Synthesis and Modification of Epoxy- and Hydroxy-Functional Microspheres

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ABSTRACT: This article describes the synthesis and surface modification of epoxy- and hydroxy-functional polymeric microspheres. The functionalized microspheres were synthesized using aqueous and nonaqueous cationic suspension photopolymerizations using multifunctional silicon-containing epoxy monomers with iodonium salt photoinitiators. Although generally solid microspheres were obtained using these techniques, macroporous spheres could be obtained though the use of porogens. Various rapid and facile acid- and base-catalyzed ring-opening addition reactions were performed on the epoxy-functional microspheres. These reactions include the additions of mercaptans, acid chlorides, isocyanates, amines, sodium azide, water, and alcohols. Similar functionalization reactions were performed on the hydroxy-functional microspheres. The particle size and size distribution were determined using scanning electron microscopy. Fourier transform infrared spectroscopy was used to monitor the functionalization reactions. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 97: 1574–1585, 2005

Key words: microspheres; cationic polymerization; ring-opening polymerization; surface modification; photopolymerization

INTRODUCTION

There is an increasing interest in the use of polymer-bound reagents in many fields of modern technology. The most common method of employing polymer-bound reagents is in the form of crosslinked beads or microspheres. Functionalized polymer microspheres find applications as catalyst supports,[1] chromatographic materials,[2] metal ion complexing agents,[3] drug delivery materials,[4] enzyme entrapment materials,[5] medical diagnostic agents, polymer reinforcing additives as well as many others. Polymer microspheres bearing a wide diversity of different types of functional groups have been prepared. Depending on their intended use, these functional groups are subsequently used to bind various organic agents, metals, complexing agents, dyes, enzymes, nucleic acids, proteins, and other polymers. Epoxy-functional microspheres are of particular interest because they can be employed directly for attachment of the above-mentioned agents or modified using a wide variety of both electrophilic and nucleophilic ring opening addition reactions. However, there are few reports in the literature concerning the synthesis of such microspheres. One method that has been used involves the initial free radical suspension polymerization of allyl functional acrylate monomers followed by epoxidation using various peroxides.[6] Although this technique provides highly functional microspheres, the multistep synthesis and epoxidation of the microspheres makes this synthetic approach less desirable. Alternatively, the free radical emulsion or suspension polymerization of monomers such as glycidyl methacrylate containing epoxy groups also affords epoxy-functional microspheres.[7–9] However, side reactions that occur during the synthesis of the crosslinked microspheres appear to substantially lower their epoxy content. In addition, such microspheres possess ester linkages that are prone to hydrolysis.

Recently,[10] we have reported that highly functional microspheres bearing epoxy groups can be obtained directly by the cationic suspension photopolymerization of multifunctional epoxy monomers. The general concept is depicted in Scheme 1. The suspension photopolymerizations are carried out by the uv irradiation of a multifunctional epoxy oligomer containing a soluble photoinitiator under conditions of high agitation in either aqueous or nonaqueous suspending media. In some cases, agents that undergo phase separation during polymerization are added to generate pores. Due to the high epoxide functionality of these monomer systems, gelation to form solid microspheres
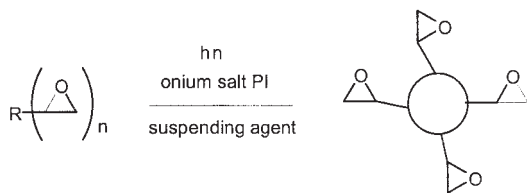
Scheme 1

takes place at relatively low conversions. When this occurs, polymerization of the remaining epoxy groups proceeds very slowly due to reduced molecular diffusion in the solid state.[11] If the cationic polymerization is terminated at this point, the crosslinked microspheres that are formed bear a large number of residual unreacted epoxy groups, especially at their surfaces. These epoxy groups are available for further chemical modification reactions.

In this article, we describe the synthesis of epoxy-functional microspheres utilizing cationic ring-opening suspension photopolymerizations and their postsynthetic modification using various epoxide ring-opening and addition derivitization reactions. These reactions were monitored by Fourier transform infrared spectroscopy (FT-IR) and also through the use of various titrametric techniques. Scanning electron microscopy (SEM) was employed to characterize the detailed microsphere morphology, particle size, and size distribution.

EXPERIMENTAL PROCEDURE

Materials

All organic starting materials and solvents employed in this investigation were reagent quality and were used as purchased from the Aldrich Chemical Co. (Milwaukee, WI) unless otherwise noted. Decahydronaphthalene (mixture of *cis* and *trans* isomers) and bicyclohexyl were purified first by washing with concentrated sulfuric acid followed by vacuum distillation. Nitromethane was purified by drying over calcium hydride followed by vacuum distillation. Mineral oil (Aldrich #33,076-0) employed in this work had a viscosity of 34.5 centistokes at 40°C and a density of 0.845–0.905 g/mL. The epoxy–silicone monomer PC1000 and oligomer PC2003 were gifts from the Polyset Company, Mechanicville, NY. The photoinitiators, (4-*n*-pentadecyloxyphenyl)phenyliodonium hexafluoroantimonate (IOC15 SbF$_6$) and (4-*n*-octyloxyphenyl)phenyliodonium hexafluorophosphate (IOC8 PF$_6$),[12] were synthesized following previously published procedures.

Apparatus

The apparatus and preparative techniques used for the synthesis of the polymeric microspheres were adapted from a previously published article from this laboratory.[10] The apparatus shown in Figure 1 consists of a cylindrical quartz reaction vessel (7.6 cm in diam by 12.7 cm) and an overhead stirrer (IKA, Inc. Wilmington, NC) equipped with a 5 cm diam three-paddle stainless-steel stirrer obtained from Fisher Scientific (Burr Ridge, IL) and a ultrasonication wand (13 cm) powered by a Vibra-Cell 750 W ultrasonicator (VCX 750, Vibracell Sonics, Newton, CT). The UV irradiation was supplied by a Hanovia 679A36 medium pressure mercury are lamp (Hanovia Ltd, Slough, UK) equipped with a 200 W power supply. The uv source was isolated behind a sliding shutter. Both aqueous and nonaqueous photopolymerizations were employed. The same apparatus was used for nonaqueous suspension photopolymerizations except for the following modifications: a 6 cm (diam) model DN2B Cowles stainless-steel stirrer (Indco, Inc. New Albany, IN) replaced the three-paddle stirrer and the sonication probe was removed. Depending on the method of preparation, the resulting microspheres bear either epoxy or hydroxy surface functional groups.

Synthesis of polymeric microspheres

Two different types of suspending media were employed depending on whether epoxy- or hydroxyfunctional particles were desired. Four different samples of microspheres were prepared for use in this investigation; one was produced by photopolymerization in a mineral oil suspension and the other three were prepared using the aqueous suspension photopolymerization technique. The following general synthetic procedures were employed for the micro-
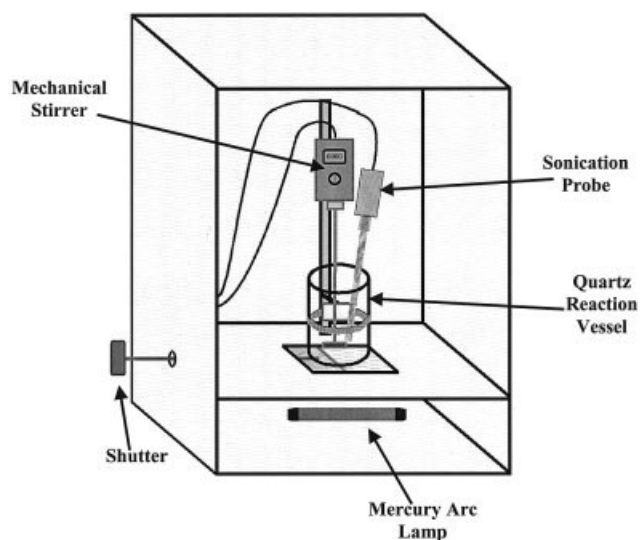

Figure 1 Schematic diagram of the photochemical apparatus for the synthesis of microspheres.

	Porogen/solvent	Initiator	Mixing time[a] (min)	UV Exposure time (min)	Epoxy equivalent (mEq/100 g)	Hydroxy content (mEq/g)	Average particle size[b] (μm)	Yield (%)
I[c]	Nitromethane	IOC15	4	5	359	—	20	75
II[d]	Decahydronapthalene	IOC15	20	5	127	—	7	50
III[d]	Decahydronapthalene	IOC15	60	5	202	—	5	20
IV[d]	Bicyclohexyl	IOC8	20	15	—	157	15	52

[a] The time of sonication or agitation with a Cowles stirrer before irradiation.
[b] Determined by SEM microscopy on a minimum of 50 particles.
[c] Nonaqueous suspension polymerization in mineral oil.
[d] Aqueous suspension polymerization.

spheres. Table I summarizes the reaction parameters employed in the synthesis of the microspheres used in this work.

Aqueous suspension photopolymerization

An aqueous suspending medium (200 mL) composed of a solution of polyvinyl alcohol (85% hydrolyzed polyvinyl acetate, $0.05 \text{g} \cdot \text{L}^{-1}$) in deionized water was added to the reaction vessel. Separately, the monomer solution consisting of PC2003 (10 g) with a porogen or solvent (2.5 g) and 1 mol % (per mol epoxy groups) of IOC15 SbF_6 was mixed using a Vortex Genie 2 Agitator (VWR International, West Chester, PA). The homogenous monomer solution was poured into the reaction vessel while the suspending medium was stirred with a three-paddle stirrer at 400 rpm and simultaneously the ultrasonicator was run at 70% power. The suspension was allowed to mix for a given length of time (20 min for **II** and **IV** and 60 min for **III**). The shutter was then opened exposing the suspension to UV light ($\sim 5,000 \text{ mJ} \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$) for the specified length of time shown in Table I. To generate the hydroxy functional microsphere sample **IV,** the UV exposure time was increased to 15 min. After exposure to UV the shutter was closed and 0.25 mL of triethylamine was added to terminate the polymerization reaction. The resulting suspension mixture was transferred to 50-mL polypropylene centrifuge tubes and spun in a Beckman Model J2-21 Centrifuge (Beckman-Coulter, Corp., Fullerton, CA) for 10 min at 10,000 rpm. A white cake of microspheres was formed on the bottom of the tubes and the clear supernatant liquid was decanted and 25 mL of deionized water was added to each tube. The tubes were agitated until the particles were resuspended and the cloudy fluid was centrifuged again in the same manner. This process of washing the microspheres was repeated using water as the wash solvent followed by two additional washings with methyl ethyl ketone. The white solid was transferred to a 60°C vacuum oven and dried over-

night to give solid or porous epoxy- or hydroxy-functional microspheres depending on the length of time of the UV irradiation. Scanning electron micrographs of the products are shown in Figure 2. The addition of decahydronaphthalene or bicyclohexyl as porogens produces macroporous microspheres, while nitromethane, a good solvent for PC2003, gives solid, nonporous microspheres.

Nonaqueous suspension photopolymerization

Mineral oil (200 mL) was added to the quartz reaction vessel. A Cowles stirrer was inserted and spun at 1,500 rpm. Separately, the monomer solution was prepared by combining 10.0 g of PC2003 with 0.3018 g of IOC8 PF_6 (1 mol % per mol epoxy group) and 2.5 g of nitromethane. The monomer solution was mixed until homogeneous on a Vortex Genie II stirrer and then slowly poured into the quartz reaction vessel as the suspending medium was stirred at 1,500 rpm. The suspension was allowed to mix for 4 min and then the shutter was opened. The UV irradiation was continued for 5 min followed immediately by the addition of 0.25 mL of triethylamine to quench the polymerization. Light tan polymer particles were isolated by suction filtration using a 100-nm alumina filter membrane (Anodisc 47, Whatman International, Ltd., Maidstone, UK). The particles were washed with 500 mL of cyclohexane to remove residual monomer and suspending medium. The particles were transferred to a 60°C vacuum oven and dried overnight. A 75% yield of polymer microspheres was obtained as a white powder.

Microsphere characterization

Epoxy titration using the HCl–dioxane method[13]

A $0.2N$ solution of hydrochloric acid in 1,4-dioxane was prepared by pipetting 1.6 mL of concentrated HCl into 100 mL of 1,4-dioxane. Cresol red indicator solu-
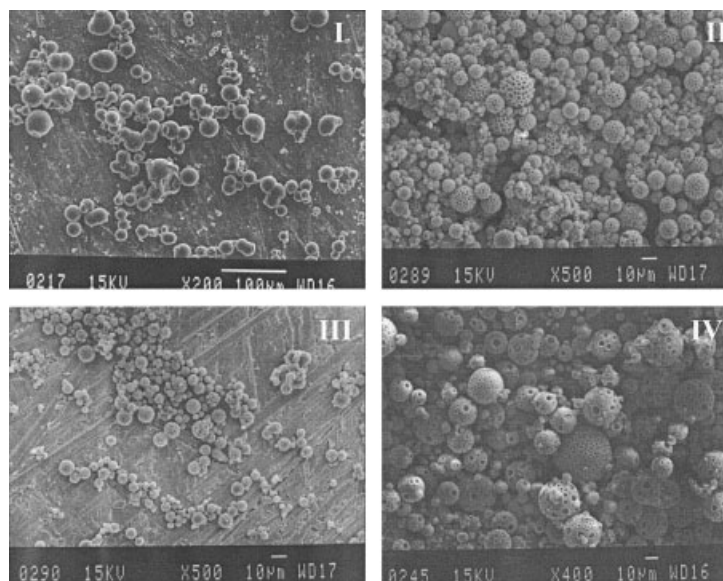
Figure 2 SEM images of the four types of polymeric microspheres used in this study. **II– IV** were synthesized using the aqueous suspension technique while **I** was produced using the nonaqueous suspension technique.

tion was prepared by adding 0.1 g of cresol red sodium salt to a 100 mL solution of 50% by volume ethanol and water. A sodium hydroxide solution (0.1M) was prepared by dissolving 4 g of sodium hydroxide in 1 L of methanol. The titration was performed as follows. The polymer microspheres (1.0 g) was added to a 250-mL Erlenmeyer flask. The HCl–dioxane solution 25 mL was then transferred using a pipette into the flask. The suspension was allowed to stand for 15 min and swirled occasionally. Ethanol (25 mL) and 5 mL of the indicator solution were added to the flask and the red solution was titrated with the sodium hydroxide solution until the suspension turned bright yellow. A blank was run in the absence of microspheres to determine the normality of the HCl–dioxane solution. A separate titration was performed on the microspheres in which the HCl solution was omitted. It was determined that the pH of the microspheres as prepared was neutral. The epoxy content was calculated from the following equation:

$$\frac{\text{mEq epoxy groups}}{100\text{g}} = \frac{(B - S)(N)}{10M}(1{,}000)$$

where B is the volume (mL) of sodium hydroxide solution used in titrating the blank; S is the volume (mL) of sodium hydroxide solution used in titrating the sample; N is the normality of sodium hydroxide solution; and M is the mass (g) of sample.

Hydroxy group determination

This procedure was adapted from ASTM E 222-00 Method C. Into a 1-L volumetric flask was placed 800

mL of 1,2-dichloroethane, 12 mL of 67–72% perchloric acid, and 110 mL of acetic acid. After the initial exothermic reaction was complete and the solution was cooled to room temperature, the solution was diluted to 1 L with 1,2- dichloroethane. The indicator solution was prepared by dissolving 0.10 g of cresol red in 13.1 mL of 0.02N sodium hydroxide solution and then diluted to 100 mL with water. Separately, 0.10 g of thymol blue was dissolved in 10.75 mL of 0.02N sodium hydroxide solution and then diluted to 100 mL with water. A mixture of 1 part of the cresol red solution and 3 parts of the thymol blue solution was used as the indicator solution.

Approximately 1 g of polymeric microspheres was added to a 250-mL Erlenmeyer flask. The acetylating agent (20.0 mL) was added and the mixture was left to stand for 30 min. 35 mL of a solution consisting of 600 mL of DMF, 300 mL of pyridine, and 100 mL of water was then added. The flask was covered with parafilm and placed in a 50°C oil bath for 30 min and then cooled to room temperature. Indicator solution (1 mL) was added into the flask, followed by the immediate titration with 0.5N methanolic sodium hydroxide solution to a violet endpoint. A blank titration was perfomed by following the same procedure but omitting the addition of the polymer. The hydroxyl number was calculated according to the following equation.

$$\text{Hydroxyl Number} = \frac{(A - B) \times N_t \times 56.1}{W}$$

where A is the NaOH solution (mL) required for blank; B is the NaOH solution (mL) required for so-

lution; N_t is the normality of the NaOH solution; and W is the mass of sample used (g).

Procedures for chemical modification of microspheres

The following general procedures were used for the derivitization of microsphere samples **I–IV** by reaction with various reagents. In all cases, the modified microspheres were isolated from their reaction mixtures by first washing and then filtering using a 100-nm alumina membrane followed by drying in a 60°C vacuum oven overnight.

Water

Deionized water (25 mL) and 0.1 g of microsphere sample **III** (0.0020 mol of epoxy groups) were added to a 100-mL round bottom flask. Perchloric acid (0.25 mL, 70%) was added and the suspension was stirred and heated under reflux for 30 min.

2-Phenoxyethanol

2-Phenoxyethanol (25 mL, 0.16 mol) was added to a 100-mL round-bottom flask equipped with a condenser and a magnetic stirrer. Microsphere sample **II** (0.25 g, 0.00032 mol epoxy groups) was added and the mixture was stirred in an oil bath at 60°C. Sulfuric acid (3 drops) was added to the reaction vessel and the reaction mixture was allowed to stir at 60°C for 12 h followed by isolation by filtration and washing first with 500 mL of dichloromethane and then with 500 mL of cyclohexane.

Hydrochloric acid

II (1.0 g, 0.0013 mol of epoxy groups) was added to 25 mL of dioxane. A 25-mL aliquot of a 0.2N HCl solution in 1,4-dioxane was added and the mixture was agitated for 15 min. The chlorohydrin functionalized microspheres were isolated by suction filtration and washed first with 1,4-dioxane and then with distilled water.

2-Naphthoyl chloride

Dry toluene (50 mL) and 1.0 g of **IV** (0.157 mol of hydroxy groups) were placed into a 100-mL three-neck round-bottom flask equipped with a condenser. 2-Naphthoyl chloride and 0.63 g of 1,4-diazobicyclo-[2.2.2]octane (DABCO) were added and the suspension was heated at reflux temperature for 23 h. The product was filtered and washed with 500 mL of toluene followed by 500 mL of acetone.

1-Naphthyl isocyanate

IV (1.0 g, 0.157 mol of hydroxy groups) was added to a 100-mL three-neck round- bottom flask equipped with a condenser, magnetic stirrer, and nitrogen inlet. The flask was purged with nitrogen and 50 mL of dry toluene was added. 1-Naphthyl isocyanate (2 g, 0.012 mol) was added to the flask and the mixture heated at reflux temperature for 40 h. After cooling, the suspension was centrifuged in 50 mL polypropylene centrifuge tubes at 10,000 rpm for 10 min. The supernate liquid was decanted and the polymer particles were resuspended in 30 mL of toluene and then once again centrifuged. This process was repeated three times with toluene followed by two additional washings with N,N-dimethylformamide. The particles were transferred to a petri dish and dried overnight in a 60°C vacuum oven.

Methacryloyl chloride

Dry toluene (25 mL) and 10 mL of methacryloyl chloride were added to a 100-mL round-bottom flask equipped with a condenser. Pyridine (3 drops) was added, followed by 0.25 g of **III.** The solution was heated under reflux for 5 h. The reaction vessel was allowed to cool to room temperature and methanol was added dropwise to react with the excess methacryloyl chloride. The light purple microspheres were isolated by filtration and washed with 500 mL of methanol followed by 500 mL of acetone.

2-Mercaptobenzothiazole

Triton B (0.10 g of 40% benzyltrimethylammonium hydroxide in methanol) was added to 50 mL of ethanol and 2.40 g (0.014 mol) of 2-mercaptobenzothiazole in a 100- mL round-bottom flask fitted with a reflux condenser and magnetic stirbar. Epoxy functional microspheres (1.0 g of **I**, 0.00359 mol epoxy groups) were added and the suspension was heated under reflux for 24 h. The product was isolated by centrifugation followed by washing three times with a total of 150 mL of ethanol, centrifuging between each wash. The particles were suspended in a small amount of ether and transferred to a 500-mL beaker and allowed to air dry. They were then placed in a 60°C vacuum oven overnight.

Sodium azide

To a 250-mL three-necked flask equipped with a condenser and a magnetic stirrer were added microspheres (2.0 g of **I**, 0.0072 mol of epoxy groups), 1.9 g (0.03 mol) of sodium azide, 25 mL of acetone, and 25 mL of deionized distilled water. The reaction mixture was placed in an oil bath, brought to reflux, and held

at this temperature for 23 h. Following suction filtration, the spheres were washed first with water (250 mL) and then with acetone (250 mL).

4-Nitrophenol

Dry dioxane (25 mL), 0.10 g of 18-crown-6 ether, and 0.15 g of potassium hydroxide were added to a 50-mL round-bottom flask equipped with a condenser. **II** (0.25 g, 0.00032 mol epoxy groups) was added to the yellow solution and the reaction mixture was brought to reflux using an oil bath. After 16 h, the polymeric microspheres were isolated by suction filtration and washed with acetone (500 mL) and methylene chloride (500 mL).

Addition of thiophenol and benzyl mercaptan

Absolute ethanol (25 mL) was added to a 100-mL round-bottom flask equipped with a condenser and a magnetic stirbar. Potassium hydroxide was added (0.15 g, 0.0027 mol) and 20 mL of either thiophenol (0.17 mol) or benzyl mercaptan (0.15 mol) was added and the pale yellow solution was mixed until homogenous. Epoxy functional microspheres (**II**) (0.25 g; 0.00032 mol of epoxy groups) were added and the flask was placed in an oil bath and the reaction mixture was heated under reflux for 16 h. The thiol- ester modified microspheres were filtered and washed successively with 500 mL of ethanol, 500 mL of acetone, and, finally, 250 mL of dichloromethane.

Benzyl amine

Benzyl amine (25 mL) was placed in a 100-mL round-bottom flask equipped with a magnetic stirbar and a reflux condenser. Epoxy functional polymeric microspheres (0.25 g of **II,** 0.00051 mol of epoxy groups) were added followed by 3 drops of boron trifluoride–terahydrofuran complex. The reaction vessel was heated under reflux for 48 h and then isolated and washed with 500 mL of toluene and 500 mL of dichloromethane.

RESULTS AND DISCUSSION

Synthesis of epoxy-functional microspheres

Employing the basic concept described in Scheme 1, we have used the epoxy–silicone oligomer PC2003 containing an average of nine functional groups per molecule for the synthesis of microspheres by cationic ring-opening suspension photopolymerization.[14] The structure of PC2003 as shown below bears epoxycyclohexyl groups tethered as pendant groups by nonhydrolyzable carbon–silicon bonds. Since this oligomer is quite viscous, we have also employed PC1000 and nitromethane, respectively, as reactive and inert diluents to lower the viscosity. Although various onium salt cationic photoinitiators can be employed, in this communication we have made exclusively use of diaryliodonium salts, such as IOC15-bearing long chain alkoxy groups, that are soluble in the above epoxy–silicone substrates.

PC2003

PC1000

IOC15
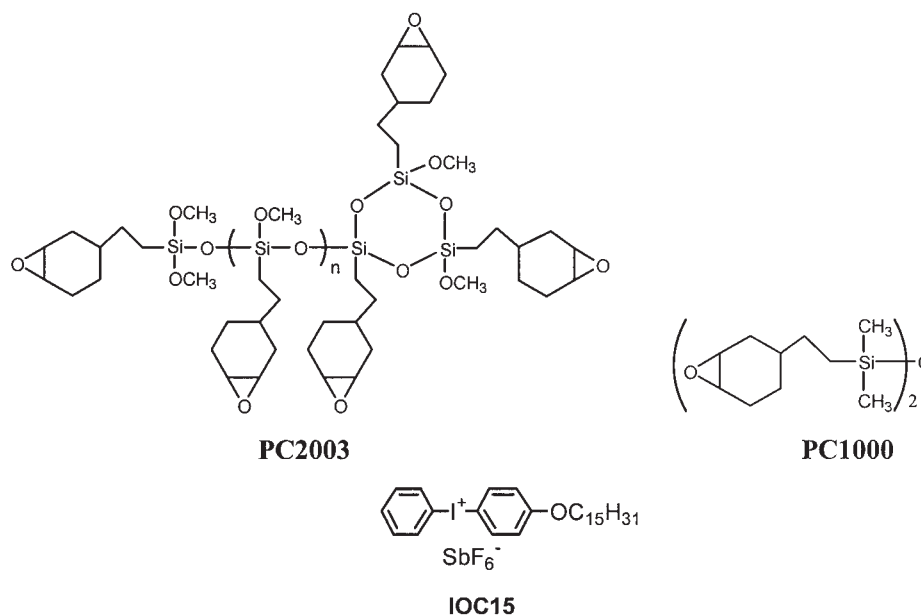
The high reactivity of the two epoxy–silicone monomers in cationic ring-opening photopolymerizations has been well documented in prior publications from this laboratory.[15,16] When these monomers are sus-

pended under conditions of high agitation in a UV-transparent medium such as mineral oil or water, small droplets are formed that undergo rapid crosslinking photopolymerization resulting in formation of solid spherical particles. Photopolymerization times are very short and typically on the order of 1 to 5 min. Microspheres prepared in mineral or silicone oils bear exclusively epoxy functional groups at their surfaces. In contrast, when the photopolymerizations are carried out in water, a small amount of acid-catalyzed hydrolytic ring-opening reaction with water also takes place and the resulting microspheres contain both epoxy and hydroxy groups. Typically, the microspheres can be prepared as solid spherical beads. Alternatively, highly porous beads can be prepared by the incorporation of porogens such as decahydronaphthylene or bicyclohexyl that undergo phase separation from the polymer during photopolymerization. SEM studies have shown that the pores occur randomly throughout the bulk of the microsphere and are at least partially interconnected. Porous beads have a larger surface area than their solid counterparts and, therefore, possess a higher level of available epoxy groups that can be used for further derivitization.

It was initially surprising that it was possible to effectively conduct cationic ring- opening suspension photopolymerizations of epoxides using water as a suspending medium. It appears that one reason for the success of these polymerizations is a result of the very low solubility of water within droplets of the highly hydrophobic epoxy–silicone monomers. Thus, polymerization takes place readily within the essentially water-free center of the monomer droplet and progresses outward toward the surface, where further polymerization is inhibited and where chain transfer and water addition reactions predominate. An additional reason is, since the monomer is very highly functional ($\sim$ 9 epoxy groups/molecule), the system can tolerate modest levels of the above side reactions and still produce highly crosslinked microspheres. Aqueous suspension photopolymerizations can be carried out to make microspheres with diameters as small as approximately 1 μm. Below this limit, the surface to volume ratio increases so as to favor the side reactions rather than polymerization, and solid microspheres are not obtained.

Using the above-described synthetic methods, four different samples of microspheres were prepared and their characteristics are displayed in Table I. Microsphere sample I was prepared by suspension polymerization in mineral oil while the remaining samples were prepared using aqueous suspension polymerizations in the presence of various porogens. As may be noted, the epoxy content in samples I–III as determined by titration ranged from 127 to 359 mEq/g microspheres.

## Chemical modification of epoxide-functional microspheres

Epoxide-functional microspheres were subjected to a number of chemical modification reactions that involve opening of the epoxide ring. These facile reactions fall into two basic classifications: acid-catalyzed addition reactions and base-catalyzed addition reactions. Selected examples of these derivitization reactions are presented in the following two sections and demonstrate the general utility of epoxy-functional microspheres in potential applications. After reaction, the microbeads were exhaustively washed with various solvents to remove traces of starting reagents. The resulting modified microspheres were characterized chiefly by the use of infrared spectroscopy.

Acid catalyzed epoxide ring-opening addition reactions

In Scheme 2 are shown the acid-catalyzed reactions that were performed on epoxy-functional microspheres. Acid-catalyzed ring-opening addition reactions of water and alcohols to oxiranes, especially cycloaliphatic oxiranes, occur rapidly at moderate temperatures.[17,18] A sample of microspheres (III) was refluxed for a short time with a mixture of perchloric acid and water. Under these conditions, water undergoes addition to the epoxycyclohexane group to give the corresponding glycol in high yields.[19] Shown in Figure 3 are the IR spectra obtained comparing III before [Fig. 3 (a)] and after [Fig. 3 (b)] the addition reaction with water. There is a large peak at 880 cm^{-1} that is assigned to the epoxy peak in the spectrum of unmodified III. After the water addition, the epoxy peak was dramatically reduced. Similar results were obtained when hydrochloric acid was added across the epoxy group to form the chlorohydrin-functionalized microspheres.

To examine the addition of an alcohol to the microspheres, 2-phenoxyethanol was selected to provide characteristic and unobscured aromatic absorption bands for IR spectral analysis. 2-Phenoxyethanol was combined with microsphere sample III together with a catalytic amount of sulfuric acid and the addition reaction was conducted at 60°C in an oil bath. The IR spectra of the microspheres (III) before [Fig. 4 (a)] and after [Fig. 4 (b)] the addition of 2-phenoxyethanol are shown in Figure 4. A dramatic decrease in the epoxy band at 880 cm^{-1} was observed together with the formation of aromatic absorptions at 1600 and 1497 cm^{-1} due, respectively, to the benzene quadrant and semicircle stretching vibrations.[20]

Primary amines are well known to react with epoxides.[21,22] However, if the amine or the epoxide is sterically hindered, addition can be slow even at elevated temperatures, and Lewis acids are required to catalyze the reaction.[23,24] This is the case with the epoxycyclo-
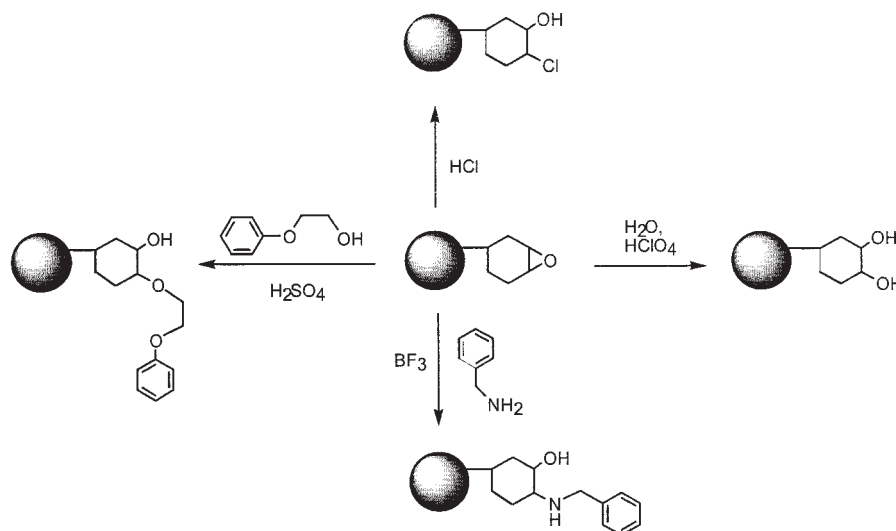
Scheme 2

hexane groups bound to the surface of the microspheres. To examine the efficiency of this reaction, a sample of microspheres (**II**) was refluxed with benzylamine in the presence of a trace of boron trifluoride–tetrahydrofuran complex. The FT-IR spectrum (Supplementary Fig. 1) shows the absence of the epoxy band that is replaced by the relatively weak bands located at 1540 and 1695 cm^{-1} that correspond to the phenyl group. Under these conditions benzylamine adds across the cycloaliphatic epoxy group.

Base-catalyzed ring opening addition reactions

Scheme 3 depicts several base-catalyzed and nucleophilic epoxide ring-opening reactions that were con-

ducted on epoxy-functional microspheres during the course of this investigation. The azide anion is a strong nucleophile that undergoes a facile ring-opening reaction with the epoxy groups of the microspheres to introduce both azide- and hydroxy-functional groups.[25] The appearance of the especially strong, sharp IR absorption band at 2095 cm^{-1} due to the azide group is evident in the spectrum shown in Figure 5 coincident with the collapse in the epoxy band at 880 cm^{-1} indicating that this reaction proceeds to completion.

Mercaptans also readily undergo nucleophilic addition reactions to the oxirane ring under basic conditions.[26–28] The reaction of microsphere sample **I** pre-
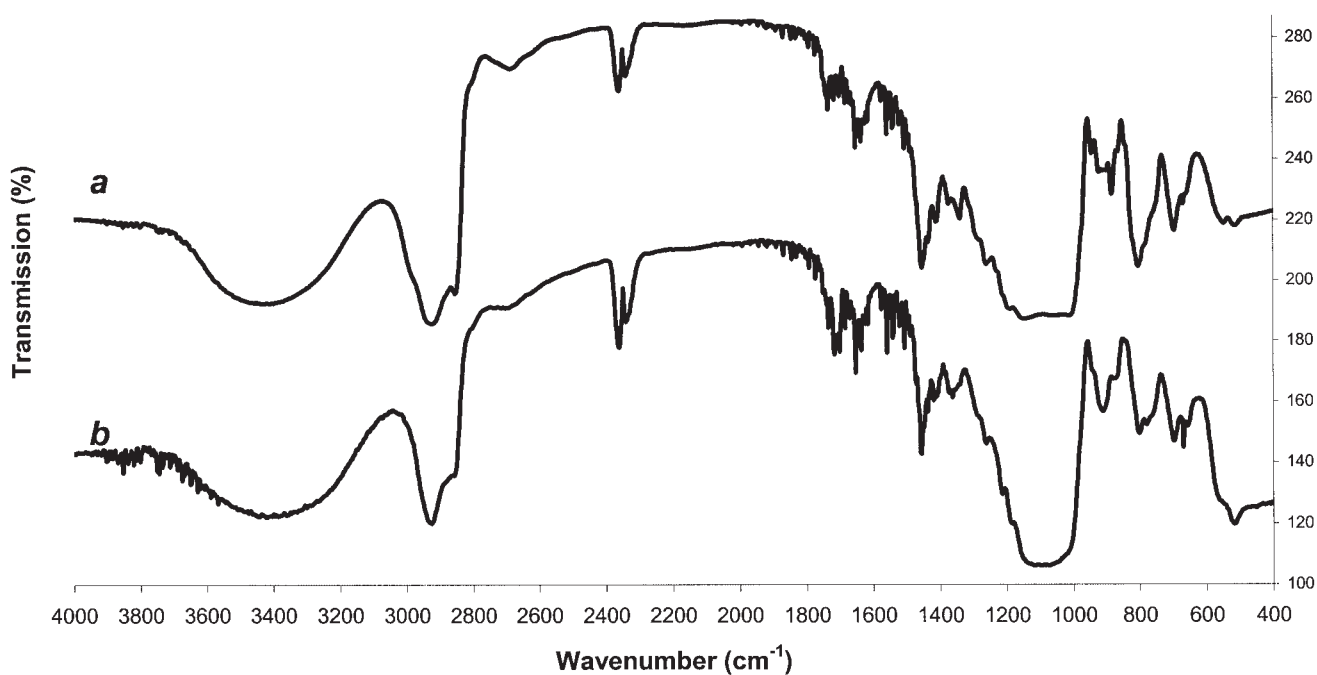

Figure 3 FT-IR spectra of **III** before (a) and after (b) the ring-opening addition of water.
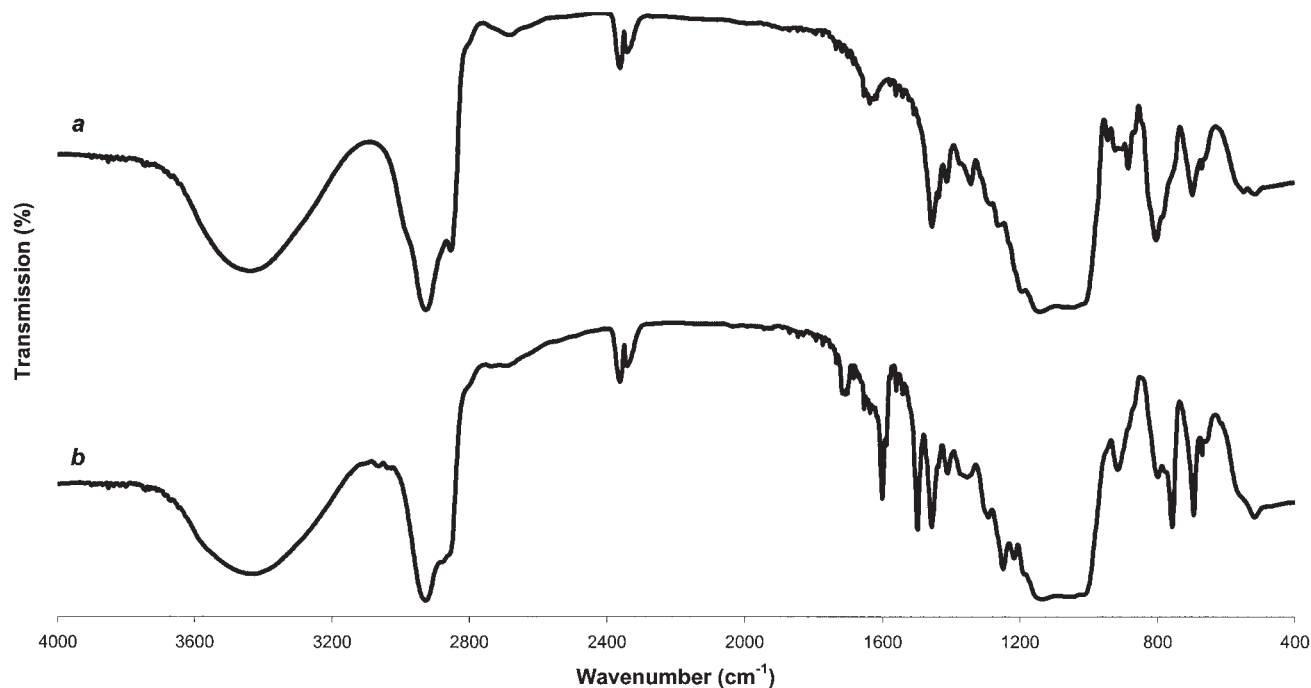
Figure 4 FT-IR spectra of **III** before (a) and after (b) the ring-opening addition of 2- phenoxyethanol.

pared by the suspension photopolymerization of PC2003 containing 25 wt % nitromethane in mineral oil with 2-mercaptobenzothiazole was carried out using methanolic benzyltrimethylammonium hydroxide (Triton B) as a catalyst. The results are depicted in Figure 5. After reaction, a band appears at 1425 cm^{-1} that is due to the aromatic ring in 2- mercaptobenzothiazole.

Similarly, benzyl mercaptan, thiophenol, and 2-mercaptobenzothiazole were successfully bound to the surface of the microspheres. The reactions with microsphere sample **II** were carried out under reflux using

ethanolic potassium hydroxide as a catalyst. Once again, during the addition reactions the epoxide band at 880 cm^{-1} disappears and aryl absorption bands appear at 1462, 1581, and 3050 cm^{-1} for thiophenol and similar bands at 1492 and 3020 cm^{-1} appear for benzyl mercaptan (Supplementary Fig. 2).

Carboxylic acid halides undergo base-catalyzed addition to epoxy groups.[29] Methacryloyl chloride was added to the polymeric microspheres (**III**) in the presence of a trace amount of pyridine as a catalyst. The acid chloride adds directly to the epoxy group and, further, reaction also takes place with any hydroxy
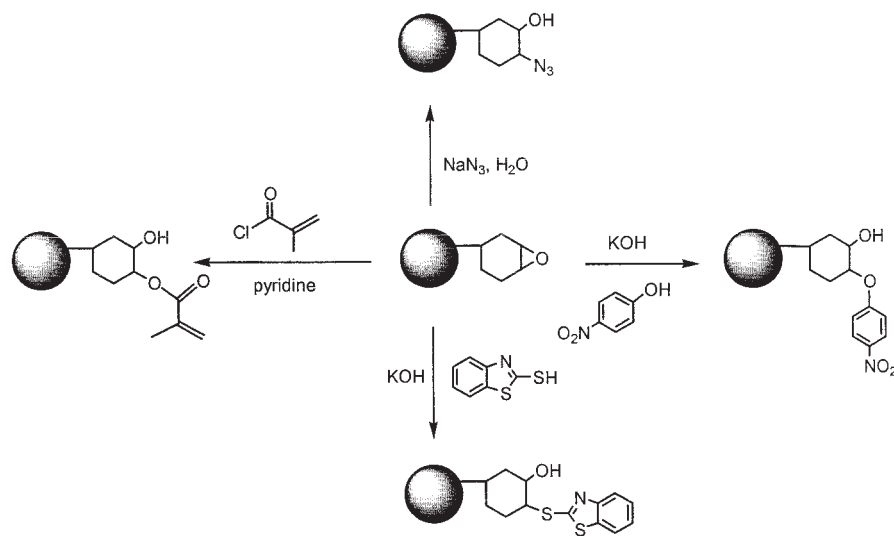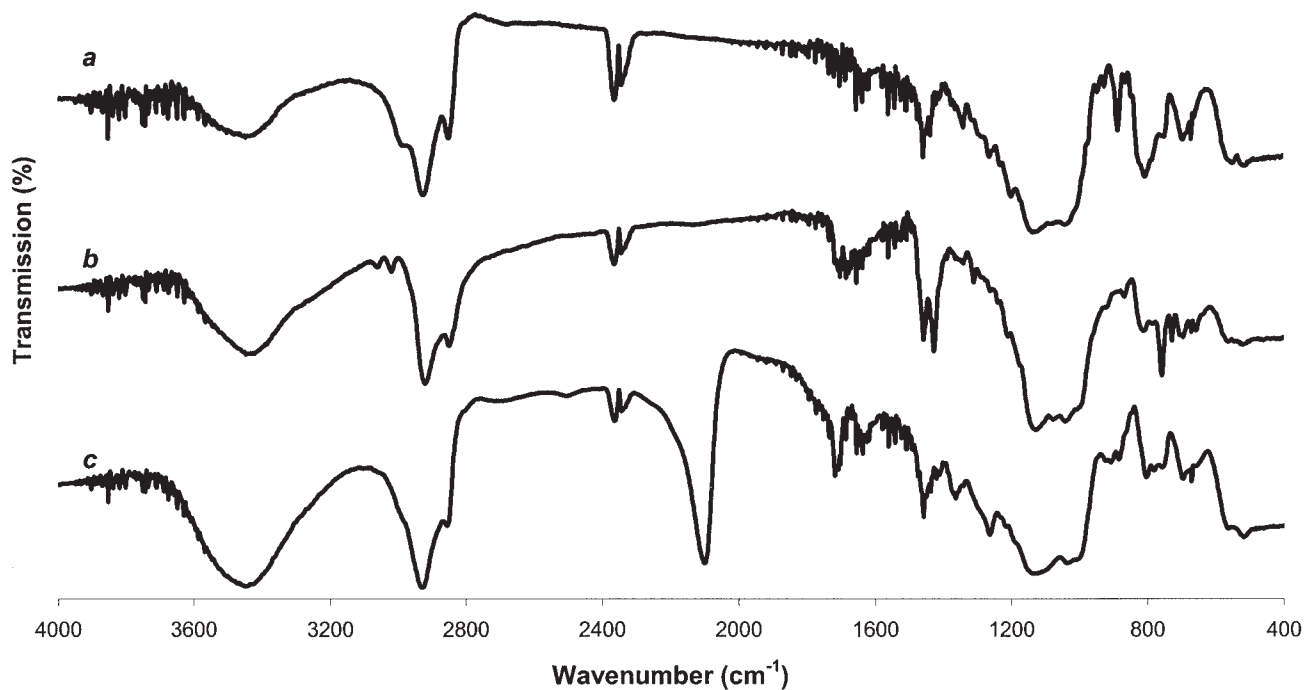

Scheme 3

Figure 5 FT-IR spectra of microspheres (**I**) synthesized by nonaqueous suspension photopolymerization (a) and modified microspheres with 2- mercaptobenzothiazole (b) and sodium azide (c).

groups present on the surface of the microspheres producing hydrochloric acid as a byproduct. It is, therefore, necessary to add a sufficient amount of pyridine both to catalyze the addition reaction as well as to react with the hydrochloric acid that is also formed. This avoids unintentional reaction of hydro-

chloric acid with epoxide groups. Shown in Figure 6 are the FT-IR spectra of **III** before and after the methacryloyl chloride addition reaction. The appearance of the strong bands at 1715 and 1636 cm^{-1} are attributed to the carbonyl group and vinyl groups of the bound methacrylate esters, respectively.
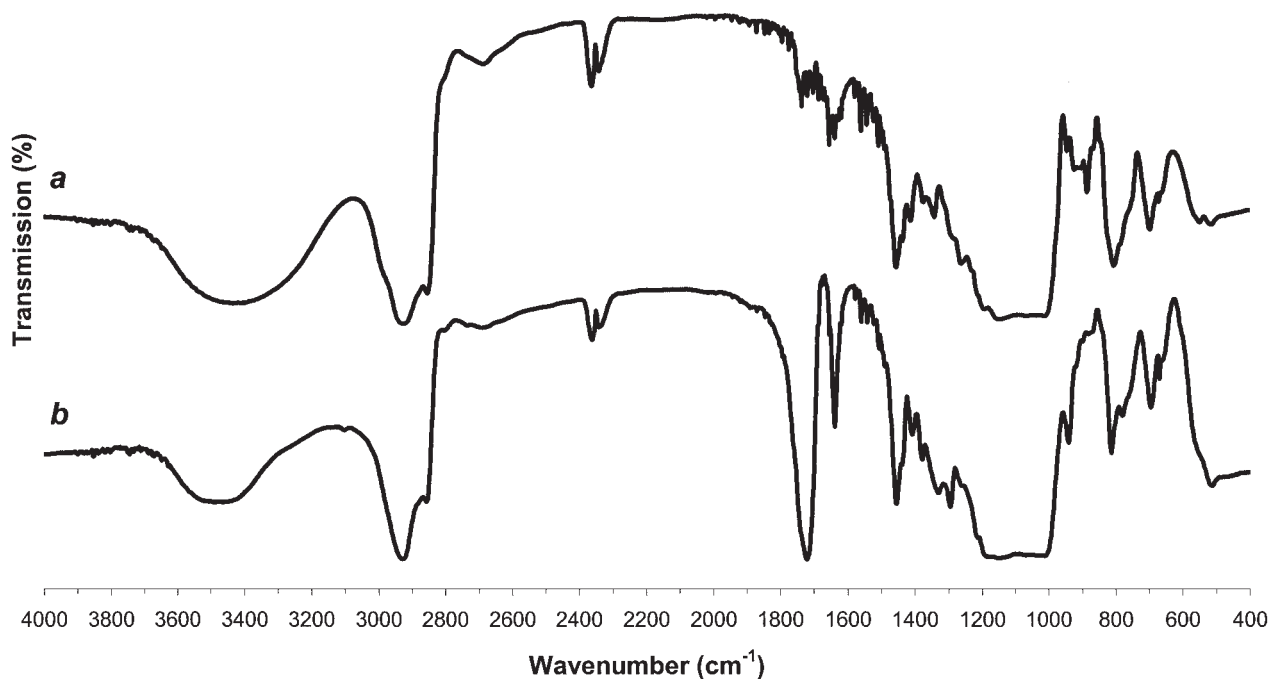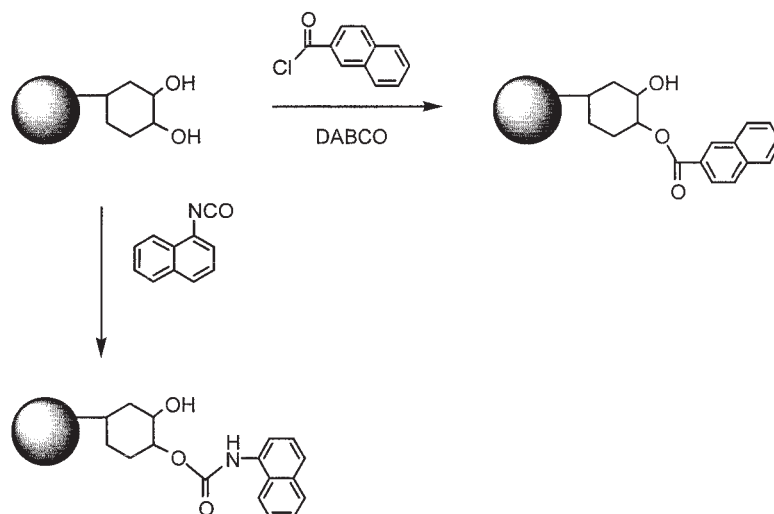

Figure 6 FT-IR spectra of **III** before (a) and after (b) the ring-opening addition of methacryloyl chloride.

Scheme 4

Phenols react with epoxy groups under basic conditions.[30–32] In the present case, we chose to examine the addition of 4-nitrophenol to microspheres (**III**). The reaction was carried out under reflux conditions and catalyzed using an aqueous solution of potassium hydroxide in dioxane with 18-crown-6 as a phase transfer catalyst. The FT-IR spectra (Supplementary Fig. 3) show that a dramatic reduction in the epoxide band at 880 cm^{-1} was observed together with the appearance of bands at 1514, 1340, and 844 cm^{-1} due to the nitro group as well as peaks at 1591 and 1258 cm^{-1} that are assigned to the phenyl ring.

Hydroxy-functional microbeads

As mentioned previously, microspheres produced by cationic ring-opening photopolymerizations carried out in aqueous suspensions contain an appreciable number of surface hydroxy groups due to inadvertent reaction with water. To further increase the hydroxy content, one can carry out the acid-catalyzed ring-opening addition of water as described previously. Alternatively, adjusting the reaction parameters for the aqueous suspension photosynthesis of the polymeric microspheres, hydroxy-functional microspheres can be obtained directly. During the synthesis of microsphere sample **IV** the reaction mixture was exposed to the UV source for an extended amount of time as compared to samples **II** and **III.** The increase in the uv exposure as well as the extended contact time with water results in a dramatic increase in the hydroxy content of the microspheres. As may be noted in Table I, sample **III** has a very high hydroxy content (57 mEq/g). The FT-IR spectrum of this sample of microspheres shows the absence of a band at 830 cm^{-1}, indicating that nearly all the epoxy groups have been consumed.

Chemical modification of hydroxy-functional microspheres

Several chemical modifications on hydroxy functional microspheres were carried out. These are depicted in a general fashion in Scheme 4. Shown in Figure 7 are the FT- IR spectra of microsphere sample **IV** before [Fig. 7 (a)] and after the additions of 2-naphthoyl chloride [Fig. 7 (b)] and 1-naphthyl isocyanate [Fig. 7 (c)]. The addition of 2-naphthoyl chloride was performed in the presence of the acid acceptor 1,4-diazobicyclo[2.2.2]octane (DABCO). Evidence of the presence of the aryl ester group is clearly apparent by the appearance of bands at 1281 and at 1715 cm^{-1}.

Similarly, the addition of isocyanates to hydroxy groups is well-established chemistry.[33,34] 1-Naphthyl isocyanate was added to microspheres (**IV**) in toluene and refluxed for 2 days. The FT-IR spectrum of the product (Supplementary Fig. 1, spectrum c) indicate that there is a considerable growth in a peak at 1660 cm^{-1} due to the α-substituted naphthalene moiety. Several bands appearing in the region 1490 to 1550 cm^{-1} and from 1200 to 1390 cm^{-1} are attributed, respectively, to the amide II and III absorbances of the urethane group.[20]

CONCLUSION

Epoxy- and hydroxy-functional microspheres were produced using both aqueous and nonaqueous suspension photopolymerization techniques. Hydroxy-functional microspheres can be obtained by either ring-opening addition of water to epoxy functional groups or by modifying the synthesis parameters of the photopolymerization. Both acid- and base-catalyzed ring-opening addition reactions were performed on the epoxy-functional microspheres. These reactions
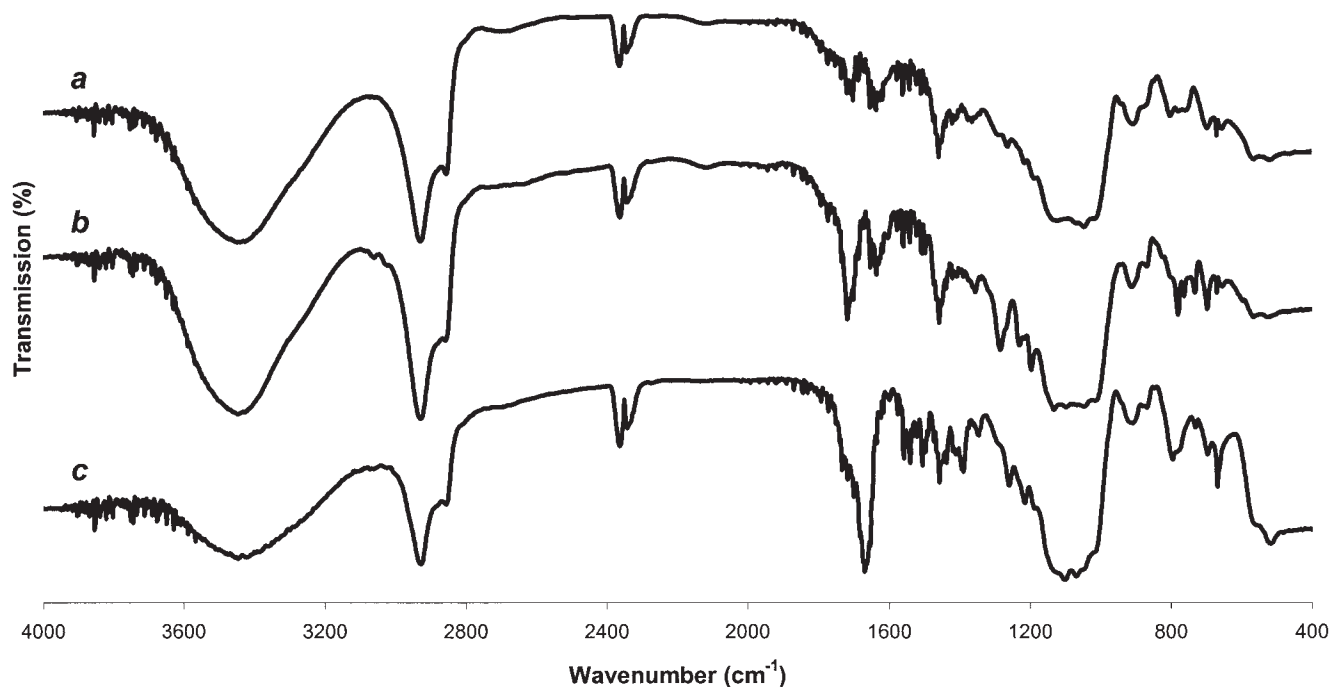
Figure 7 FT-IR spectra of the hydroxy functional microspheres (**IV**) before (a) and after the modification with 2-naphthoyl chloride (b) and 1-napthyl isocyanate (c).

include addition of alcohols, aryl and alkyl mercaptans, alkyl amines, and sodium azide. By varying the reaction conditions of the synthesis of microspheres, hydroxy-functional particles can be obtained directly from the reaction vessel. These highly hydroxy-functional microspheres were further modified with isocyanates and acid chlorides. This initial survey of the reactivity of the epoxy- or hydroxy-functional microspheres is by no way complete. Further investigation of the plethora of chemical modifications and applications is ongoing in this laboratory.

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