the signals at 3.5–4.8 ppm (2H, FOMA; 6H, sugar moiety). The monomer mole ratio in the copolymer was close to the monomer feed mole ratio.

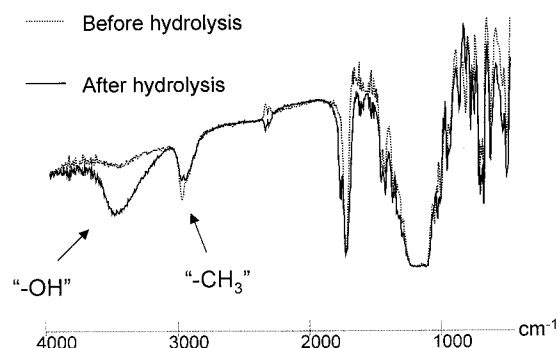
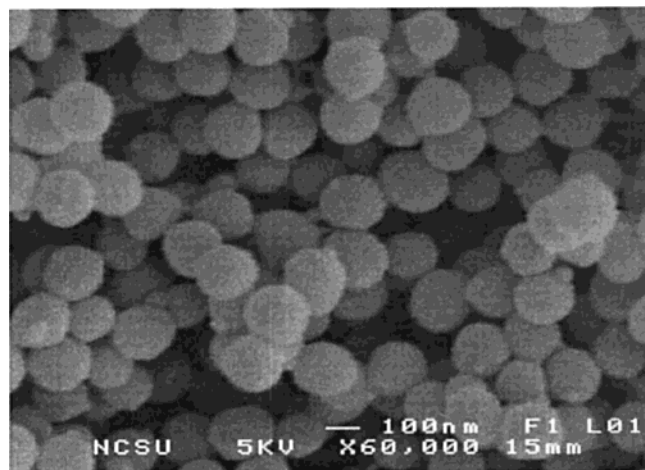
Hydrolysis of the protected copolymer **1b** was performed in a α,α,α -trifluorotoluene solution under acid catalysis by a trifluoroacetic acid/water mixture with a yield of 67%. We also tried sulfuric acid and formic acid as acid catalysts, but these hydrolytic reactions were too slow. The deprotection procedure was also performed in liquid CO₂ at room temperature, resulting in a low yield (<30%). FT-IR spectra showed a significant –OH absorption (around 3500 cm^{–1}) and a weaker –CH₃ absorption (Figure 2).

Solubility in CO₂. The solubility of poly(FOMA-*r*-MAIpGlc) (**1b**) and poly(FOMA-*r*-MAGlc) (**1c**) in CO₂ was studied at 1 w/v % in a 2.5 mL high-pressure view cell under 4000 psi at room temperature (Table 1). The random copolymers were categorized as being either (1) soluble, forming a clear and homogeneous solution; (2) cloudy, forming a hazy and translucent solution; or (3) insoluble, with nondissolved precipitates in the CO₂. For either the protected or hydrolyzed copolymer, the solubility in CO₂ was strongly influenced by the fraction of CO₂-philic (FOMA) incorporation. Only copolymers with a monomer mole ratio of less than 0.3:1 for poly(FOMA-*r*-MAIpGlc) or a ratio below 1:1 for poly(FOMA-*r*-MAGlc) were not soluble in CO₂. We also found that changing the chemical structure of the sugar segment could influence the solubility. Before hydrolysis, the acetal-protected copolymers **1b** with 1.1:1 and 0.7:1 ratios were totally soluble in CO₂. However, after hydrolysis, these more polar deprotected polymers became insoluble. We also synthesized and studied the solubility of a small-molecule fluoroester containing a protected or deprotected monosaccharide head. Similarly, the protected fluoroester, 6-*O*-perfluorooctanoyl-1,2:3,4-di-*O*-isopropylidene- α -D-galactopyranose, was very easy to dissolve in CO₂ (>9 wt %), while the hydrophilic deprotected one, 6-*O*-perfluorooctanoyl- α -D-galactose, was insoluble (<0.1 wt %). Strong polar hydrogen-bonding interaction between the deprotected sugar segments makes a contribution to the decreased solubility.

Moreover, we found that the presence of water in CO₂ could affect the solubility of the hydrophilic copolymer. Copolymer **1c** (4 w/v %) was used to examine the ability to disperse a solution (0.4 wt %) of water and methyl orange (a CO₂-insoluble dye) in CO₂ (5700 psi) at 32 °C. No obvious color change of the CO₂ phase or disappearance of the water droplets was noted. However, the originally clear CO₂ phase gradually became cloudy

Table 1. Solubility of Sugar Fluorinated Copolymer in CO₂ (1 w/v %, 4000 psi)

feed mole ratio		yield (%)	before hydrolysis [poly(FOMA- <i>r</i> -MAIpGlc)]	after hydrolysis [poly(FOMA- <i>r</i> -MAGlc)]
FOMA	MAIpGlc			
PFOMA	0	87	soluble	soluble
10	1	88	soluble	soluble
5.0	1	90	soluble	soluble
2.0	1	91	soluble	soluble
1.4	1	91	soluble	soluble
1.1	1	90	soluble	insoluble
0.7	1	83	soluble	insoluble
0.3	1	87	cloudy	
0.1	1	84	insoluble	
0	PMAIpGlc		insoluble	insoluble

**Figure 2.** FT-IR spectrum of protected copolymer **1b** and deprotected copolymer **1c**.**Figure 3.** SEM of poly(HEMA) latex particles synthesized with 10 wt % (based on the monomer weight) **1c** (5:1) and 10 w/v % HEMA under 6000 psi at 65 °C for 20 h, with 1 wt % (based on the monomer weight) AIBN as the initiator.

because of the copolymer aggregation. Such a phenomenon did not occur with the hydrophobic copolymer **1b**.

We also investigated the hydrophilic random copolymer **1c** as the stabilizer in dispersion polymerizations of HEMA, a hydrophilic monomer, in CO₂. The polymerization was run at 6000 psi and 65 °C for 20 h according to the procedure reported previously.¹³ A stable milky-white dispersion solution was observed when the surfactant concentration was greater than 5 wt %. After 20 h, without further stirring, the white latex would slowly settle. The SEM image (Figure 3) shows poly(HEMA) particles obtained from 10 wt % of **1c** with a monomer conversion of 92%. In contrast, the polymerization in the absence of stabilizer was conducted in CO₂, resulting in a nonspherical polymer product with a yield of 88%. In addition, Shiho and DeSimone studied the dispersion polymerization of HEMA in CO₂ using poly(1,1-dihydroperfluorooctyl

acrylate) as a stabilizer, and no spherical polymer particles were found.¹⁴ As shown in Figure 3, the random copolymer **1c** could successfully stabilize the CO₂-insoluble poly(HEMA) in supercritical CO₂, and the spherical polymer particles in submicron size range were obtained.

Conclusions

New fluorinated random copolymers, sugar-based CO₂-philic amphiphiles, were synthesized. The solubility of CO₂-philic/hydrophobic and CO₂-philic/hydrophilic surfactants was influenced by the fraction of CO₂-philic segment, polarity of the sugar moiety, and the presence of a water phase. The hydrophilic copolymer was also shown to stabilize poly(HEMA) particles in dispersion polymerization in CO₂.

Acknowledgment

The authors gratefully acknowledge the financial support from the Kenan Center for the Utilization of Carbon Dioxide in Manufacturing and the NSF Science and Technology Center for Environmentally Responsible Solvents and Processes.

Literature Cited

- (1) Murphy I. P. *Am. Drycleaner* **1999**, 3, 24.
- (2) DeSimone, J. M.; Guan, Z.; Elsbernd, C. S. *Science* **1992**, 257, 945.
- (3) Kendall, J. L.; Canelas, D. A.; Young, J. L.; DeSimone, J. M. *Chem. Rev.* **1999**, 99, 543–563.
- (4) McCoy, M. *Business* **1999**, 77, 11–13.
- (5) Hyatt, J. A. *J. Org. Chem.* **1984**, 49, 5097.
- (6) DeSimone, J. M.; Maury, E. E.; Menciloglu, Y. Z.; McClain, J. M.; Romack, T. J.; Combes, J. R. *Science* **1994**, 265, 356–359.
- (7) Consani, K. A.; Smith, E. D. *J. Supercrit. Fluids* **1990**, 3, 51–65.
- (8) Johnston, E. J.; Harrison, K. L.; Clarke, M. J.; Howdle, S. M.; Heitz, M. P.; Bright, F. V.; Carlier, C.; Randolph, T. W. *Science* **1996**, 271, 624.
- (9) Maury, E. E.; Barren, H. J.; Killian, S. K.; Menciloglu, Y. Z.; Combes, J. R.; DeSimone, J. M. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **1993**, 34, 664.
- (10) Cooper, A. I.; Londono, J. D.; Wignall, G.; McClain, J. B.; Samulski, E. T.; Lin, J. S.; Dobrynin, A.; Rubinstein, M.; Burke, A. L. C.; Frechet, J. M. J.; DeSimone, J. M. *Nature* **1997**, 389, 368.
- (11) Ohno, K.; Tsujii, Y.; Fukuda, T. *J. Polym. Sci., Part A: Polym. Chem.* **1998**, 36, 2473.
- (12) Betts, D. Ph.D. Dissertation, The University of North Carolina at Chapel Hill, Chapel Hill, NC, 1998.
- (13) Hsiao, Y.-L.; Maury, E. E.; DeSimone, J. D.; Mawson, S.; Johnston, K. P. *Macromolecules* **1995**, 28, 8159–8166.
- (14) Shiho, H.; DeSimone, J. M. Dispersion Polymerization of 2-Hydroxyethyl Methacrylate in Supercritical Carbon Dioxide. Unpublished results.

Received for review February 4, 2000
 Revised manuscript received July 7, 2000
 Accepted July 11, 2000

IE000184Q