Emulsion Templating Using Supercritical Fluid Emulsions

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Introduction

Herein we describe the preparation of porous monolithic type polymers by oil-in-water emulsion templating using supercritical carbon dioxide ($scCO_2$) as the internal oil phase[1].

Emulsion templating is a versatile method for the preparation of well-defined porous polymers[2] and inorganic materials[3]. The technique involves forming a high internal phase emulsion (HIPE) (>74.05 v/v internal phase) and then locking in the structure *via* polymerization of monomers dissolved in the external phase. Removal of the internal phase (*i.e.*, the emulsion droplets) leaves a skeletal replica of the emulsion.

Porous hydrophilic polymers have applications such as separation media and biological tissue scaffolds. In principle, these types of material can be produced by oil-in-water emulsion templating. However, this process would be very solvent intensive due to the large volume of the oil phase (usually an organic solvent). Furthermore, removal of the organic phase after reaction may be difficult. This is especially important for biological / biomedical applications where solvent residues are undesirable. We have overcome this problem by $scCO_2$ as the internal droplet phase. Carbon dioxide is an inexpensive, non-toxic, and non-flammable solvent alternative for polymer synthesis and processing[4]. Removal of the template phase is simple since the CO_2 reverts to the gaseous phase upon depressurization.

Supercritical CO_2 has been used previously for production of microcellular polymeric foams[5] and biodegradable composite materials[6]. Both of these supercritical fluid (SCF) techniques involve a foaming mechanism. This limits the range of porous materials that can be produced because many materials cannot be foamed.

We present here an entirely new approach to synthesis of porous materials from high internal phase SCF emulsions. Our technique allows the synthesis of materials with well-defined pore structures without the use of any volatile organic solvents – just water and CO_2
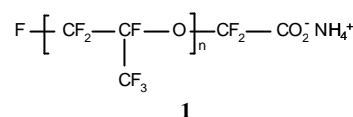
Experimental

Materials. Poly(hexafluoropropylene-*co*-difluoromethyleneoxide) mono carboxylic acid (M_w = 554 g mol^{-1}, Aldrich), ammonia solution (BDH Chemicals), acrylamide (AM, 99+%, Aldrich), *N,N'*-methylenebisacrylamide (MBAM, 99%, Aldrich), potassium persulfate (99+%, Aldrich), PVA (M_w = 9–10 kg mol^{-1}, 80% hydrolyzed, Aldrich) glutaraldehyde (50% w/v solution in water, Aldrich) and Nile Red (Aldrich) were all used as received.

Synthesis. Surfactant **1** was synthesized according to published procedures[7]. High-pressure reactions were carried out in a stainless steel reactor (10 cm^3), equipped with a sapphire window for observation of phase behaviour. In a typical polymerization, the reactor was charged with an aqueous solution of monomers (40% w/v), initiator ($K_2S_2O_8$, 2% w/v based on monomer), surfactant **1**, and a cosurfactant (*e.g.*, PVA) before purging with a slow flow of CO_2 for 15 min. The reactor was then pressurized with liquid CO_2 (20 ± 2°C, 100± 5 bar) and stirring was commenced (PTFE stir bar), whereupon a white, milky C/W emulsion was formed. For experiments involving crosslinked PVA materials (*e.g.*, sample 11), a motor driven impeller stirrer (500–1500 rpm) was used to achieve emulsification because of the higher viscosity of the aqueous phase. Stirring was continued for 30 min and then ceased before heating to the required reaction temperature overnight (60°C, 275 ± 20 bar). (*SAFETY NOTE:* The onset of polymerisation was sometimes accompanied by a reaction exotherm, which caused a sudden increase in temperature and pressure. An adequately vented safety rupture device is strongly recommended for these experiments.) After cooling to room temperature, the CO_2 was vented and the templated polymers were removed from the reactor. Residual water was removed from the samples by drying under vacuum at 50°C overnight.

Characterisation. Pore size distributions were recorded by mercury intrusion porosimetry using a Micromeritics Autopore IV 9500 porosimiter. Polymer surface areas were measured using the BET method with a Micromeritics Tristar nitrogen adsorption analyzer. Polymer morphologies were investigated with a Hitachi S-2460N SEM. Samples were mounted on aluminium studs using adhesive graphite tape and sputter-coated with approximately 10 nm of gold before analysis. Cell sizes and structures were investigated using a Zeiss LSM510 confocal microscope. The samples were mounted on microsope slides with glass rings and filled with Nile Red dissolved in benzyl alcohol. The Nile Red was excited using the 488 nm laser line and detection was by a photomultiplier mounted behind a 505 nm long pass filter.

Results and Discussion

Johnston has shown that perfluoropolyether (PFPE) surfactants (*i.e.*, **1**) can form both water-in-CO_2 (W/C) and CO_2-in-water (C/W) macroemulsions, and that these emulsions can exhibit kinetic stability[7].

$$F\left[\!\!-CF_2\!-\!\!\underset{\underset{CF_3}{|}}{CF}\!\!-\!\!O\right]_n\!\!CF_2\!-\!CO_2^-\,NH_4^+$$

1

The general procedure for templating a C/W emulsion is shown in Figure 1. A relatively low M_w PFPE ammonium carboxylate surfactant (M_w = 567 g mol^{-1}) was used, since Johnston has shown that this type of surfactant is significantly water-soluble and has a propensity to form C/W rather than W/C emulsions.
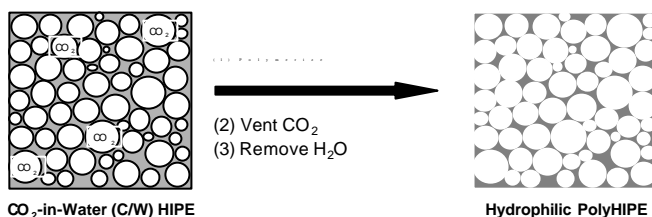

(2) Vent CO_2
(3) Remove H_2O

CO_2-in-Water (C/W) HIPE   **Hydrophilic PolyHIPE**

Figure 1. Preparation of a porous material via SCF emulsion templating. External phase is an aqueous solution, internal phase is $scCO_2$

Initially, a simple water and CO_2 system was investigated (volume fraction CO_2 = 70%, temperature = 25°C, CO_2 pressure 100–300 bar, concentration **1** = 1–10% with respect to water). Milky-white emulsions were formed, filling the entire reaction vessel, which were stable for more than 1 hour after stirring was ceased. Settling occurred after several hours. This system appeared suitable for emulsion templating since the polymerization reaction might be expected to occur before the emulsion collapsed. This was not found to be the case, because the addition of monomers to the aqueous phase (40% w/v AM + MBAM, AM:MBAM = 8:2 w/w) was found to strongly destabilize the C/W emulsions, which settled almost immediately after stirring was ceased. When the system was heated (60°C) to initiate the polymerization reaction, the instability became even more pronounced. Analysis of the resulting polymer by SEM showed that the material contained isolated cells, showing that only a small amount of CO_2 had been emulsified and 'templated'. Mercury intrusion porosimetry analysis confirmed that the total pore volume was low (0.2–0.5 cm^3 g^{-1}).

It was found that the addition of a poly(vinyl alcohol) (PVA) to the aqueous phase increased the stability of the emulsion. As before, the kinetic stability decreased on heating but the emulsions were now sufficiently stable for templating to occur. A porous, open-cell material was produced which conformed closely to the interior of the reaction vessel (Figure 2).

Table 1 summarizes materials synthesized under a variety of reaction conditions. All materials were porous and open-cell, with pore volumes in the range 1.8-2.6 cm^3 g^{-1} and median pore diameters in the range 1.5–5.4 μm.

Figure 2. Material made using SCF emulsion templating

The concentration of surfactant **1** with respect to the aqueous phase was varied from 0.25–5% w/v. Neither the intrusion volume nor the median pore diameter varied greatly although the morphology varied significantly (Figure 3). In general, a higher surfactant concentration lead to open-cell materials with an increased number of interconnecting pores in the cell walls. Surface area of all samples was found to be relatively low ($<5 \mathrm{m}^2\mathrm{g}^{-1}$) suggesting that no additional permanent dry porosity was retained within the walls of the templated structure.

Table 1. Emulsion Templating Using C/W Emulsions

	Volume fraction CO_2 (%)	% **1** (w/v based on H_2O)	% **1** (w/v based on CO_2)	V_{pore} [$cm^3 g^{-1}$] [a]	median pore diameter (µm) [b]
1	70	0.25	0.11	2.0	3.8
2	70	0.5	0.21	2.6	3.8
3	70	1	0.43	2.1	5.4
4 [c]	70	1	0.43	1.8	1.5
5	70	5	2.14	2.0	1.8
6 [d]	70	5	2.14	2.4	3.1
7	75	1	0.33	1.2	2.3
8	80	1	0.25	5.9	55
9	80	2	0.50	3.9	3.9
10	80	3	0.75	3.8	4.0
11 [e]	75	2	0.66	2.4	7.7

Reaction conditions (samples 1–10): Acrylamide (AM) + *N,N*-methylene bisacrylamide (MBAM) (40% w/v in H_2O, AM:MBAM = 8:2), $K_2S_2O_8$ (2% w/v), poly(vinyl alcohol) (10% w/v based on H_2O, 80% hydrolyzed, M_w = 9–10 kg mol^{-1}), 60 °C, 250–290 bar, 12 h. [a] Total intrusion volume, as measured by mercury intrusion porosimetry over the pore size range 7 nm–100 **nm**. [b] Measured by mercury intrusion porosimetry. [c] 2-hydroxyethyl acrylate used in place of AM. [d] AM:MBAM = 9:1 w/w. [e] 20% w/v PVA based on H_2O, glutaric dialdehyde (12% w/w based on PVA), 70 °C, 355 bar, 12 h.
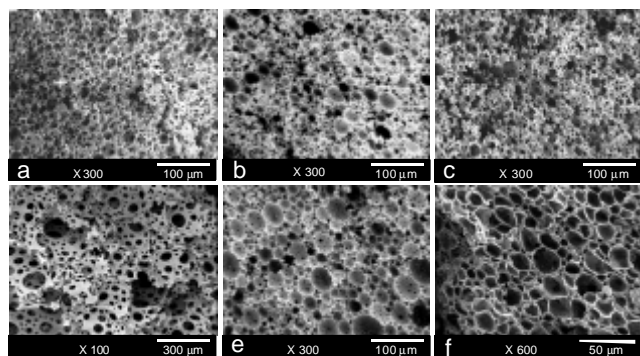

Figure 3. SEM images of templated porous polymers produced from C/W emulsions. a) Sample 3 (CO_2/H_2O = 70:30 v/v, 1% w/v surfactant **1** based on H_2O). b) Sample 5 (CO_2/H_2O = 70:30 v/v, 5% w/v surfactant **1**). c) Sample 7 (CO_2/H_2O = 75:25 v/v 1% w/v surfactant **1**). d) Sample 8 (CO_2/H_2O 80:20 v/v, 1% w/v surfactant **1**). e) Sample 9 (CO_2/H_2O = 80:20 v/v, 2% w/v surfactant 1). f) Sample 11 (CO_2/H_2O 75:25 v/v, PVA cross-linked with glutaraldehyde, 2% w/v surfactant 1, see Table 1).

It was found that it was possible to increase the volume fraction of the CO_2 to 80% and still form stable emulsions which filled the reaction vessel. This has a significant effect on the system as the internal phase exceeds the close packed sphere limit (74.05%) causing the emulsion droplets to distort into polyhedra. This creates a more open structure in the templated material.

Equation 1 was used to calculate average cell densities (average number of cells per unit volume). The average cell size, D, was statistically calculated from confocal microsope images (Figure 4) of the cells (>400 cells measured, A = analyzed area, n = the number of cells within that area[8]).

$$N = \frac{\left(\dfrac{n}{A}\right)^{3/2}}{1 - \dfrac{4}{3}p\left(\dfrac{D}{2}\right)^3 \dfrac{n^{3/2}}{A}} \tag{1}$$

The cell densities were found to vary with the exact experimental conditions. They ranged from 0.5×10^8 / cm^3 to 4.5×10^8 / cm^3 for the sample made with 1% surfactant **1** and varying concentrations of PVA.
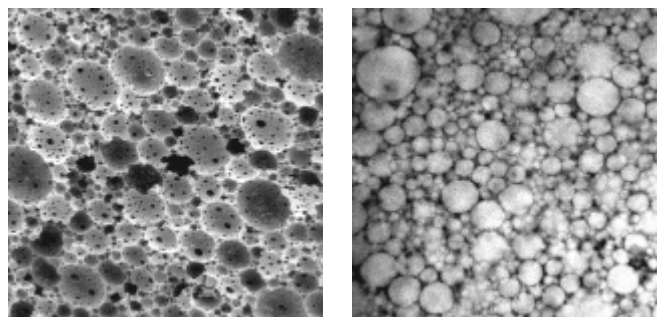

Figure 4. Electron micrograph (left) and confocal microscope image (right) of a material made by SCF emulsion templating (both images 230 x 230 µm).

Preliminary studies have involved substituting AM for less toxic monomers such as 2-hydroxyethyl acrylate (sample 4). Initial results are promising, with porous, open-cell materials being produced. Templated materials have also been synthesised by crosslinking PVA with glutaric dialdehyde (sample 11). These results suggest that our technique may be suitable for generating a wide range of porous materials.

Conclusion

In summary, we have developed a new method for producing well-defined porous materials by templating scCO$_2$ emulsions. In contrast to other O/W templating techniques, our approach does not involve any volatile organic solvents. Future work will focus on extension of this approach to other materials, particularly porous biocompatible materials.

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