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Synthesis and Characterization of Highly Cross-Linked Polyacrylamides and Polymethacrylamides. A New Class of Macroporous Polyamides

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ABSTRACT: The polymerization of *N*-methylacrylamide (**1a**) and *N*-methylmethacrylamide (**1b**) with alkylbis(acrylamide) and alkyl- and arylbis(methacrylamide) cross-linkers was studied. The polymerizations were carried out in bulk with free-radical initiation (AIBN) in the presence of various solvents (porogens). Nonporous materials resulted from polymerizations with cross-linkers that contained flexible tethers. Cross-linkers with rigid hydrocarbon or aromatic tethers gave rise to macroporous materials. The more polar solvents (H_2O, MeOH) produced materials with higher surface area and internal pore volume than those of identical materials prepared with less polar solvents (DMSO). Analysis of the solvatochromic shift of the *N,N*-(dimethylamino)naphthalenesulfonamide (dansyl) probe, covalently incorporated into the polyacrylamide networks, revealed that these matrices are permeable to polar solvents and less permeable to nonpolar solvents. Functionalization of these materials is readily achieved by copolymerization using suitably functionalized monomers.

Molecular imprinting by template polymerization[1] places stringent demands on the materials used to provide the rigid matrix. As more sophisticated applications of this procedure emerge, a wider range of materials will be necessary to satisfy these demands. Our previous efforts with molecular imprinting utilized macroporous styrene/divinylbenzene[2,3] and styrene/diisopropenylbenzene[4,5] copolymers (ca. 50% nominal cross-linking). These relatively hydrophobic, highly cross-linked materials provided both rigidity and chemical inertness needed to withstand the subsequent chemical transformations. The design of synthetic, enzyme-like catalysts by molecular imprinting may require a more hydrophilic matrix in addition to rigidity, high surface area, and chemical inertness. A proteinaceous material was deemed as most suitable for the aqueous-based chemistry, and a survey of network polyacrylamides was undertaken.

The most common polyacrylamide networks are cross-linked lightly with methylenebis(acrylamide) (2–5%)[6] or with 1,4-bis(1-oxo-2-propenyl)piperazine.[7] The former is hydrolytically unstable. The polyacrylamide gels formed by copolymerization of *N,N*-dimethylacrylamide and 1,2-ethylenediaminebis(acrylamide) (6%)[8] or from *N*-(pyrrolidylamino)acrylamide and 1,2-ethylenediaminebis(acrylamide) (5%)[9] under reverse-phase emulsion polymerization conditions are used as supports for solid-phase synthesis.[10] These materials swell up to 20 times their original size in polar protic solvents. More closely related to the current work are the macroporous styrene/divinylbenzene (26%) copolymers of Sherrington and Akelah, which employ pendent *p*-*N,N*-dimethylcarboxamide functionality on the styrene residues.[11] These give a somewhat polar-macroporous material with the chemical resistance of polystyrene.

Macroporous polyacrylamide networks were targeted that would hopefully possess the elements of rigidity, hydrophilicity, and low chemical reactivity. To this end, we report the preparation of a number of highly cross-linked copolymers of *N*-methylacrylamide (**1a**) or *N*-methylmethacrylamide (**1b**) with alkyl- and arylbis(acrylamide) and -bis(methacrylamide) cross-linkers (**2–7**). In the present study, an effort has been made to systematically vary both the nature of the cross-linker, percent cross-linker, and choice of porogen in order to understand relationships between these variables and the morphology of the resulting material. Furthermore, since molecular imprinting often introduces latent functional groups by copolymerization followed by subsequent chemical modification to liberate the functionality, the gel phase must be permeable to both reagents and solvents. To examine this property, both chemical and spectroscopic diagnostics have been employed. Finally, the introduction of functional groups into these networks by copolymerization has also been investigated.

Experimental Section

General Procedures. Proton nuclear magnetic resonance spectra (^{1}H NMR) were recorded on Bruker WM-250 (250-MHz), General Electric QE-300 (300-MHz), or General Electric GN-500 (500-MHz) spectrometers.

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Fluorescence emission and excitation spectra were measured with a Hitachi Perkin-Elmer MPF-2A spectrophotometer equipped with a cuvette stirrer. A Nicolet 5DXB FTIR spectrophotometer was used to obtain infrared spectra (IR). A Thomas Hoover capillary melting point apparatus was used to observe uncorrected melting points.

Low-resolution mass spectral data were acquired on a Finnigan Model 4000 GC/MS/DS and are reported as mass/charge (CI, isobutane) or mass/charge (EI, 70 eV) and percent relative abundance. High-resolution mass spectra (E1, 22 eV, unless otherwise stated) were obtained on a VG 7070e high-resolution mass spectrometer.

Elemental analyses were performed by Galbraith Laboratories, Inc. (Knoxville, TN). Scanning electron micrographs (SEMs) were obtained at the UCI Electron Microscope Facility. BET surface area analysis was carried out by Quantachrome Corp. (Syosset, NY).

All reagents and solvents were obtained from commercial suppliers and were purified according to standard procedures.[12] Reactions were conducted in oven-dried (160 °C) or flame-dried glassware under a positive nitrogen atmosphere unless otherwise stated.

N-Methyl-2-propenamide (1a). Into a solution of acryloyl chloride (7.76 mL, 95.7 mmol) in THF (150 mL) was added dropwise 40% (w/w) aqueous methylamine (16.5 mL, 191 mmol) at 0 °C. This was stirred at room temperature overnight. The layers were separated, and the aqueous layer was extracted with ether (2 × 100 mL). The organics were combined, dried ($MgSO_4$), and evaporated to provide a light yellow oil. This oil was then passed through a plug of silica with ether/hexane (1/1) as eluent. An inhibitor, hydroquinone monomethyl ether (1 mg), was added, and the monomer was flash distilled on a high-vacuum line (0.1 mmHg, 60 °C) to give a clear oil (6.68 g, 82%). ^{1}H NMR (250 MHz, $CDCl_3$): δ 7.50 (br s, 1 H, NH), 6.25 (m, 2 H, vinyl), 5.60 (dd, 1 H, J = 5.2 and 6.7 Hz, vinyl), 2.86 (d, 3 H, J = 4.9 Hz, NCH_3). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 167.4, 131.4, 126.1, 26.7. IR (neat): 3284 (br), 1656, 1626, 1562, 1406, 1252, 1163, 986, 960, 807 cm^{-1}.

N,2-Dimethyl-2-propenamide (1b). The above procedure for **1a** was followed with methacryloyl chloride (9.35 mL, 95.7 mmol) in place of acryloyl chloride. The distilled product was a clear oil (7.68 g, 81%). ^{1}H NMR (250 MHz, $CDCl_3$): δ 6.72 (br s, 1 H, NH), 5.71 (t, 1 H, J = 1.0 Hz, vinyl), 5.31 (quin, 1 H, J = 1.4 Hz, vinyl), 2.85 (d, 3 H, J = 4.9 Hz, NCH_3), 1.96 (q, 3 H, J = 0.8 Hz, $C{=}CCH_3$). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 169.9, 140.4, 119.9, 27.0, 19.2. IR (neat): 3325 (br), 2957, 1656, 1616, 1542, 1456, 1410, 1328, 1225, 1157, 929 cm^{-1}.

N,N'-1,2-Ethanediylbis(2-propenamide) (2).[13] To a solution of acryloyl chloride (18.0 mL, 222 mmol) in acetonitrile (500 mL) at 0 °C was added dropwise a mixture of diaminoethane (14.9 mL, 223 mmol) in acetonitrile (300 mL). After addition, the reaction was stirred at room temperature for 3 h. The salts were filtered and washed thoroughly with hot acetonitrile. The combined filtrates were concentrated to approximately 250 mL and placed in a freezer (−20 °C). After 24 h, white platelike crystals were filtered out, the solution was further concentrated, and additional crystals were grown. Several crystallizations provided 15.3 g (84%) product (mp 138–139 °C). ^{1}H NMR (250 MHz, $CDCl_3$): δ 6.86 (br s, 2 H, NH), 6.27 (dd, 2 H, J = 1.8 and 17.1 Hz, vinyl), 6.16 (dd, 2 H, J = 9.8 and 17.0 Hz, vinyl), 5.66 (dd, 2 H, J = 1.8 and 9.8 Hz, vinyl), 3.51 (m, 4 H, NCH_2). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 167.6, 131.3, 127.4, 40.8. IR (KBr): 3249, 3083, 2883, 1656, 1624, 1563, 1478, 1407, 1251, 1064, 985, 960, 791, 716 cm^{-1}.

N,N'-1,2-Ethanediylbis(2-methyl-2-propenamide)[13] (3). The procedure for preparing **2** was followed with methacryloyl chloride (21.7 mL, 222 mmol) in place of acryloyl chloride. This reaction provided 19.6 g (90%) of platelike crystals (mp 169–170 °C). ^{1}H NMR (250 MHz, $CDCl_3$): δ 6.92 (br s, 2 H, NH), 5.75 (s, 2 H, vinyl), 5.35 (t, 2 H, J = 1.4 Hz, vinyl), 3.49 (m, 4 H, NCH_2), 1.96 (m, 6 H, $C{=}CCH_3$). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 170.3, 139.9, 120.9, 41.0, 19.2, 19.1. IR (KBr): 3350, 1654, 1615, 1542, 1442, 1302, 1241, 1216, 928, 890 cm^{-1}.

N,N'-1,4-Butanediylbis(2-methyl-2-propenamide) (4). The procedure for preparing **2** was followed by using methacryloyl chloride (14.0 mL, 143 mmol) and 1,4-diaminobutane (Aldrich; 11.9 g, 135 mmol). Several crystallizations provided white plates (11.8 g, 78%, mp 122–123 °C). ^{1}H NMR (250 MHz, $CDCl_3$): δ 6.22 (br s, 2 H, CONH), 5.70 (d, 2 H, J = 1.0 Hz, vinyl), 5.32 (t, 2 H, J = 1.4 Hz, vinyl), 3.35 (q, 4 H, J = 6.3 Hz, $CONHCH_2$), 1.96 (d, 6 H, J = 1.2 Hz, CH_3), 1.60 (m, 4 H, CH_2CH_2). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 169.2, 140.8, 119.9, 39.8, 30.1, 26.7, 19.4. IR (KBr): 3321, 2944, 1652, 1605, 1534, 1482, 1212, 926 cm^{-1}. MS (CI, isobutane, relative percent): m/z 225 (MH^+, 100), 185 (3), 172 (1), 156 (6), 142 (3), 140 (6), 138 (5), 128 (3), 126 (3), 114 (4), 112 (4), 102 (12), 98 (5), 88 (21), 86 (19), 85 (23), 83 (13), 81 (17), 71 (20), 70 (19). High-resolution MS (CI, methane, 50 eV). Calcd for $C_{12}H_{20}N_2O_2$: 225.1603. Found: 225.1619.

N,N'-Hexanediylbis(2-methyl-2-propenamide)[13] (5). A procedure similar to the preparation of **2** was followed by using methacryloyl chloride (17.5 mL, 179 mmol) in acetonitrile (500 mL) and 1,6-diaminohexane (Aldrich; 24.0 g, 207 mmol) in acetonitrile (200 mL). After several crystallizations, the white crystals were combined (18.1 g, 80%, mp 108–110 °C). ^{1}H NMR (250 MHz, $CDCl_3$): δ 6.02 (br s, 2 H, CONH), 5.69 (d, 2 H, J = 0.6 Hz, vinyl), 5.31 (m, 2 H, vinyl), 3.30 (q, 4 H, J = 6.6 Hz, $CONHCH_2$), 1.97 (d, 6 H, J = 0.8 Hz, CH_3), 1.55 (m, 4 H, $CONHCH_2CH_2$), 1.37 (m, 4 H, CH_2CH_2). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 169.2, 140.8, 119.9, 39.8, 30.1, 26.7, 19.4. IR (KBr): 3334, 2933, 2856, 1655, 1616, 1541, 1460, 1433, 1376, 1317, 1226, 1178, 925 cm^{-1}.

N,N'-1,3-Phenylenebis(2-methyl-2-propenamide) (6). In a manner similar to the preparation of **2**, methacryloyl chloride (20.0 mL, 205 mmol) in acetonitrile (400 mL) and 1,3-diaminobenzene (Kodak; 24.0 g, 222 mmol) in acetonitrile (200 mL) gave **6** (19.2 g, 77%, mp 148–149 °C). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.94 (t, 1 H, J = 2.0 Hz, ArH), 7.66 (s, 2 H, CONH), 7.32 (m, 3 H, ArH), 5.80 (d, 2 H, J = 0.6 Hz, vinyl), 5.47 (dd, 2 H, J = 1.3 and 2.0 Hz, vinyl), 2.06 (dd, 6 H, J = 1.0 and 1.4 Hz, CH_3). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 167.4, 141.3, 139.0, 130.2, 120.8, 116.5, 112.2, 19.4. IR (KBr): 3250, 1656, 1605, 1547, 1481, 1421, 1221, 948, 936, 925, 861, 801, 774 cm^{-1}.

1,4-Bis(2-methyl-1-oxo-2-propenyl)piperazine (7). In a manner similar to the preparation of **2**, methacryloyl chloride (20.0 mL, 205 mmol) in acetonitrile (500 mL) and piperazine (19.00 g, 221 mmol) in acetonitrile (200 mL) gave white crystals of **7** (16.1 g, 71%, mp 114–115 °C). ^{1}H NMR (250 MHz, $CDCl_3$): δ 5.25 (t, 2 H, J = 1.4 Hz, vinyl), 5.06 (t, 2 H, J = 1.0 Hz, vinyl), 3.60 (s, 4 H, CH_2CH_2), 1.97 (t, 3 H, J = 1.4 Hz, CH_3). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 171.7, 140.3, 116.5, 47.2 (br), 42.1 (br), 20.9. IR (KBr): 3469 (br), 2976, 2947, 2918, 1617 (br), 1436, 1288, 1270, 1204, 1026, 922, 912 cm^{-1}.

N-(2-Aminoethyl)-5-(dimethylamino)-1-naphthalenesulfonamide[14] (8). To a solution of ethylenediamine (4.63 mL, 69.3 mmol) in THF (300 mL) at 0 °C was added dropwise dansyl chloride (1.87 g, 6.93 mmol) in THF (150 mL). The reaction was stirred at 0 °C for 3 h, and 1 N KOH (20 mL) was added. The THF was evaporated, and the aqueous layer was extracted with CH_2Cl_2 (4 × 100 mL). The combined organics were dried ($MgSO_4$) and evaporated to leave a pale yellow-green oil. Crystallization from benzene/hexane provided light green needles (1.16 g, 57%, mp 145–147 °C). ^{1}H NMR (250 MHz, $CDCl_3$): δ 8.53 (d, 1 H, J = 8.5 Hz, ArH), 8.31 (d, 1 H, J = 8.6 Hz, ArH), 8.24 (d, 1 H, J = 7.2 Hz, ArH), 7.55 (m, 2 H, ArH), 7.17 (d, 1 H, J = 7.3 Hz, ArH), 2.88 (m, 8 H, $N(CH_3)_2$ and SO_2NHCH_2), 2.69 (m, 2 H, CH_2NH_2). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 152.6, 135.3, 131.0, 130.5, 130.2, 129.0, 123.8, 119.3, 115.8, 46.1, 46.0, 41.5. IR (KBr): 3350, 2947, 2839, 2795, 1589, 1571, 1319, 1147, 1105, 1093, 944, 904, 796, 620 cm^{-1}.

N-[2-[[[5-(Dimethylamino)-1-naphthalenyl]sulfonyl]amino]ethyl]-2-propenamide (9). To a solution of **8** (0.500 g, 1.70 mmol) in THF (50 mL) at room temperature was added acryloyl chloride (0.139 mL, 1.70 mmol) and triethylamine (0.238 mL, 1.70 mmol). This was stirred at room temperature overnight. The salts were then filtered and washed with THF. The combined filtrates were evaporated, and the residue was chromatographed on silica with ether/hexane (4/1) as eluent to provide a light green solid **9** (0.469 g, 79%, mp 105–107 °C). ^{1}H NMR (250 MHz, $CDCl_3$): δ 8.52 (d, 1 H, J = 8.5 Hz, ArH), 8.28 (d, 1 H, J = 8.5 Hz, ArH), 8.19 (d, 1 H, J = 7.2 Hz, ArH), 7.51 (m, 2 H, ArH), 7.14 (d, 1 H, J = 7.5 Hz, ArH), 6.67 (br t, 1 H, CONH), 6.33 (t, 1 H, J = 5.8 Hz, SO_2NH), 6.13 (d, 1 H, J = 16.9 Hz, vinyl),

5.91 (dd, 1 H, J = 10.1 and 16.9 Hz, vinyl), 5.49 (d, 1 H, J = 10.2 Hz, vinyl), 3.36 (m, 2 H, CONHCH_2), 3.06 (m, 2 H, SO_2NHCH_2), 2.86 (s, 6 H, N(CH_3)$_2$). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 167.0, 152.6, 134.9, 131.2, 131.0, 130.5, 130.1, 130.0, 129.2, 127.3, 123.8, 119.3, 115.9, 46.0, 43.6, 40.0. IR (KBr): 3381, 2981, 2950, 2869, 2794, 1662, 1542, 1319, 1161, 1144, 791, 732 cm^{-1}. MS (CI, isobutane, relative percent): m/z 348 (MH^+, 100), 236 (7), 204 (6), 172 (23), 115 (23), 85 (10). High-resolution MS. Calcd for $C_{17}H_{21}N_3O_3S$: 347.1303. Found: 347.1320.

N-[2-[[[5-(Dimethylamino)-1-naphthalenyl]sulfonyl]-amino]ethyl]-2-methyl-2-propenamide (10). The procedure for synthesis of **9** was followed with methacryloyl chloride (0.167 mL, 1.70 mmol) in place of acryloyl chloride. The product was a light green solid (0.525 g, 85%, mp 129–130 °C). ^{1}H NMR (250 MHz, $CDCl_3$): δ 8.52 (d, 1 H, J = 8.5 Hz, ArH), 8.27 (d, 1 H, J = 8.6 Hz, ArH), 8.19 (dd, 1 H, J = 1.0 and 7.3 Hz, ArH), 7.50 (m, 2 H, ArH), 7.16 (d, 1 H, J = 7.5 Hz, ArH), 6.58 (br t, 1 H, J = 5.2 Hz, CONH), 6.15 (t, 1 H, J = 5.9 Hz, SO_2NH), 5.59 (s, 1 H, vinyl), 5.22 (s, 1 H, vinyl), 3.36 (m, 2 H, CONHCH_2), 3.07 (m, 2 H, SO_2NHCH_2), 2.87 (s, 6 H, N(CH_3)$_2$), 1.81 (s, 3 H, C=CCH_3). ^{13}C NMR (125.8 MHz, $CDCl_3$): δ 169.7, 152.6, 139.7, 135.0, 131.2, 130.5, 130.1, 130.0, 129.1, 123.8, 121.0, 119.3, 115.9, 46.0, 43.6, 40.1, 19.1, 19.0. IR (KBr): 3402, 3084, 2945, 2871, 1664, 1612, 1552, 1438, 1322, 1310, 1160, 1144, 1104, 925, 805, 786 cm^{-1}. MS (CI, isobutane, relative percent): m/z 362 (MH^+, 100), 236 (10), 228 (8), 204 (14), 172 (58), 131 (24), 129 (61), 127 (10), 100 (16), 99 (18), 98 (17). High-resolution MS. Calcd for $C_{18}H_{23}N_3O_3S$: 361.1460. Found: 361.1457.

Synthesis of Linear Poly(N,2-dimethyl-2-propenamide) Doped with Fluorescent Probe 10 [LPDP(10)]. A 35-mL-capacity, medium-walled tube was charged with N,2-dimethyl-2-propenamide (**1b**; 8.44 g, 85.1 mmol), probe **10** (0.003 08 g, 8.52 μmol), AIBN (0.0850 g, 0.518 mmol), and methanol (10 mL). This was freeze–thaw degassed three times and sealed under vacuum. The tube was heated in an oil bath for 12 h at 75 °C. The viscous contents of the tube were extracted into hot methanol, and the polymer was precipitated with ether. Several precipitations from methanol with ether provided a white powder (7.26 g, 86%). ^{1}H NMR (250 MHz, CD_3OD): δ 7.42 (br s, 1 H, NH), 2.51 (br s, 3 H, NCH_3), 1.73 (br s, 2 H, CH_2), 0.88 (br m, 3 H, CCH_3). ^{13}C NMR (125.8 MHz, CD_3OD): δ 180.5 (br), 57.0 (br), 47.0 (br), 28.0 (br), 19.5 (br), 18.0 (br). IR (KBr): 3292 (br), 2945, 1637 (br), 1540, 1486, 1411, 1284, 1206, 1156, 1025, 962, 850 cm^{-1}. Elemental analysis on the polymers gave consistently low values for carbon (ca. 4%) and nitrogen (1.5%) and high values for oxygen (6%). These results indicate approximately 15% MeOH is present. Even after exposure (12 h) to high vacuum (10^{-3} mm), TGA analysis revealed a 4% loss in weight between 70 and 80 °C.

Synthesis of Acrylamide Networks Doped with Fluorescent Probe 9 [EDBP-35-B-M(9)]. To a 35-mL-capacity, medium-walled tube was added N-methyl-2-propenamide (**1a**; 5.73 g, 67.3 mmol), finely ground N,N'-ethanediylbis(2-propenamide) (**2**; 6.09 g, 36.2 mmol), probe **9** (3.60×10^{-3} g, 10.3 μmol), AIBN (0.120 g, 0.731 mmol), and methanol (12.0 mL). This was freeze–thaw degassed three times and sealed under vacuum. The tube was shaken vigorously in a water bath at 60 °C until all of the cross-linker dissolved and then immediately transferred to an oil bath (70 °C). After 12 h, the solid polymer obtained was gently ground in a mortar and Sohxlet extracted with methanol for 12 h. The particles were dried in a vacuum oven (60 °C, 12 h) and sieved for the appropriate size ranges (see Results). IR (KBr): 3300 (br), 2950, 1718, 1654 (br), 1548, 1447, 1249 (br), 1168 cm^{-1}.

Synthesis of Methacrylamide Networks Doped with Fluorescent Probe 10 via Bulk Polymerization [EDBMP-35-BAc,M,W,D(10); BDBMP-35-B-M(10); HDBMP-35-B-M(10); PDBMP-35-B-M(10); PDBMP-50-B-F(10); HDBMP-50-B-F(10)]. These polymers were prepared in a manner identical with that of the polyacrylamides. The amounts and type of monomers are summarized in Table I. IR (EDBMP-35-B-Ac,M,W,D(10), KBr): 3400 (br), 2931, 1654 (br), 1541 (br), 1458, 1405, 1204 cm^{-1}. IR (HDBMP-35-B-M(10), KBr): 3400 (br), 2950, 1644 (br), 1544 (br), 1475, 1413, 1300, 1200, 963, 869, 788 cm^{-1}. IR (PDBMP-35-B-M(10), KBr): 3400 (br), 2931 (br), 1638 (br), 1525 (br), 1450 (br), 1406, 1275, 1200, 1025, 963, 850 cm^{-1}. IR (PDBMP-50-B-F(10), KBr): 3400 (br), 2983 (br), 1521 (br), 1457 (br), 1200, 789 cm^{-1}. IR (HDBMP-50-B-F(10), KBr): 3400 (br), 2983 (br), 1635 (br), 1520 (br), 1203, 667 cm^{-1}.

Table I
Bulk Methacrylamide Polymerization Recipes

polym code[a]	1b, g	cross-linker (no.), g	10, mg	AIBN, g	porogen, mL
EDBMP-35-B-Ac(10)	4.73	5.04(3)	2.65	0.100	9.77
EDBMP-35-B-M(10)	4.73	5.04(3)	2.65	0.100	9.77
EDBMP-35-B-W(10)	4.88	5.21(3)	2.74	0.100	8.00
EDBMP-35-B-D(10)	4.88	5.21(3)	2.74	0.100	8.00
BDBMP-35-B-M(10)	6.57	8.00(4)	3.68	0.146	14.56
HDBMP-35-B-M(10)	4.38	6.00(5)	2.46	0.104	10.40
PDBMP-35-B-M(10)	5.27	7.00(6)	2.96	0.123	12.30
PDBMP-50-B-F(10)	2.84	7.00(6)	2.07	0.0984	9.84
HDBMP-50-B-F(10)	2.75	7.00(5)	2.00	0.0975	9.75

[a] Polymer code refers to cross-linking monomer [EDBMP = N,N'-ethanediylbis(2-methyl-2-propenamide), BDBMP = N,N'-butanediylbis(2-methyl-2-propenamide), HDBMP = N,N'-hexanediylbis(2-methyl-2-propenamide), PDBMP = N,N'-1,3-phenylenebis(2-methyl-2-propenamide)]-percent of cross-linker in monomer mixture (35)-type of polymerization (B = bulk)-porogen (M = methanol, Ac = acetic acid, W = water, D = DMSO, F = DMF).

Attempted Hydrolysis of Acrylamide Networks. A suspension of polymer (EDBP-35-B-M(9); 0.543 g) in 10% methanolic KOH (20 mL) was heated at reflux for 13 h. The polymer was removed by filtration, washed with methanol, and dried in a vacuum oven (60 °C, 8 h). The weight of polymer obtained was 0.516 g. This procedure was repeated with EDBMP-35-B-M-(10) (0.551 g) to provide 0.594 g of polymer. The IR spectra of both treated materials were identical with the starting polymers.

Solvent-Swelling Studies. Dry polymer (approximately 1 cm^3, 150–250 μm) was placed in a 5-mL graduated cylinder that was calibrated at each tenth of a milliliter. Excess solvent was added to solvate the polymers. The polymer was stirred to permit escape of trapped air bubbles and to allow complete solvation of particles. The particles were then packed down by vibrating and tapping down on the cylinder until no further settling was noted. Swelling equilibration occurred in a matter of approximately 4 h; however, measurements were taken after 24 h. Percent swelling is given as the ratio of the final polymer volume to the initial dry polymer volume.

Solvent-Uptake Studies. Dry polymer particles (1.00 g, 150–250 μm) were placed in a scintillation vial, capped, and weighed. Cyclohexane was added several drops at a time, and after each addition the polymer was thoroughly agitated. Addition of solvent was stopped when the particles lost their ability to flow freely (i.e., they clumped up). At this time, the solvent was allowed to evaporate slowly until the particles just became free-flowing. The weight of the vial was then obtained. Solvent uptake is given as the weight of solvent adsorbed per gram of polymer.

Solvatochromic Shift Studies on LPDP(10) and Polyacrylamide or Polymethacrylamide Networks. Polymer (0.100 g, 125–150 μm if cross-linked) was soaked in an excess of spectral-grade solvent (3.0 mL) for 24 h. Approximately half of this polymer was transferred to a quartz, dual-path-length microcuvette (10 mm × 2 mm). Emission and excitation spectra were then recorded (scan rate = 100 nm/min). Spectra obtained after only 30 min of soaking were irreproducible and indicated incomplete equilibration. All polymers had excitation maxima in the range 350–370 nm. Cross-linked polymers were insoluble in all solvents, and the cuvette was aligned in the spectrophotometer so that the light beam passed through the polymer layer. Due to the broadness of the emission curve for the dansyl chromophore, the error in determining the peak maximum was ±2 nm.

Synthesis of 1,3-Bis[N-(4-vinylbenzyl)formimidoyl]-benzene (11). Benzene (50 mL) with isophthalaldehyde (1.06 g, 7.87 mmol) and vinylbenzylamine (1.80 g, 15.9 mmol) was refluxed with a Dean–Stark trap for 3 h. The solvent was removed in vacuo to provide a white solid. Recrystallization of this solid in benzene/hexane provided white crystals of **11** (2.50 g, 87%; mp 83.5–84.5 °C). ^{1}H NMR ($CDCl_3$): δ 8.35 (s, 2 H, –CH=N–), 8.11 (t, 1 H, J = 1.4 Hz, ArH), 7.84 (dd, 2 H, J = 1.7 and 7.7 Hz, ArH), 7.35 (m, 9 H, ArH), 6.69 (dd, 2 H, J = 10.9 and 17.6 Hz,

-CH=), 5.71 (dd, 2 H, J = 1.0 and 17.6 Hz, =CH), 5.20 (dd, 2 H, J = 0.9 and 10.9 Hz, =CH), 4.77 (s, 4 H, $ArCH_2$-). ^{13}C NMR ($CDCl_3$): δ 162.1, 139.3, 137.2, 137.1, 130.9, 129.6, 129.1, 128.9, 127.1, 114.3, 65.4. IR (KBr): 2848, 2839, 1639, 1629, 1405, 1012, 993, 970, 913, 900, 850, 828, 800, 691 cm^{-1}. High-resolution MS. Calcd for $C_{26}H_{24}N_2$: 364.1938. Found: 364.1953.

Synthesis of 1,3-Bis[*N*-[2-(2-methylpropenamido)ethyl]-formimidoyl]benzene (12). Benzene (30 mL) with isophthalaldehyde (0.269 g, 2.01 mmol) and *N*-(2-aminoethyl)-2-methyl-2-propenamide (0.565 g, 4.41 mmol) was refluxed with a Dean–Stark trap for 3 h. The solvent was removed in vacuo to provide a yellow solid. Recrystallization of this solid in benzene/hexane provided white crystals (0.59 g, 83%; mp 104.0–104.5 °C). ^1H NMR ($CDCl_3$): δ 8.35 (s, 2 H, -CH=N-), 8.07 (s, 1 H, ArH), 7.81 (dd, 2 H, J = 1.6 and 7.7 Hz, ArH), 7.49 (t, 1 H, J = 7.6 Hz, ArH), 6.40 (s, 2 H, -NH-), 5.68 (s, 2 H, =CH), 5.31 (s, 2 H, =CH), 3.79 (m, 4 H, $CONHCH_2$), 3.65 (m, 4 H, $C{=}NCH_2$-), 1.96 (t, 6 H, J = 1.1 Hz, CH_3). ^{13}C NMR ($CDCl_3$): δ 168.4, 161.9, 139.7, 136.1, 130.2, 128.8, 127.4, 119.4, 60.0, 40.1, 18.5. IR (KBr): 3301, 2848, 1653, 1620, 1541, 1464, 1448, 1437, 1419, 1373, 1333, 1225, 1107, 918, 687 cm^{-1}. High-resolution MS: Calcd for $C_{20}H_{26}N_4O_2$: 354.2054. Found: 354.2057.

Copolymerization of Styrene and *m*-Diisopropenylbenzene with Schiff Base Template 11 (DIB-50-B-F(11)). A 35-mL-capacity, medium-walled tube was charged with styrene (5.95 g, 57.2 mmol), *m*-diisopropenylbenzene (9.05 g, 57.2 mmol), 1,3-bis[*N*-(*p*-vinylbenzyl)formimidoyl]benzene (**11**; 0.417 g, 1.14 mmol), AIBN (0.150 g, 0.913 mmol), and acetonitrile (15 mL). This was freeze–thaw degassed three times and sealed under vacuum. The tube was heated in an oil bath for 14 h at 80 °C, after which time the temperature was increased to 125 °C for an additional 12 h. The solid polymer obtained was crushed in a mortar and sized. The 120–200-mesh particles were Sohxlet extracted with tetrahydrofuran for 24 h and then dried in a vacuum oven (50 °C, 12 h). The polymer was then further dried on high vacuum for 12 h. IR (KBr): 3442 (br), 2941, 1653, 1606, 1539, 1481, 1412, 1300, 1200, 1169, 787, 690 cm^{-1}.

Copolymerization of *N*,2-Dimethyl-2-propenamide, *N,N'*-1,3-Phenylenebis(2-methyl-2-propenamide), and Schiff Base Template 12 (EDPMP-35-B-F(12)). A 35-mL-capacity, medium-walled tube was charged with *N*,2-dimethyl-2-propenamide (**1b**) (5.27 g, 53.2 mmol), *N,N'*-1,3-phenylenebis(2-methyl-2-propenamide) (**6**) (7.00 g, 28.7 mmol), Schiff base template monomer **12** (0.290 g, 0.819 mmol), AIBN (0.123 g, 0.749 mmol), and dimethylformamide (12.3 mL). This was freeze–thaw degassed three times and sealed under vacuum. The tube was heated in an oil bath for 12 h at 70 °C. The solid polymer obtained was crushed in a mortar, and the 120–200-mesh particles were Sohxlet extracted with tetrahydrofuran for 24 h and then dried in a vacuum oven (50 °C, 12 h). The polymer was then further dried on high vacuum for 12 h. IR (KBr): 3442 (br), 2941, 1653, 1606, 1539, 1481, 1437, 1412, 1300, 1200, 1169, 787, 690 cm^{-1}.

Hydrolysis and Rebinding to Templated Polymers (Schiff Base Template). Hydrolysis Procedure. Templated polymer (0.500 g) was placed in 10 mL of acetonitrile and 1 mL of 10% H_2SO_4. The solution was stirred at reflux for 24 h. The solution was filtered hot through a glass funnel and washed with hot acetonitrile (2 × 10 mL) and hot benzene (3 × 10 mL). The filtrate was evaporated, and the residue was dissolved in 2 mL of benzene. Gas chromatograph analysis was then conducted on the concentrate. A Hewlett-Packard 5710A was used with a packed column (8 ft × 1/8 in. packed with 10% SP-2100 on 100/120 Supelcoport) with a splitless injection port. Decane was used as the standard for isophthalaldehyde analysis.

Rebinding Procedure. The dried hydrolyzed templated polymer (450 mg) was refluxed with a Dean–Stark trap for 12 h in a solution of isophthalaldehyde (15.0 mg, 7.46 mmol) in dry benzene (30 mL). The mixture was then filtered through a glass funnel and washed with hot benzene (4 × 15 mL). The filtrate was evaporated, and the residue was dissolved in 3 mL of benzene. Gas chromatograph analysis was then conducted.

Bis[(*p*-vinylbenzyl)ammonium] 1,3-Benzenedicarboxylate (16). To a solution of vinylbenzylamine (1.01 g, 7.60 mmol) in methanol (40 mL) at room temperature was added isophthalic acid (**15**; 0.631 g, 3.80 mmol). This was stirred at room temperature for 24 h. The solvent was removed in vacuo to provide a white solid. Recrystallization of this solid in methanol/acetonitrile provided white crystals **16** (1.59 g, 97%; mp 161–162 °C). ^1H NMR (CD_3OD): δ 8.30 (t, 1 H, J = 1.2 Hz, ArH), 7.77 (dd, 2 H, J = 1.5 and 7.4 Hz), 7.16 (m, 9 H, ArH), 6.47 (dd, 2 H, J = 10.9 and 17.6 Hz, -CH=), 5.54 (d, 2 H, 17.8 Hz, =CH), 5.01 (dd, 2 H, 0.6 and 10.9 Hz, =CH), 4.78 (s, 4 H, $ArCH_2$-). ^{13}C NMR (CD_3OD): δ 175.3, 139.9, 138.8, 137.7, 134.8, 132.6, 131.4, 130.5, 128.7, 128.1, 115.4, 44.4. Anal. Calcd for $C_{26}H_{28}O_4N_2$: C, 72.20; H, 6.52; N, 6.48. Found: C, 71.66; H, 6.57; N, 6.79. IR (KBr): 2983, 2887 (br), 2636, 1628, 1604, 1539, 1475, 1425, 1410, 1369, 989, 910, 847, 752, 708 cm^{-1}.

Bis[*N*-[2-(2-methyl-2-propanamido)ethyl]ammonium] 1,3-Benzenedicarboxylate (14). To a solution of *N*-(2-aminoethyl)-2-methyl-2-propanamide (0.214 g, 1.67 mmol) in methanol (20 mL) at room temperature was added isophthalic acid (**15**; 0.139 g, 0.837 mmol). This was stirred at room temperature for 3 h. The solvent was removed in vacuo to provide a yellow oil (0.354 g, 100%). Polymerization often accompanied the neat monomer even at or below room temperature so it was used in polymerization attempting to crystallize the residue. ^1H NMR (CD_3OD): δ 8.41 (t, 1 H, J = 1.6 Hz, ArH), 7.89 (dd, 2 H, J = 1.7 and 7.8 Hz, ArH), 7.26 (t, 1 H, J = 7.6 Hz, ArH), 5.66 (d, 2 H, J = 1.1 Hz, =CH), 5.28 (d, 2 H, J = 1.3 Hz, =CH), 3.40 (t, 4 H, J = 6.0 Hz, $CONHCH_2$-), 2.96 (t, 4 H, J = 5.9 Hz, $N^+H_3CH_2$-), 1.82 (d, 6 H, J = 1.3 Hz, $-CH_3$). ^{13}C NMR (CD_3OD): δ 175.6, 172.0, 141.2, 139.0, 132.4, 131.3, 128.6, 121.4, 41.5, 40.9, 19.0.

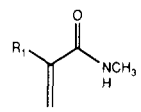
Synthesis of Styrene/*m*-Diisopropenylbenzene Networks Containing Bis Salt Template 16. A 35-mL-capacity, medium-walled tube was charged with styrene (5.95 g, 57.2 mmol), *m*-diisopropenylbenzene (9.05 g, 57.2 mmol), bis ammonium template monomer **16** (0.495 g, 1.14 mmol), AIBN (0.150 g, 0.913 mmol), and dimethylformamide (15 mL). This was freeze–thaw degassed three times and sealed under vacuum. The tube was heated in an oil bath for 14 h at 80 °C, after which time the temperature was increased to 125 °C for an additional 12 h. The solid polymer obtained was crushed in a mortar and sized. The 120–200-mesh particles were Sohxlet extracted with hexane for 12 h, after which time they were dried in a vacuum oven (50 °C, 12 h). The polymer was then further dried on high vacuum for 12 h. IR (KBr): 3082, 3059, 3024, 2968, 2922, 1714, 1699, 1599, 1576, 1453, 1452, 887, 796, 758, 700 cm^{-1}.

Synthesis of Methacrylamide Networks Containing Bis Salt Template 14. A 35-mL-capacity, medium-walled tube was charged with *N*,2-dimethyl-2-propenamide (**1b**; 4.93 g, 49.7 mmol), *N,N'*-1,3-phenylenebis(2-methyl-2-propenamide) (**6**; 6.54 g, 26.8 mmol), bis ammonium salt template monomer **14** (0.323 g, 0.765 mmol), AIBN (0.115 g, 0.70 mmol), and dimethylformamide (11.5 mL). This was freeze–thaw degassed three times and sealed under vacuum. The tube was heated in an oil bath for 12 h at 70 °C. The solid polymer obtained was crushed in a mortar and sized. The 120–200-mesh particles were Sohxlet extracted with hexane for 12 h, after which time they were dried in a vacuum oven (50 °C, 12 h). The polymer was then further dried on high vacuum for 12 h. IR (KBr): 3381 (br), 2941, 1668, 1606, 1533, 1481, 1412, 1300, 1200, 1167, 1097, 785, 690 cm^{-1}.

Removal of Isophthalic Acid from Templated Polymers. The template polymer (0.500 g) was placed in 50 mL of methanol and 1 mL of 10% NaOH. The solution was stirred at room temperature for 40 h. The solution was filtered and washed with hot methanol (3 × 15 mL). The filtrate was evaporated and analyzed. Yields in the removal experiments were determined by HPLC analysis. A Millipore Waters 501 was used with a reversed-phase column RP-18. Benzoic acid was used as the standard for isophthalic acid analysis.

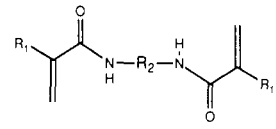
Results

Monomer Synthesis. The monomers used for the polyacrylamide synthesis are summarized in Figure 1. Monofunctional amides, **1a,b**, were prepared from the corresponding acid chloride and aqueous methylamine in THF at 0 °C. The cross-linkers, **2–7**, were prepared similarly by condensing equimolar amounts of acid chloride and diamine at 0 °C in CH_3CN.[13] The dihydrochloride salt precipitates from solution, and the bis(acrylamide) and



1a,b

a R_1= H
b R_1= CH_3



2 R_1=H, R_2= -$(CH_2)_2$-
3 R_1=CH_3, R_2= -$(CH_2)_2$-
4 R_1=CH_3, R_2= -$(CH_2)_4$-
5 R_1=CH_3, R_2= -$(CH_2)_6$-
6 R_1=CH_3, R_2= 1,3-C_6H_4

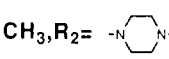
7 R_1=CH_3, R_2= 

Figure 1.

bis(methacrylamides) are isolated by concentration and crystallization (cold) in high yield. The solubility characteristics of these compounds are summarized in Table II.

Polymerizable derivatives of the fluorescent probe, *N,N*-(dimethylamino)naphthalenesulfonamide (dansyl) were also prepared for incorporation into both linear and network copolymers. Their synthesis is outlined in Figure 2.

Synthesis of Linear Poly(*N*,2-dimethyl-2-propenamide). The solution polymerization of *N*,2-dimethyl-2-propenamide (**1b**) and *N*-methyl-2-propenamide (**1a**) was achieved by free-radical initiation at 70 °C (Figure 3). Methanol was used as solvent and AIBN as initiator. In this and all subsequent polymerizations, a small amount (ratio of probe/monomer = 10^{-4}) of fluorescent probe (**9** or **10**) was incorporated into the polymers for diagnostic purposes. The low level of dopant (10^{-4} M) is not expected to produce changes in polymer morphology. The solubility of this polymer is also included in Table II.

Synthesis of Network Copolymers. A series of 10 network copolymers was prepared by bulk copolymerization (Figures 4 and 5). The amounts of monomers and porogen used to prepare these materials are summarized in Table I. A standard formulation regarding the relative amount of cross-linker and porogen was employed. The polymerizations were conducted at 70 °C and initiated by AIBN (1%) and were complete within 12 h. The solid materials were crushed, and then Sohxlet extracted with MeOH, after which time they were dried in a vacuum oven and sized. A summary of selected physical properties is given in Table III.

An additional polymerization was attempted with piperazinebis(methacrylamide) (**7**) and *N*-methylmethacrylamide in methanol. N,N-Disubstituted acrylamides do not homopolymerize but generally undergo copolymerization with primary amides such as acrylamide and methacrylamide.[15] In this experiment, however, no gel formation was observed and all of the cross-linker (**7**) was recovered; only homopolymer of **1b** was observed (Figure 6). Apparently, **7** does not copolymerize with N-monosubstituted methacrylamides.

Template Functionalized Polymers. Latent methylamine functional groups were incorporated into three selected polymer networks by copolymerization. The template monomers and their incorporation in polymer networks are outlined in Figures 7 and 8.

Templates **11** and **12** (1 mol, 1%) were incorporated into styrene/diisopropenylbenzene copolymers and *N*,2-dimethyl-2-propenamide/*N,N'*-1,3-phenylenebis(2-methyl-2-propenamide) copolymers, respectively. The degree of cross-linking, porogen, and polymerization conditions are given in the Experimental Section. Each material was processed in a manner similar to that of nontemplated polymers and then subjected to a hydrolysis reaction to quantify the amount of benzenedicarbaldehyde (**13**) liberated. These results are given in Figure 7. Noncovalent templates,[16] **14** and **16** (1%), were incorporated into a *N*,2-dimethyl-2-propenamide/*N,N'*-1,3-phenylenebis(2-methyl-2-propenamide) copolymer (PDBMP-35-B-F(**14**)) and styrene/diisopropenylbenzene copolymers, respectively. The resulting materials were analyzed for the amount of dicarboxylic acid **15** liberated upon extraction (Figure 8).

Discussion

Synthesis of Macroporous Polyacrylamides. Macroporosity arises from a microphase separation that takes place during polymerization. The precipitated polymer particles aggregate and, depending upon the porogen, can further agglomerate to produce materials with a complex permanent porosity.[17] The porosity in these materials arises from the interstitial voids between the precipitated polymer particles. There are a number of variables that influence the formation of macroporous materials including the nature and the percent of cross-linker, as well as the type and amount of porogen.[18] Some insight into the selection of a porogen can be obtained from consideration of the solubility behavior of the monomers and the corresponding linear polymers. *N*-Methylmethacrylamide (**1b**) is soluble in most organic solvents and water. Its linear homopolymer, LPDP(**10**), is insoluble in solvents of low polarity (toluene, CH_3CN, and THF), partially soluble in DMSO and CH_2Cl_2, and completely soluble in polar protic solvents including water (Table II). It would be desirable to examine the effect of the entire range of porogens on polymer morphology; however, the low solubility of the cross-linkers in nonpolar solvents prevented this. The limited solubility of the cross-linkers in all solvents also restricted the upper limit of cross-linking that could be achieved. A uniform set of polymerization conditions was established so that all resulting materials could be compared. These conditions employed a free-radical initiator (AIBN, 1%) with 35 mol % of cross-linker to monofunctional monomer (**1a** or **1b**). In DMF as porogen, cross-linking up to 50% could be achieved for several monomers. In all cases, equal weights of porogen and monomer mixtures were used. Suitable polymerization conditions for all monomers were found to be 70 °C for 12 h.

The first material, a polyacrylamide employing ethylenediaminebis(acrylamide) as cross-linker (EDBP-35-B-M(**9**)), was prepared by using the above conditions. The yield of material is nearly quantitative, and FTIR analysis of the C–H out of plane bend at 935 cm^{-1} indicates essentially complete reaction of the double bonds (Figure 9). This behavior is to be contrasted with styrene/divinylbenzene copolymers at comparable cross-linking where a significant residue of unreacted double bonds is noted.[19]

Polymerization of the corresponding methacrylamide monomers (MeOH porogen) under identical conditions produced a very similar material (EDBMP-35-B-M(**10**)). The FTIR spectrum was less informative for this material due to the absence of a clean C–H out of plane bending mode at 930 cm^{-1} (Figure 10). Nevertheless, the high chemical yield and the resulting spectral analysis reveal that a significant fraction of vinyl groups is incorporated during polymerization. The polymerization behavior of more highly cross-linked acrylamides and methacrylamides parallels the high double-bond consumption observed for acrylates and methacrylates.[20] This observation may be influenced by the similar reactivity

Table II
Solubility[a] of Bis(methacrylamide) Monomers and LPDP(11)

solvent	EDBMP(4)	HDBMP(5)	PDBMP(6)	PZBMP(7)	LPDP(11)
AcOH	S	S	S	S	S
MeOH	S	S	S	S	S
EtOH	S	S	S	P	S
DMSO	S	S	S	I	P
DMF	S	S	S	I	I
H_2O	P	I	I	S	S
THF	I	S	S	I	I
CH_3CN	I	P	S	I	I
CH_2Cl_2	I	S	P	I	P
toluene	I	P	P	I	I

[a] 0.100 g in 5.0 mL of solvent; S = completely soluble; P = partly soluble; I = insoluble.

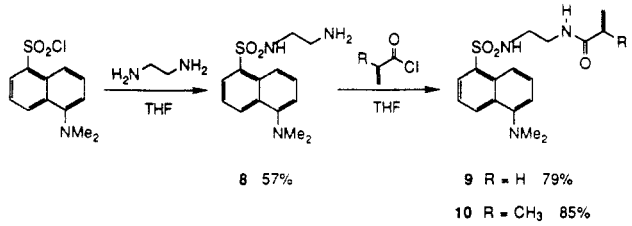


Figure 2. Synthesis of fluorescent probes **9** and **10**.

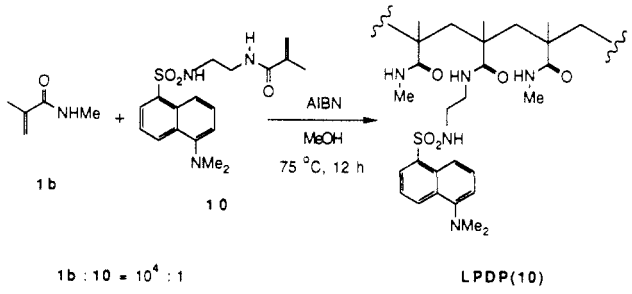
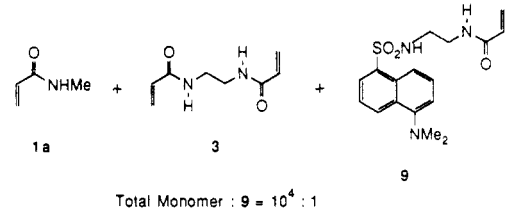


Figure 3. Synthesis of linear poly(*N*,2-dimethyl-2-propenamide).



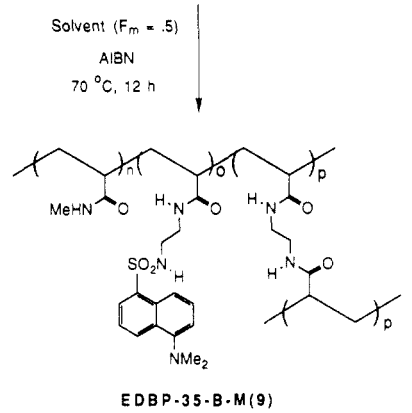


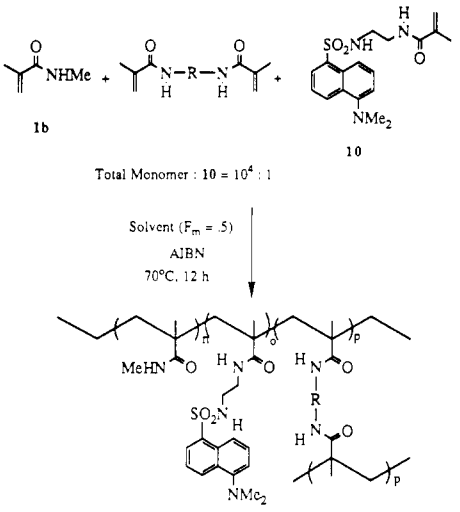
Figure 4. Synthesis of acrylamide network doped with probe **9**.

of the two double bonds in difunctional acrylate and acrylamide systems when compared with divinylbenzene derivatives[21] and the intrinsic reactivity differences between styrene and acrylamides.[22] A further difference is the resonance energy of a benzylic radical vs an acrylate or acrylamide radical. The significantly higher resonance energy of the former may result in a "stiffer" propagating radical that is less effective at adding to unreacted monomers in geometrically less accessible locations.

A series of network polymers prepared by varying both cross-linker and porogen were synthesized by a formulation identical with that used for the preparation of EDBMP-35-B-M(**10**). After a uniform workup procedure, the resulting materials were analyzed. A summary of selected properties is given in Table III. All materials, regardless of type, cross-linker, or porogen swell approximately the same in MeOH (60–90% increase in volume). A similar behavior was found in H_2O. The limited expansion of these networks, even in good swelling solvents, arises from the rather high effective level of cross-linking. One interesting phenomenon is the observation that dry materials actually contract (5–10%) when placed in hydrocarbon solvents (i.e., hexanes).

It was our intention to prepare macroporous materials. The porosity of a material can be measured in a variety of ways. Simple surface area analysis (N_2, BET) and uptake of a nonswelling solvent (cf. cyclohexane) are two that we have chosen for characterization. The data in Table III reveal that some, but not all, of the polymers can be classified as macroporous. Furthermore, there are marked trends with regard to cross-linker and porogen that can serve as clues to the important determinants giving rise to porosity.

With methanol as porogen, the methacrylamide network (EDBMP-35-B-M(**10**)) is characterized by a higher surface area but lower pore volume than the acrylamide material (EDBP-35-M(**9**)). Although we have not carried out a pore size distribution analysis, this result suggests a greater weighting toward micropores in the methacrylamide material (EDBMP-35-B-M(**10**)). Within the series of methacrylamides, the role of cross-linker on the tendency to form macroporous materials is clear: decreased cross-linker flexibility, i.e., **5** → **4** → **3**, promotes macroporosity. Indeed, HDBMP-35-B-M(**10**) has no internal pore volume (nonporous). For related, although probably more complicated reasons, networks prepared with the 1,3-phenylenediamine cross-linker **6** (PDBMP-35-B-M(**10**))



	R	Solvent
EDBMP-35-B-M(10)	-$(CH_2)_2$-	Methanol
EDBMP-35-B-Ac(10)	-$(CH_2)_2$-	Acetic acid
EDBMP-35-B-W(10)	-$(CH_2)_2$-	Water
EDBMP-35-B-D(10)	-$(CH_2)_2$-	DMSO
EDBMP-35-B-F(10)	-$(CH_2)_2$-	DMF
BDBMP-35-B-M(10)	-$(CH_2)_4$-	Methanol
HDBMP-35-B-M(10)	-$(CH_2)_6$-	Methanol
PDBMP-35-B-M(10)		Methanol
PDBMP-35-B-A(10)		Acetonitrile
HDBMP-50-B-F(10)	-$(CH_2)_6$-	Methanol
PDBMP-50-B-M(10)		Methanol

Figure 5. Synthesis of methacrylamide networks doped with 10.

Table III
Network Swelling, Solvent Uptake, and Surface Area

polymer code[a]	MeOH swelling,[b] % vol inc.	cC_6H_{12} uptake,[b] mL/g of polym	surface area, m^2/g, N_2
EDBP-35-B-M(9)	71	0.03	9.3
EDBMP-35-B-M(10)	85	0.1	40.1
EDBMP-35-B-Ac(10)	90	0.02	0.2
EDBMP-35-B-W(10)	63	0.2	56.5
EDBMP-35-B-D(10)	80	0.0	
EDBMP-35-B-F(10)	120	0.07	
BDBMP-35-B-M(10)	100	0.01	
HDBMP-35-B-M(10)	85	0.02	
PDBMP-35-B-M(10)	56	0.31	83.9
PDBMP-35-B-A(10)	50	0.60	
PDBMP-50-B-F(10)	51	0.02	
HDBMP-50-B-F(10)	108	0.02	
LPDP	soluble		

[a] The naming scheme codes are the following: cross-linking monomer (EDBP = 2, EDBMP = 3, BDBMP = 4, HDBMP = 5, or PDBMP = 6)-percent of cross-linker in monomer mixture (35)-type of polymerization (B = bulk)-porogen (M = MeOH; Ac = AcOH; W = H_2O; D = DMSO; F = DMF). [b] Particle size = 150–250 mm.

give the highest surface area and greatest cyclohexane uptake. *Smaller, more rigid cross-linkers seem to be best able to produce a material capable of sustaining permanent porosity.* One is tempted to draw upon a microscopic (or molecular level) explanation to account for this trend; however, the porosity model is macroscopic in origin and does not readily lend itself to molecular-based explanations. For example, one complication is that the solubilities of

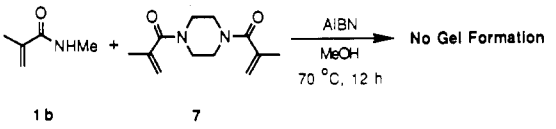


Figure 6. Attempted copolymerization of piperazinebis(methacrylamide) with *N*,2-dimethyl-2-propenamide.

cross-linkers **2–6** differ significantly and may, therefore, influence the timing of phase separation.

Within the same cross-linker, the effect of porogen also produces a clear trend. *More polar porogens promote permanent porosity.* At 35% cross-linking, DMSO produces a nonporous material. A progressive increase in both cyclohexane uptake and surface area is observed as one proceeds from acetic acid to MeOH to H_2O. This is a series of increasing solvent polarity.[23] Several materials were prepared with 50% cross-linker (PDBMP-50-B-F(**10**), HDBMP-50-B-F(**10**)). Solubility limitations necessitated the use of DMF as porogen. Neither of these materials possessed any significant porosity.

It is interesting to compare these results with those involving the influence of porogen on the formation of macroporous ST/DVB materials. In good solvents for polystyrene such as toluene, porous materials are produced that contain high surface areas and a relatively narrow distribution of small (micro) pores (case A). However, with poor solvents such as CH_3CN, macroporous materials are also produced; this time there is a broad distribution of pores with a lower overall surface area (case B).[24] Because of the limited solubility of the cross-linkers used in the present study, one is prohibited from examining the effect of poorly solvating porogens (i.e., toluene). It remains to be seen if morphologies corresponding to case B can be prepared using acrylamide monomers; perhaps this will require a higher degree of cross-linker, although the results involving 50% cross-linker in DMF did not produce a macroporous material.

Scanning electron micrographs allow visualization of the morphology differences (Figures 11 and 12). At 350×, the four materials, EDBMP-35-B-W, -M, -Ac, and -D, are indistinguishable. At 10 000 magnification (Figure 11), the material prepared with DMSO as porogen reveals a smooth featureless surface. A progression is observed as one proceeds from acetic acid to water, the latter of which has a rough-textured surface with many features smaller than 0.2 μm. This same contrast can be observed upon changing from a flexible to a rigid cross-linker (Figure 12). Little difference at 350× between EDBMP-35-B-M and PDBMP-35-B-M is noted. However, at 10 000×, the rough-textured surface of the latter, arising from the precipitated and aggregated polymer particles, is clearly visible.

Network Solvation. Past experience has revealed that a high surface area and a substantial internal pore volume does not necessarily result in a penetrable gel phase.[25,26] Since network penetrability is an important property of materials for use in our template program[4] and for other applications,[27] we have utilized two independent diagnostics to evaluate gel-phase penetrability of solvents and reagents. The first employs fluorescent probes (**9** and **10**), covalently incorporated into the polymer matrix. The fluorescence emission maxima of the doped materials, imbibed in various solvents, reveal solvent-induced changes in the microenvironment of these network materials.[25,26] A summary of the fluorescence emission wavelength of **9** in various organic solvents and for probes **9** and **10** in cross-linked networks is given in Table IV. The removal of residual solvent from these materials to produce a uniform fluorescence emission of dry polymer required heating

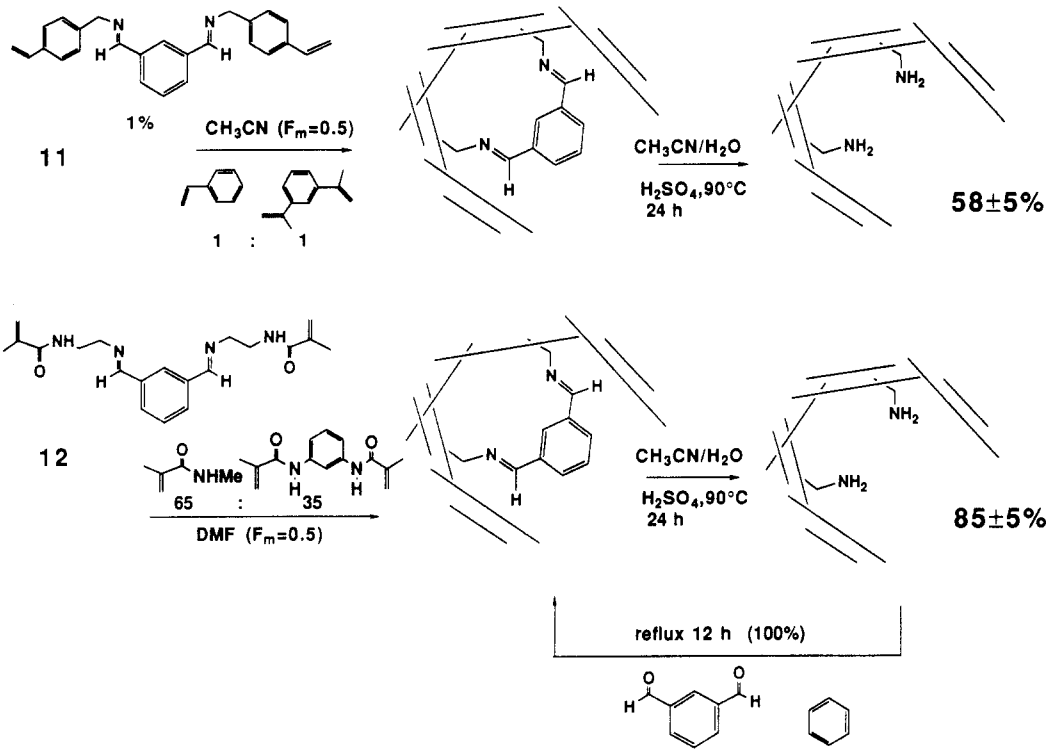


Figure 7. Functionalization of styrene/diisopropenylbenzene and methacrylamide network copolymers with bis Schiff bases 11 and 12.

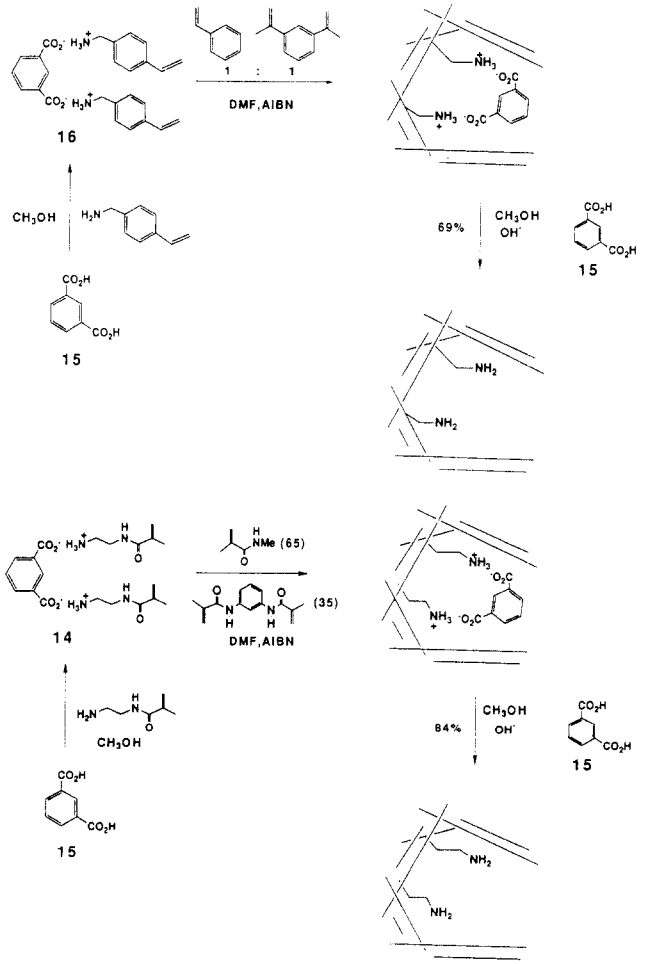


Figure 8. Functionalization of styrene/diisopropenylbenzene and methacrylamide network copolymers using noncovalent templates 14 and 16.

under vacuum for extended periods of time. For the present study, a standard and reproducible protocol was employed for the preparation of dry polymers to be used in the fluorescence studies. Quite reasonably, the probe microenvironment created by the dry polymethacrylamide polymer backbone is significantly red shifted when compared with the same probe in a polystyrene network (λ_{max} 473 vs 457 nm; Table IV). Only minor differences in the solvatochromic shifts were noted between the materials prepared with different porogens.

The fluorescence results are also presented as plots of fluorescence emission (λ_{max}) of doped polymer imbibed in a range of solvents (Figures 13 and 14). Reference points include the fluorescence emission of the dry material (as the crosshatched horizontal bar) and a pure solvent line, an empirically derived relationship of the dependence of the fluorescence emission maximum of probe **9** or **10** in the indicated pure organic solvents (diagonal line).[25] Qualitative information regarding solvent penetrability is obtained by observing the displacement of λ_{max} from the dry material by various solvents.

The solvatochromic shifts of probe-doped linear polystyrene and linear poly(*N*-methylmethacrylamide) as a function of solvent are given in Figures 13 and 14. The difference between the two materials is quite striking. Whereas PS in nonpolar solvents (toluene, CH_3CN, and CH_2Cl_2) parallels the pure solvent correlation line (highly solvated polymer chains) and "looks" like dry polymer in nonsolvents such as MeOH and EtOH, the fluorescence emission from doped LPDP parallels the pure solvent correlation in H_2O, EtOH, and MeOH and then levels off in the "dry" polymer region with all solvents less polar than methanol (CH_2Cl_2, THF, toluene, and hexane). The behavior of the cross-linked networks is somewhat more complicated (Figure 15) but materials such as EDBMP-35-B-M(**10**) and EDBP-35-B-M(**9**) are found to be accommodating to a wide range of solvents. Within the limited range of porogens explored, we have not noticed significant differences in the penetrability of the gel phase as one changes from acrylamide- to methacrylamide-based monomers. These fluorescence studies provide

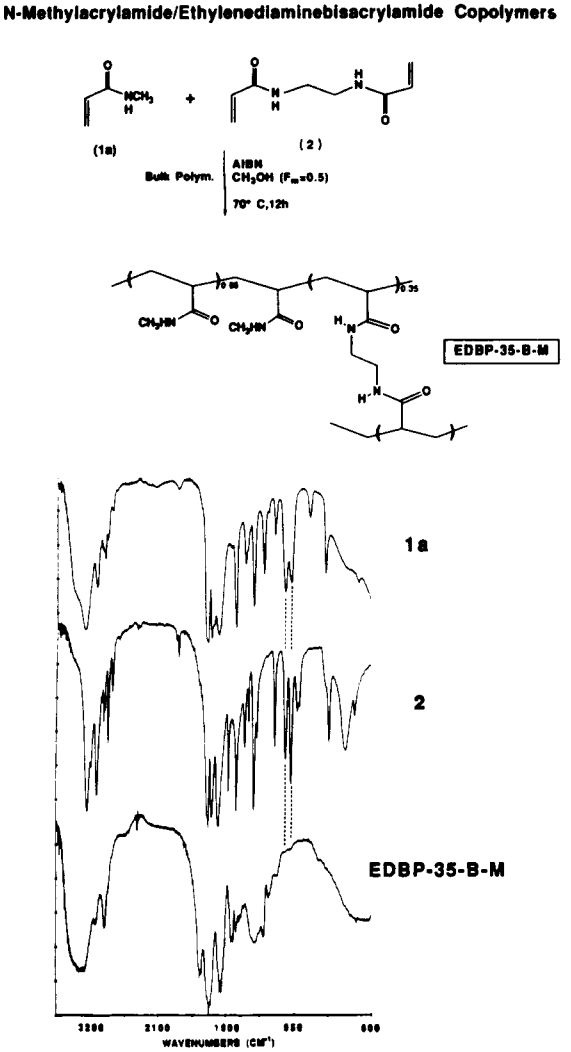


Figure 9. FTIR spectrum of the monomers and copolymers of EDBP-35-B-M. Dashed lines identify C–H out of plane bend at 935 cm^{-1}.

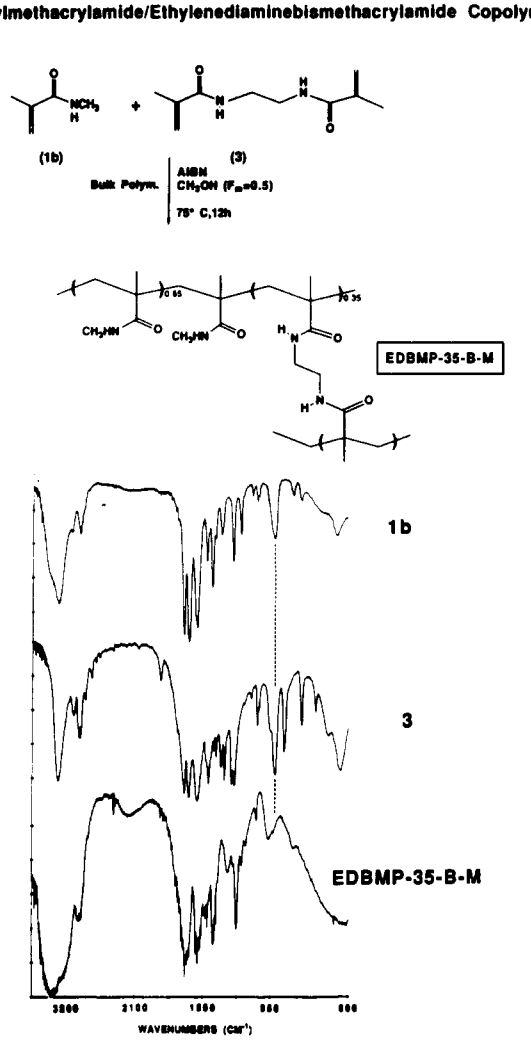


Figure 10. FTIR spectrum of the monomers and copolymers of EDBMP-35-B-M. Dashed lines identify C–H out of plane bend at 935 cm^{-1}.

guidelines for the selection of suitable solvents for reactions at, or near, the polymer surface.

Although quantitative quenching experiments were not carried out, it was noted that EDBMP-35-B-M(**10**) soaked in methanol for 5 min was quenched immediately upon addition of excess 1 M HCl. This encouraging result suggests that simple quenching experiments are possible and can provide important data relating to proton diffusion within these networks.[26,28]

Polymer Functionalization. Several template molecules containing imine linkages were incorporated into the polymer networks to permit evaluation of the facility to which templates can be hydrolyzed from the polymer. The hydrolysis leaves a polymer site functionalized with amine groups. Two related network materials, one a styrene/diisopropenylbenzene network (1/1), DIB-50-B-A(**11**), and the second PDBMP-35-B-F(**12**), were prepared (Figure 7). The diisopropenylbenzene matrix has been optimized with regard to template hydrolysis.[4] After processing, the materials were subjected to identical hydrolysis conditions. Interestingly, the acrylamide materials liberated 85% of the theoretical amount of 1,3-benzenedialdehyde. The diisopropenyl matrix, on the other hand, liberated only 58% of the theoretical amount of dialdehyde under the identical hydrolysis conditions. The higher hydrolysis yield of PDBMP-35-B-F(**12**) compared with the styrene/diisopropenylbenzene matrix suggests that it provides a superior matrix for reactions that require a hydrophilic medium. In a followup study, when hydrolyzed PDBMP-35-B-F(**12**) was subjected to rebinding conditions (1,3-benzenedialdehyde (**13**), benzene, azotropic removal of H_2O), quantitative rebinding of the diamine sites as the Schiff base was observed. Our past experience with rebinding experiments suggests that the quantitative rebinding yield may be interpreted as evidence that a majority of sites retain their integrity after hydrolysis.[5] The level of functionalization achieved by this method is 0.1–0.2 mequiv/g of polymer. Finally, template salt **14**, when incorporated in the methacrylamide network PDBMP-35-B-F(**14**), yielded 84% of the theoretical amount of dicarboxylic acid **15** upon washing with CH_3OH (Figure 8b). This is to be contrasted with a similar noncovalent template **16** (Figure 8a) incorporated into a diisopropenylbenzene/styrene copolymer. Its hydrolysis resulted in only a 69% yield of **15**. These methods permit a convenient procedure for functionalizing these network materials. Qualitative rebinding studies of templated sites are currently under investigation.

Conclusions

The synthesis of macroporous polyacrylamides has been achieved. The porous nature of these materials was determined by a combination of solvent uptake, scanning electron microscopy, and nitrogen adsorption. Interestingly, when long flexible tethers are used for the crosslinker, the materials prepared have a relatively smooth,

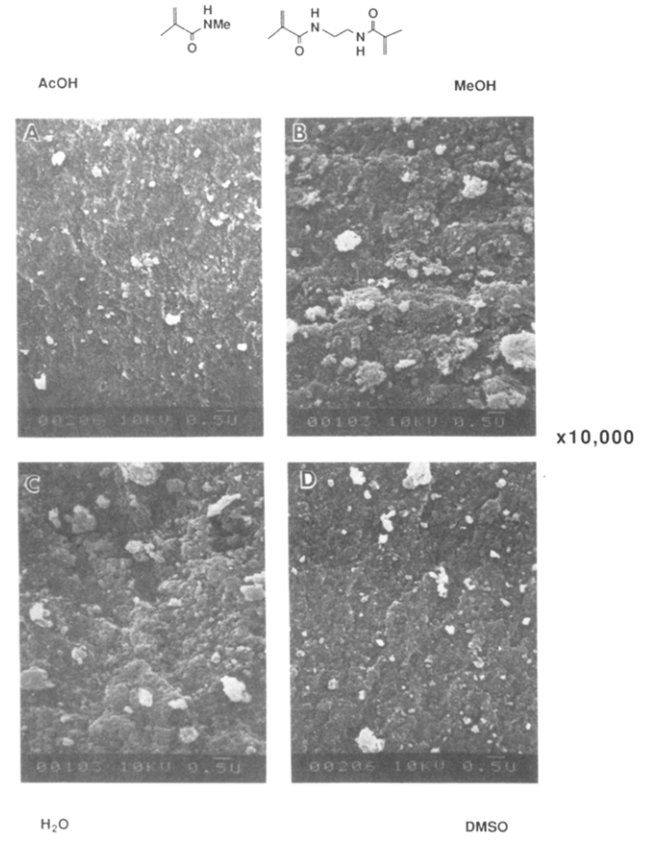


Figure 11. Scanning electron micrographs of EDBMP-35-B-M, -Ac, -W, and -D at ×10 000 magnification.

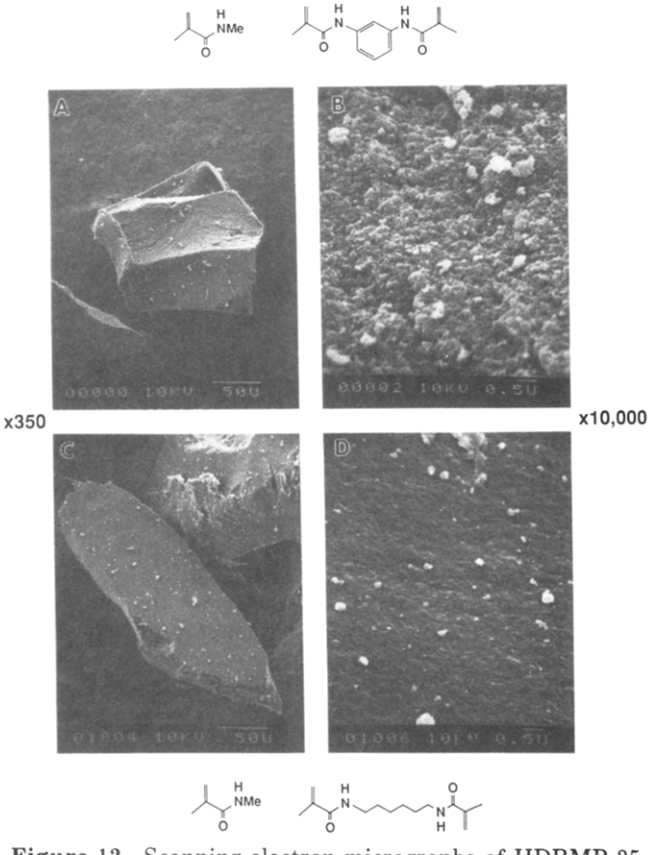


Figure 12. Scanning electron micrographs of HDBMP-35-B-M and PDBMP-35-B-M at ×350 and ×10 000 magnification.

nonporous texture. More rigid small hydrocarbon or aromatic cross-linkers give rise to macroporous materials. The porogen used in the polymerization also contributes greatly to the resulting pore structure. In water and

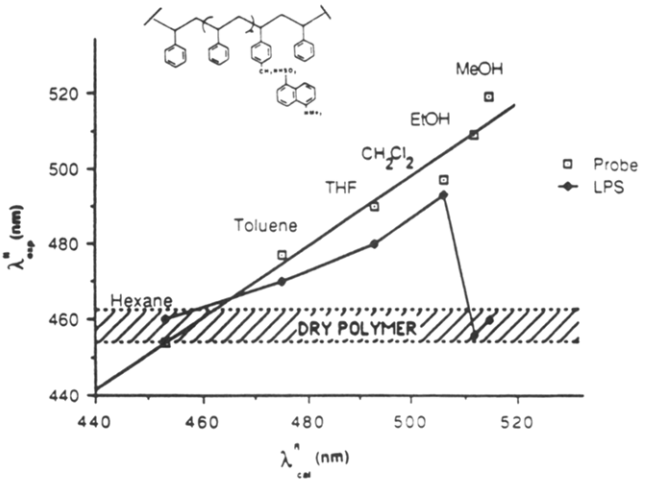
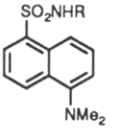
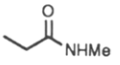
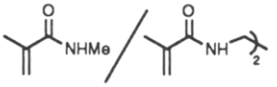
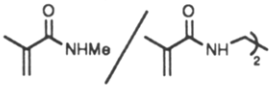
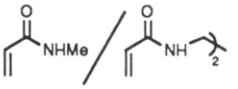


Figure 13. Plot of fluorescence emission maximum of linear polystyrene doped with dansyl probe in the indicated solvents. The straight line corresponds to the correlation line of the monomer probe in the indicated pure organic solvents. The crosshatching corresponds to the fluorescence emission maxima of probe in dry polymer.

Table IV
Characteristic Fluorescence Emission Maxima of Dansyl Probe 9 in Selected Organic Solvents and Doped in Dry Polymers

Fluorescence Emission of Dansyl Probe		
	solvent	λ_{max}(em), nm
	H_2O	537
	MeOH	522
		511
	CH_2Cl_2	499
	THF	490
	toluene	479
	hexane	456

Fluorescence Emission of Dry Polymer Bound Probes			
	dry polymer		
EDBMP-35-B-M		MeOH	497
EDBMP-35-B-A		AcOH	492
EDBP-35-B-M		MeOH	490
DVB-50-B-T			457

methanol, the porosity and surface areas are substantially higher than identical materials prepared when DMSO or acetic acid is used as porogen. The reasons for this difference are not yet fully understood.

These materials are hydrophilic and are wetted by water and other polar aprotic solvents. All of the networks swell slightly in polar solvents (e.g., methanol), whereas in nonpolar solvents (e.g., toluene) they are observed to shrink slightly. These data corroborate conclusions based on fluorescence. The solvent-induced fluorescence emission shifts of these materials reveal significant accessibility to

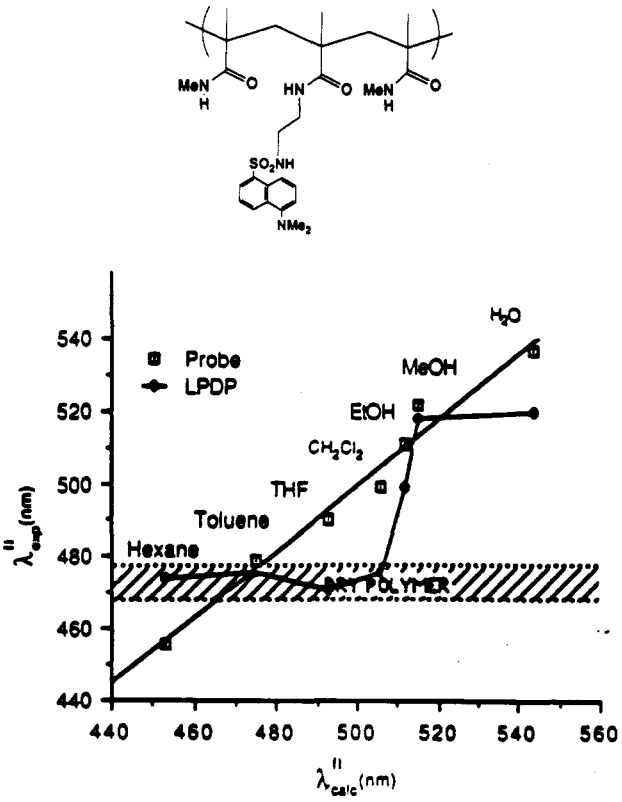


Figure 14. Plot of fluorescence emission maxima of LPDP-(10) doped with dansyl probe 10 in the indicated organic solvents.

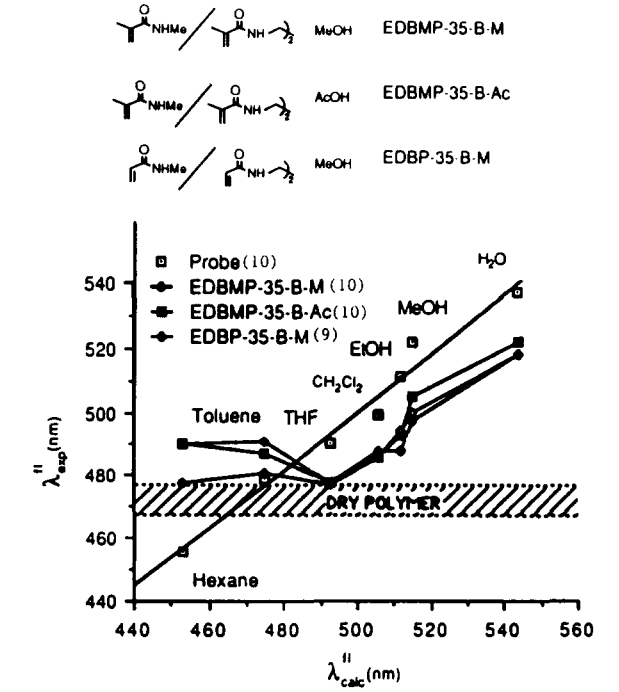


Figure 15. Plots of fluorescence emission maxima of network acrylamides and methacrylamides doped with probes 9 and 10 in the indicated organic solvents.

polar solvents while in nonpolar solvents the gel-phase collapse leads to poor solvation by external solvent. The dry-state fluorescence emission of these polymers is red shifted when compared with ST/DVB, indicating a significantly greater microenvironment polarity associated with these materials. Functionalization of these materials is readily achieved by copolymerization with suitable monomers. We are currently evaluating these materials in our template polymerization program as well as in other applications.

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