Synthesis and Characterization of Double-Hydrophilic Model Networks Based on Cross-linked Star Polymers of Poly(ethylene glycol) Methacrylate and Methacrylic Acid

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ABSTRACT: A series of model networks based on cross-linked star polymers of poly(ethylene glycol) methacrylate (PEGMA) and tetrahydropyranyl methacrylate (THPMA), a protected form of methacrylic acid (MAA), were synthesized by group transfer polymerization (GTP), covering various compositions (homopolymers and copolymers), arm architectures (homopolymer, block and statistical copolymers), and star architectures (heteroarm and star block). The synthesis took place in tetrahydrofuran (THF) using tetrabutylammonium bibenzoate (TBABB) as the catalyst and 1-methoxy-1-(trimethylsiloxy)-2-methylpropene (MTS) as the initiator, and comprised a four- or six-step procedure: first, the formation of linear polymer chains upon the GTP of the monomer(s); next, the interconnection of the linear segments to star polymers ("arm-first" stars) by the in situ polymerization of the ethylene glycol dimethacrylate (EGDMA) cross-linker, followed by the addition of monomer(s) for a second time to grow new chains from the cores of the stars outward ("in−out" stars); finally, the cross-linking of the "in−out" stars to a network with the addition of more EGDMA. The molecular weights (MWs) and molecular weight distributions (MWDs) of all the linear and the star precursors to the networks were determined using gel permeation chromatography (GPC). The networks which contained THPMA were hydrolyzed under acidic conditions to convert the THPMA units to MAA units and thus to obtain polyelectrolytic, double-hydrophilic model networks. The aqueous degrees of swelling of all the networks were measured as a function of pH. At low pH, where MAA is protonated, low degrees of swelling were obtained, which increased with the network content in PEGMA. An increase of the degrees of swelling was observed at high pH. These high pH degrees of swelling were found to be dependent on both the composition and the structure of the network.

Introduction

Poly(ethylene oxide), PEO, is a widely used nonionic, water-soluble, biocompatible polymer. Because of its unique properties, PEO has been incorporated in polymeric materials in many different forms including macromonomers,[1] macroinitiators,[2] and graft[3] and linear polymers.[4] Amphiphilic (i.e., hydrophilic−hydrophobic) block copolymers of PEO have been proposed as efficient emulsifiers,[5,6] stabilizers,[7−9] and drug-delivery matrices.[10,11] Among them, triblock copolymers of PEO with poly(propylene oxide), known as Pluronics or Synperonics,[12−16] are extensively studied polymeric surfactants with various industrial applications. DuPont has also filed patents on the group transfer polymerization synthesis of ABC triblock copolymers containing at least one hydrophilic and one hydrophobic block and low molecular weight PEO monomethacrylate as the third comonomer. The use of these copolymers for pigment dispersion has been described.[17,18]

However, it is only during the past decade that PEO-based double-hydrophilic (i.e., hydrophilic−hydrophilic) block copolymers have attracted great scientific interest. Among the first examples are studies of the ionic interactions between mixtures of PEO-*b*-polyanion copolymers with either cationic polyelectrolytes[19] or PEO-*b*-polycations.[20] Such systems were shown to lead to the formation of complex mixed micelles with potential drug delivery applications.[21,22] In subsequent studies, various PEO-based hydrophilic−hydrophilic block copolymers were synthesized using different synthetic techniques, from conventional free radical (via a macroinitiator route),[23] to "living" ring-opening cationic,[24] oxyanionic,[25] group transfer,[26] "living" cationic,[27,28] and atom transfer radical polymerization.[29] Potential uses of these materials as stabilizers,[23,30,31] as dispersants,[32] and as gene delivery vehicles[33] have been suggested. The synthesis of both block and statistical copolymers of methacrylate-based PEO macromonomers containing acidic residues was reported using group transfer polymerization.[26,34] The block copolymer analogues exhibited interesting aqueous solution properties and reversible micellization as a function of both pH and potassium carbonate concentration.

Apart from the linear polymers, another class of interesting synthetic materials with many applications are polymer networks, in which several linear polymer chains are interconnected at both chain ends.[35] Hydrogels (water-swellable networks)[36,37] are used as superabsorbents,[38,39] tissue engineering scaffolds,[40] actuators, molecular valves, sensors, chemical memories, molecular separation systems, drug delivery systems, artificial muscles for robotics, and other biomedical materials.[41,42] These applications are based on the ability of these networks to respond to changes of the conditions of the external environment. In particular, pH-sensitive hydrogels have been proposed as promising candidates for the controlled release of peptides[43] and drugs.[44] Among them, copolymer networks of poly(methacrylic acid) (polyMAA) grafted with poly(ethylene glycol) monomethacrylate have attracted attention because they combine the pH response of the MAA units and the biocompatibility of the ethylene glycol units. The synthesis of such networks was first reported by Klier et al.[45] using conventional free-radical polymerization.

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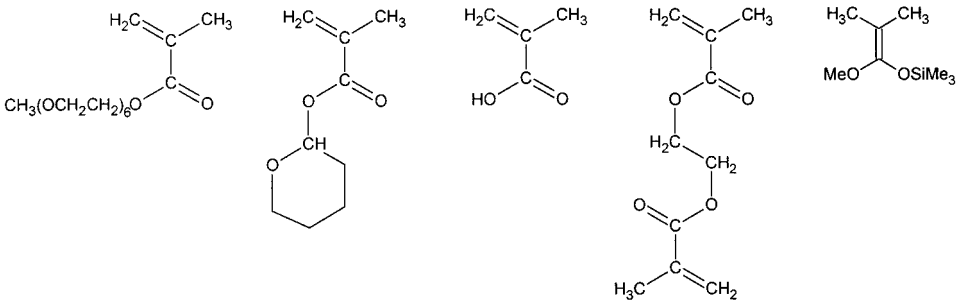

Figure 1. Chemical formulas of the main reagents used for the network synthesis. Monomers: methoxy poly(ethylene glycol) methacrylate (PEGMA), tetrahydropyranyl methacrylate (THPMA), and methacrylic acid (MAA). Cross-linker: ethylene glycol dimethacrylate (EGDMA). Initiator: 1-methoxy-1-(trimethylsiloxy)-2-methylpropene (MTS).

The swelling behavior and adsorption properties of these networks have been studied extensively.[43,46,47] However, due to limitations of the synthetic technique employed, these networks exhibited a random distribution of the two comonomers along the network elastic chains and also variable lengths of the segments between cross-links.

In the present work, anionic, double-hydrophilic model[48] networks (accurate size and composition of their components) containing MAA units and methoxy poly(ethylene glycol) methacrylate (PEGMA) (six ethylene glycol units in the side-chain) and based on both block and statistical copolymers were prepared. The network structure was more complicated than that of conventional model networks. Thus, the present networks, in addition to the elastic chains, contained an equal number of dangling chains.[49] The model networks were synthesized in a one-pot preparation by group transfer polymerization (GTP).[50−53] Both the architecture (block and statistical) and the size of the dangling and elastic chains of the networks were controlled due to the 'living' character of GTP. All networks prepared were characterized in terms of their swelling behavior in water as a function of pH. The degree of swelling was shown to be affected by both the solution pH and the network structure.

Experimental Section

Materials and Methods. All reagents used were purchased from Aldrich, with the exception of the PEGMA monomer (purity 99% w/w, 0.4% water), which was kindly donated (as Bisomer MPEG350MA) by Laporte Performance Chemicals. Figure 1 shows the chemical formulas and names of the monomers, the cross-linker and the initiator used for the network synthesis. Tetrahydropyranyl methacrylate (THPMA) is not commercially available and was in-house synthesized by the sulfuric acid-catalyzed reaction of 3,4-dihydro-2*H*-pyran (DHP, 97%) with MAA (99%), following a modification of the method reported by Hertler.[54] The polymerization catalyst, tetrabutylammonium bibenzoate (TBABB), was in-house synthesized by the method described by Dicker et al.[52] The catalyst powder was stored under vacuum until use. Tetrahydrofuran (THF, 99.8%; Labscan) served as the polymerization solvent. It was dried by refluxing it over a potassium/sodium alloy for 3 days and was freshly distilled prior to the polymerization. 1-Methoxy-1-(trimethylsiloxy)-2-methylpropene (MTS, 95%) was used as the polymerization initiator. The THPMA monomer and the cross-linker, ethylene glycol dimethacrylate (EGDMA, 98%), were passed through basic alumina columns to remove inhibitors and acidic impurities. THPMA was passed more than once (typically 3−4 times) through the alumina columns until no MAA olefinic protons were detected in its proton nuclear magnetic resonance (^{1}H NMR) spectrum (typical purity by gas chromatography 99%). Both THPMA and EGDMA were stirred overnight over calcium hydride to remove the last traces of moisture and protonic impurities in the presence of an added free radical inhibitor, 2,2-diphenyl-1-picrylhydrazyl hydrate (DPPH, 95%), to avoid thermal polymerization. MTS, THPMA, and EGDMA were all freshly distilled prior to the polymerization. PEGMA was used as a 50% v/v solution in freshly distilled THF because it is a highly viscous liquid and rather difficult to handle without dilution. The solution was passed twice through a basic alumina column to remove inhibitors and acidic impurities. It was stirred over calcium hydride for 2 h and kept in the refrigerator until use. Finally, it was syringed through a 0.45 μm filter (to keep any suspended calcium hydride) directly into the polymerization flask. All glassware was dried overnight in an oven at 120 °C and assembled hot under dynamic vacuum. The polymerizations were carried out in 100 mL round-bottom flasks. Catalytic amounts of TBABB (∼10 mg) were transferred to each flask, which was fitted with a rubber septum and purged with dry nitrogen. Freshly distilled THF was transferred from the still to the flask via a glass syringe. The initiator was added next, followed by the addition of the monomers and cross-linker.

Network Synthesis. All polymerization reactions were carried out at ambient temperature without thermostating the polymerization flasks. The polymerization exotherm was monitored by a digital thermometer and was used to follow the progress of the reaction. The synthetic sequence for all cross-linked star structures prepared is illustrated in Figure 2. Homopolymer cross-linked stars were prepared when only one monomer was added before each addition of cross-linker, and the monomer added second was the same as that used first. When the monomer added after the first cross-linking was different from that added before, heteroarm copolymer star-based networks were synthesized. The sequential or simultaneous addition of the two different monomers before each addition of the EGDMA cross-linker resulted in the preparation of arms of block or statistical architecture, and it ultimately led to the formation of block or statistical copolymer cross-linked stars, respectively. A typical polymerization procedure is detailed below which describes the synthesis of a block copolymer cross-linked star having primary and secondary arms both comprising linear diblock copolymers with 20 PEGMA units and 5 THPMA units. Freshly distilled THF (50 mL) and 0.2 mL of MTS initiator (0.98 mmol) were syringed in this order to a 100 mL round-bottom flask containing a small amount (∼10 mg) of TBABB. PEGMA (13.1 mL of 50 v/v% solution in THF, 19.6 mmol) monomer was slowly added under stirring. The polymerization exotherm (25.8−30.4 °C) abated within 5 min, samples for GPC were extracted (full monomer conversion, polymer M_n = 8400 g mol^{-1} and M_w/M_n = 1.08), and 0.84 mL of THPMA (4.9 mmol) was added slowly, giving an exotherm (30.3−31.7 °C). After sampling (full monomer conversion, polymer M_n = 8700 g mol^{-1} and M_w/M_n

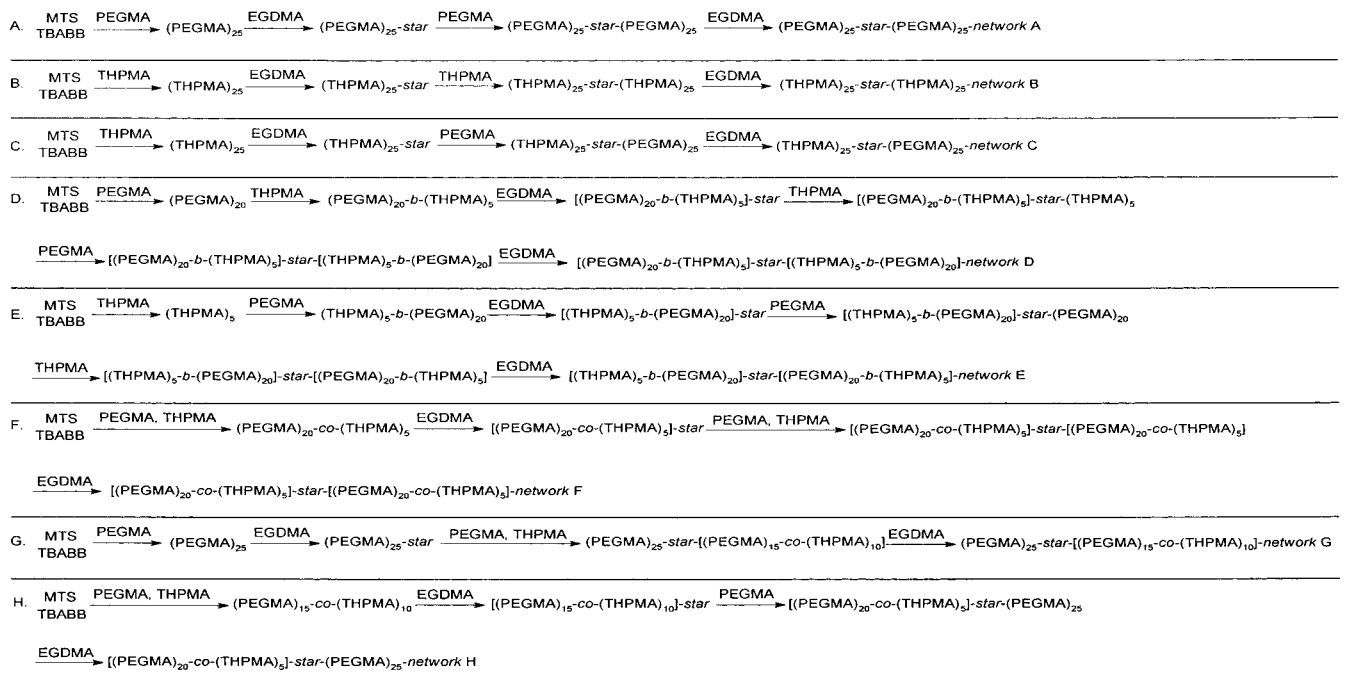

Figure 2. Synthetic sequences employed for the preparation of the various cross-linked star architectures of this study: PEGMA, methoxy poly(ethylene glycol) methacrylate; THPMA, tetrahydropyranyl methacrylate; EGDMA, ethylene glycol dimethacrylate; MTS, 1-methoxy-1-(trimethylsiloxy)-2-methylpropene; TBABB, tetrabutylammonium bibenzoate.

= 1.09), 0.75 mL of EGDMA (3.94 mmol) was added which produced an exotherm (31.4−33.7 °C). Samples were withdrawn again (full monomer conversion, polymer M_n = 16 400 g mol^{-1} and M_w/M_n = 1.47) before 0.84 mL of THPMA (4.9 mmol) was added giving an exotherm from 33.1 to 34.0 °C. Samples for GPC were withdrawn again (full monomer conversion, polymer M_n = 19 300 g mol^{-1} and M_w/M_n = 1.46), followed by the addition of 13.1 mL PEGMA (50 v/v% solution in THF, 19.6 mmol) with an exotherm from 31.2 to 32.7 °C (full monomer conversion, polymer M_n = 21 000 g mol^{-1} and M_w/M_n = 1.40). In the final stage, 0.75 mL of EGDMA (3.94 mmol) was added, which promoted gelation within seconds.

Characterization of Network Precursors by Gel Permeation Chromatography. Molecular weights (MWs) and molecular weight distributions (MWDs) of the linear, "arm-first" and "in−out" star polymer precursors to the networks were obtained by gel permeation chromatography (GPC). A Polymer Laboratories system was used, equipped with a PL-LC1120 isocratic pump, an ERC-7515A refractive index detector, and a nonthermostated (room temperature ~25 °C) PL-mixed "D" GPC column (bead size = 5 μm; pore sizes = 100, 500, 10^3, and 10^4 Å). The mobile phase was THF, delivered at a flow rate of 1 mL min^{-1}. The calibration curve was based on seven narrow MW (630, 4250, 13000, 28900, 50000, 128000, and 260000) linear poly(methyl methacrylate) standards, which provided relatively accurate MW calculations for the linear segments but only qualitative estimates for the MWs of the star polymers.

Determination of the Sol Fraction. The gels were taken out of the polymerization flasks by cutting the flasks with a diamond knife and were subsequently washed in 200 mL of THF for 1 week to remove the sol fraction. The solvent was replaced twice during that time. The THF solution was recovered by filtration each time. The solvent was evaporated and the extractables were dried under vacuum for 48 h at room temperature. The sol fraction was calculated as the ratio of the mass of the extracted polymer to the theoretical mass of the gel.

THPMA Hydrolysis. After the sol fraction was removed and while the gels were in THF, 100% mol excess HCl 2 M with respect to the theoretical number of THPMA equivalents in the gels was added to the networks containing THPMA. For example, 10 mL of a 2 M HCl solution were added to the network [(P_{20}-*b*-T_5)-*star*-(T_5-*b*-P_{20})]-*network* (still swollen in 200 mL of THF) and left for 2 weeks. Fourier transform infrared (FTIR) spectroscopy using a VECTOR 22 Bruker FTIR spectrometer was employed to qualitatively confirm the hydrolysis of the THPMA units, by comparing the spectra taken from a vacuum-dried sample of the heteroarm copolymer star network (50 mol % THPMA) before and after the addition (and washing) of HCl.

Characterization of the Degree of Swelling in Water. After hydrolysis the gels were washed in 500 mL of distilled water, which was changed every 2−3 days for 2 weeks to remove all THF and the excess HCl. Measurements of the pH and the total gel mass took place before each water change. When the pH and mass values stabilized, the water was replaced once more and the gels were allowed to equilibrate for 1 additional week. Two cubic samples of size ~1 cm were then cut from each network. The mass of the water swollen cubes was measured gravimetrically before placing them in a vacuum oven to dry for 48 h at room temperature. The dry gel mass was determined and the degrees of swelling in the aqueous phase were calculated as the ratio of wet network mass divided by the dry gel mass.

Ten cubic samples from each network of size ~1 cm were taken, and each was placed in a separate vial. Then, 10 mL of distilled water were added to each vial. The pH of the gel samples in water was varied between 2 and 12 by the addition of the appropriate volume of 0.5 M HCl or 0.1 M NaOH solutions. The samples were allowed to equilibrate for 3 weeks and the solution pH and gel mass were measured. The degree of swelling for each gel sample was calculated. All degrees of swelling were determined in triplicate and the averages of the measurements are presented.

Calculation of the Degree of Ionization and the p*K*. The degree of ionization of each sample was calculated as the number of NaOH equivalents added divided by the number of MAA equivalents (calculated from network wet mass, known degree of swelling, and network composition) in the sample. The effective p*K* of each network was estimated as the pH (of the supernatant solution) at 50% ionization.

Results and Discussion

Synthesis and Structure of Cross-Linked Star Polymers. Eight polymer networks were synthesized by GTP, using MTS as the initiator, TBABB as the

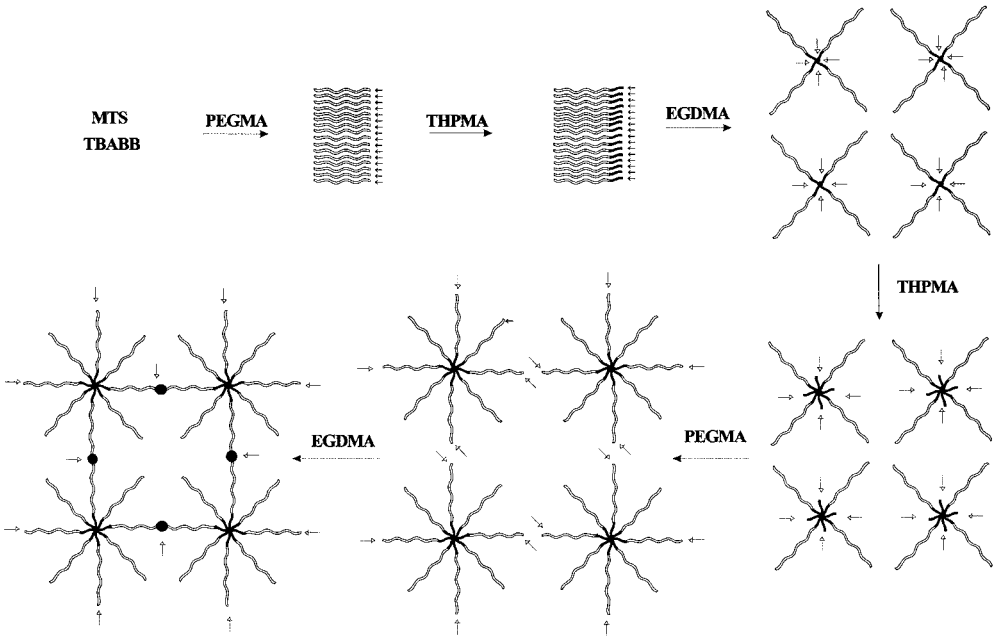

Figure 3. Schematic representation of the synthetic sequence followed for the preparation of the block copolymer-based network [(P_{20}-*b*-T_5)-*star*-(T_5-*b*-P_{20})]-*network* (D). The white color indicates methoxy poly(ethylene glycol) methacrylate (PEGMA or P), while the black indicates tetrahydropyranyl methacrylate (THPMA or T). Key: EGDMA, ethylene glycol dimethacrylate; MTS, 1-methoxy-1-(trimethylsiloxy)-2-methylpropene; TBABB, tetrabutylammonium bibenzoate. The number of arms at the cross-links is not 2, 4, or 8 as shown in the figure but around 30−60.

catalyst, and PEGMA and THPMA as the monomers. THPMA is the protected form of MAA which cannot be polymerized directly by GTP because it contains labile protons which cause termination of the polymerization. The THPMA units were readily converted to MAA units after the polymerization by acid hydrolysis. EGDMA served as the cross-linker for the formation of star polymers and cross-linked star polymer networks due to its ability to be added repeatedly at the core, bringing together a large number of chains.[55] The hydrogels obtained were model networks, having accurate MWs of the dangling chains and of the segments between cross-links, due to the "livingness" of GTP, which allows good control over MWs and MWDs.

Figure 3 is a schematic representation of the synthetic procedure used for the preparation of one of the networks, network D, which is based on diblock copolymer linear chains. The PEGMA units are shown in white, while the THPMA/MAA units are shown in black. The large black dots indicate the secondary EGDMA cores, and the active sites of the polymerization are shown by the arrows. For this particular network, the procedure included six steps, four additions of monomer and two additions of cross-linker. All steps took place in the same reactor. After the catalyst, the solvent and the initiator, the two monomers were added sequentially to the reaction flask. First, the addition of PEGMA gave linear homopolymer chains followed by the addition of THPMA, which induced chain growth and formation of diblock copolymer chains. The subsequent in situ polymerization of EGDMA in 4-fold molar excess with respect to the initiator led to the formation of "arm-first" star polymers, which maintained the active sites in the core of the star. These cross-linked chains constitute the primary arms of the stars and the dangling chains of the networks. The 4:1 ratio of cross-linker to initiator used was found in previous studies to give satisfactory incorporation of chains to stars, without using large quantities of cross-linker.[56,57] The number of arms is not four, as shown in the figure, but much higher, between 30 and 60, as determined by static light scattering on similar star polymers.[49,55] Further addition of THPMA formed secondary arms from the core of the stars outward, giving a structure known as "in−out" stars. Chain extension of the secondary arms was accomplished by addition of PEGMA leading to secondary arms of the same composition and architecture as that of the primary arms. The active sites at that point were at the ends of the secondary arms. The "livingness" of the polymerization implies that the number of secondary arms is equal to the number of primary arms.[49] The final addition of cross-linker induced the inter-*cross*-linking of the "in−out" stars via their secondary arms to form the network.

Figure 4 shows all network structures prepared in this study. These comprise the two homopolymer cross-linked stars, A and B, one equimolar heteroarm copolymer cross-linked star, C, and five isomeric copolymer cross-linked stars with 80% mol PEGMA and 20 mol % MAA, D, E, F, G, and H. The sequence of reagent addition for the preparation of each of the networks was presented in Figure 2. Table 1 shows the theoretical chemical formulas of all networks precursors and their MW characterization results.

Molecular Weight Analysis. Figure 5 shows the GPC chromatograms of the five precursors to network D. The MWDs of the linear PEGMA homopolymer, P_{20}, and the linear PEGMA-THPMA diblock copolymer, P_{20}-*b*-T_5, are narrow and unimodal. The MWD of the "arm-first" star, (P_{20}-*b*-T_5)-*star*, is bimodal, containing a small amount of unattached linear chains in addition to the stars. Similar are the chromatograms of the "in−out" stars, (P_{20}-*b*-T_5)-*star*-(T_5) and (P_{20}-*b*-T_5)-*star*-(T_5-*b*-P_{20}), which are multimodal, with a narrow MWD of the main peak corresponding to the "in−out" star. The MW of the main peak is increasing from the initial homopolymer to the final "in−out" star precursor, as expected. The relatively small difference between the GPC retention

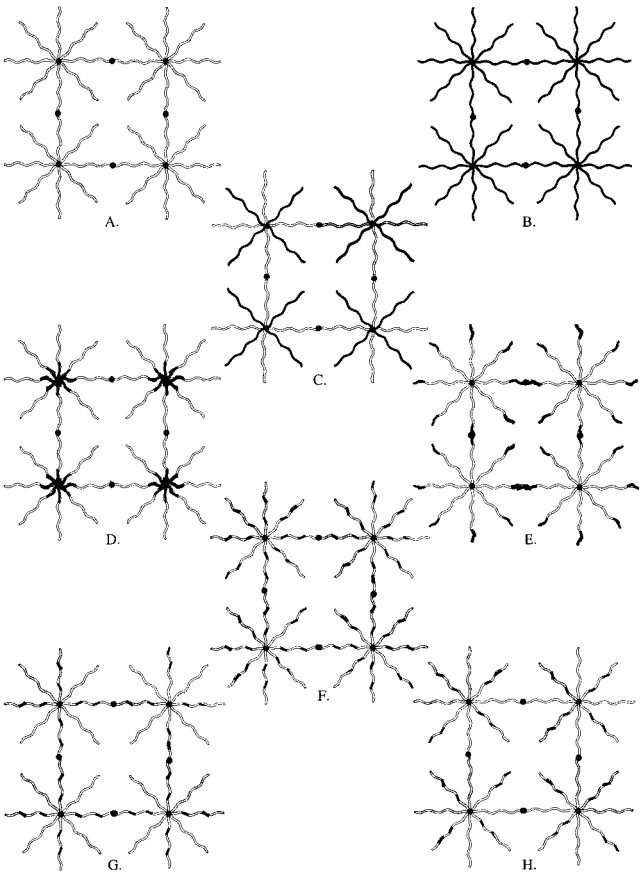

Figure 4. Schematic representation of the architectures of all the model networks prepared in this study. The methoxy poly(ethylene glycol) methacrylate (PEGMA) units are depicted in white, while in black are shown the tetrahydropyranyl methacrylate (THPMA) units, which are to be converted subsequently to methacrylic acid (MAA) units. The number of arms at the cross-links is not 2 or 8 as shown in the figure but around 30−60.

volumes of the "arm-first" and "in−out" star polymers is attributed to the small difference of the hydrodynamic volume of these two structures which is common in star polymers with numerous arms and with primary and secondary arms of similar length. This was also observed in similar work on the synthesis of "in−out" star polymers by anionic polymerization.[58]

Table 1 summarizes the GPC results for the precursors to all eight networks. These include the apparent number-average MWs, M_ns, the polydispersity indices, M_w/M_ns, and the peak MWs, M_ps. The theoretical MWs of the linear precursors are also shown. All linear polymers exhibit narrow MWDs ($M_w/M_n < 1.3$), and their apparent M_ns are reasonably close to their theoretical MWs. For the star polymers the MWDs are broader, mainly due to the incomplete incorporation of linear chains into stars and the inclusion of the unattached chain population in the calculation due to the overlap of the two peaks. Incomplete incorporation can be attributed to high solution viscosity and low chain mobility toward the later stages of the polymerization procedure.[56] An additional reason in our case is the large size of the PEGMA units, which causes considerable steric hindrance during the polymerization.

An increase in the apparent experimental MWs (M_ns and M_ps) of the network precursors in all stages of the synthetic procedure was determined by GPC, suggesting the growth of the whole distribution of the stars at each successive step. It should be noted though that both the M_ns and the M_ps determined by GPC for the star polymers are only apparent values and much lower than the actual ones due to the compact nature of the star structure compared to the linear PMMA calibration standards. Recent characterization of similar systems by static light scattering suggested that the absolute weight-average MW, $\overline{M}_w$, of the star polymers is about 10 times higher than the M_n determined by GPC.[49,59] For all the isomeric co-networks D−H the increase of the apparent M_n from the linear to the "arm-first" star as well as the increase from the "arm-first" star to the final "in−out" star is about the same, as expected.

THPMA Hydrolysis. Using acidic conditions, the gels containing THPMA were transformed into MAA gels.[60] The THPMA hydrolysis reaction is exactly the reverse to its synthesis reaction. The deprotection of THPMA was confirmed qualitatively by FTIR, using samples from gel C, which are representative for all the other gels containing THPMA, given that excess HCl was used and extensive time was allowed for hydrolysis in all gels. The appearance of a double characteristic band at 2940−2860 cm^{-1}, due to the O−H stretching vibration of the carboxylic group of MAA, provided evidence for successful hydrolysis of THPMA to MAA.[61] The hydrogen ion titrations of the hydrolyzed network samples, which indicated the presence of a concentration of carboxylic acid groups close to that stoichiometrically expected, were used for the quantitative confirmation of the hydrolysis. The final hydrogels are either hydrophilic (homopolymer networks A and B) or double-hydrophilic (heteroarm copolymer star network C and statistical and block copolymer star networks D−H) gels, containing one or two types of hydrophilic units, respectively.

Sol Fraction of the Networks. Table 2 shows the percent extractables for each network. Network B, a THPMA homopolymer network, has the highest percentage of extractables (15.1%) while all the other networks exhibit relatively low sol fractions (<10%). The low values of these sol fractions support findings of our previous work[56,57] where a 4-fold molar excess of EGDMA cross-linker with respect to the initiator has been determined as the optimal ratio for sufficiently high conversion to star polymer during "arm-first" star polymer synthesis. Similar results were also obtained for studies on both the anionic and "living" cationic "arm-first" star polymer synthesis[62,63] in which high star polymer yields (>85% for anionic) were obtained.

Swelling Behavior of the Hydrogels in Water. Figure 6 shows the pH dependence of the degrees of swelling (DSs) and the degrees of ionization for the eight hydrolyzed model networks. Network A does not contain any MAA ionizable units and, therefore, its degree of ionization is zero within the whole pH range. As expected, its DS remains practically constant and unaffected by the pH. All the other networks contain MAA ionizable units and are therefore sensitive to the pH, exhibiting similar pH dependence of their DSs. Thus, at low pH values, MAA is protonated and electrically neutral, leading to low DSs. An increase in the DS is observed due to the ionization of the MAA units at higher pH (>4). This ionization destroys the hydrogen bonds between the MAA units, it builds up repulsive forces between the now negatively charged chains of the network, and it causes an increase in the osmotic pressure due to accumulation of counterions within the

Table 1. Gel Permeation Chromatography (GPC) Characterization of the Cross-Linked Star Network Precursors

network	theoretical structure of precursor[a]	theor MW	apparent M_n by GPC	M_w/M_n by GPC	apparent peak MW (M_p) by GPC
A	P_{25}	8925	12 800	1.08	13 200
	P_{25}-*star*		25 800	1.65	59 800
	P_{25}-*star*-P_{25}		47 900	1.56	79 100
B	T_{25}	4425	4900	1.10	5300
	T_{25}-*star*		23 400	2.49	68 800
	T_{25}-*star*-T_{25}		96 300	1.79	96 100
C	T_{25}	4425	5800	1.09	6100
	T_{25}-*star*		25 600	2.26	68 800
	T_{25}-*star*-P_{25}		104 500	1.25	116 900
D	P_{20}	7175	8400	1.08	9100
	P_{20}-*b*-T_5	8025	8700	1.09	9600
	(P_{20}-*b*-T_5)-*star*		16 400	1.47	28 800
	(P_{20}-*b*-T_5)-*star*-T_5		19 300	1.46	33 000
	(P_{20}-*b*-T_5)-*star*-(T_5-*b*-P_{20})		21 000	1.40	33 000
E	T_5	1025	900	1.28	900
	T_5-*b*-P_{20}	8025	10 800	1.07	11 500
	(T_5-*b*-P_{20})-*star*		17 200	1.33	25 900
	(T_5-*b*-P_{20})-*star*-P_{20}		21 500	1.29	28 800
	(T_5-*b*-P_{20})-*star*-(P_{20}-*b*-T_5)		25 000	1.38	36 800
F	P_{20}-*co*-T_5	8025	10 500	1.08	11 200
	(P_{20}-*co*-T_5)-*star*		19 100	1.34	29 600
	(P_{20}-*co*-T_5)-*star*-(P_{20}-*co*-T_5)		25 700	1.36	36 800
G	P_{25}	8925	10 400	1.08	11 200
	P_{25}-*star*		17 200	1.36	28 100
	P_{25}-*star*-(P_{15}-*co*-T_{10})		21 700	1.36	32 100
H	P_{15}-*co*-T_{10}	7125	11 200	1.07	11 900
	(P_{15}-*co*-T_{10})-*star*		21 400	1.37	33 900
	(P_{15}-*co*-T_{10})-*star*-P_{25}		24 200	1.38	32 100

[a] P and T are (further) abbreviations for methoxy poly(ethylene glycol) methacrylate (PEGMA) and tetrahydropyranyl methacrylate (THPMA), respectively.

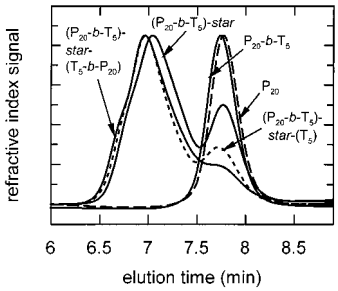

Figure 5. Gel permeation chromatograms of the five precursors to network [(P_{20}-*b*-T_5)-*star*-(T_5-*b*-P_{20})]-*network* (D): P, methoxy poly(ethylene glycol) methacrylate (PEGMA); T, tetrahydropyranyl methacrylate (THPMA). P_{20}: linear homopolymer of PEGMA; P_{20}-*b*-T_5, linear diblock copolymer of PEGMA and THPMA; (P_{20}-*b*-T_5)-*star*, "arm-first" star-block; (P_{20}-*b*-T_5)-*star*-(T_5), first "in−out" star; (P_{20}-*b*-T_5)-*star*-(T_5-*b*-P_{20}), final "in−out" star.

Table 2. Sol Extractables from the Cross-Linked Star Networks

network	theoretical structure[a]	% extractables (w/w)
A	[P_{25}-*star*-P_{25}]-*network*	9.0
B	[T_{25}-*star*-T_{25}]-*network*	15.1
C	[T_{25}-*star*-P_{25}]-*network*	10.1
D	[(P_{20}-*b*-T_5)-*star*-(T_5-*b*-P_{20})]-*network*	8.2
E	[(T_5-*b*-P_{20})-*star*-(P_{20}-*b*-T_5)]-*network*	9.1
F	[(P_{20}-*co*-T_5)-*star*-(P_{20}-*co*-T_5)]-*network*	7.6
G	[P_{25}-*star*-(P_{15}-*co*-T_{10})]-*network*	10.2
H	[(P_{15}-*co*-T_{10})-*star*-P_{25}]-*network*	8.5

[a] P and T are (further) abbreviations for methoxy poly(ethylene glycol) methacrylate (PEGMA) and tetrahydropyranyl methacrylate (THPMA), respectively.

gels,[64−66] thus leading to the expansion of the network. The DS curves reach a maximum (which is dependent on the structure of the networks as discussed in a later section) and then decrease with increasing pH. This decrease in the DS at high pH values is due to the high ionic strength of the solution at this pH, resulting from the relatively high sodium hydroxide concentration, which screens the electrostatic interactions.

The degrees of ionization also increase systematically with increasing pH. The effective p*K*s (taken as the pH at 50% ionization) were determined for the MAA containing networks from their degree of ionization curves. p*K*s of around 6.8 were found which are higher than the corresponding values for linear MAA polymers of around 5.4.[67] This is attributed to the fact that the pH was measured in the surrounding solution where proton concentration is lower due to counterion partitioning into the gel phase.[66]

In agreement with previous results for homopolymer based cross-linked stars of ionizable methacrylate monomers,[49] we have observed that homopolymer star network B, heteroarm copolymer star network C, and statistical copolymer star network G break into small pieces of size ∼1 mm above pH 9. This has also been reported by Flory[68] on ionized poly(MAA) networks. It can be attributed to intense electrostatic repulsion in the gels, which causes the rupture of the carbon−carbon bonds of the backbone. The breakage of the gels can lead to an overestimation of the DSs, caused by water entrapment between gel pieces.

Figure 7 shows the DSs for each network at low and high pH values. The DSs at low pH are composition-dependent but architecture-independent. A linear decrease of the DSs is observed as a function of the network content in MAA. This decrease is attributed to the greater hydrophilicity of PEGMA compared to protonated MAA and the formation of hydrogen bonds between the protonated MAA units, which act as additional physical cross-links and cause the shrinkage of the networks.[69] The DSs of the isomeric copolymer networks D−H are all around 10 and independent of

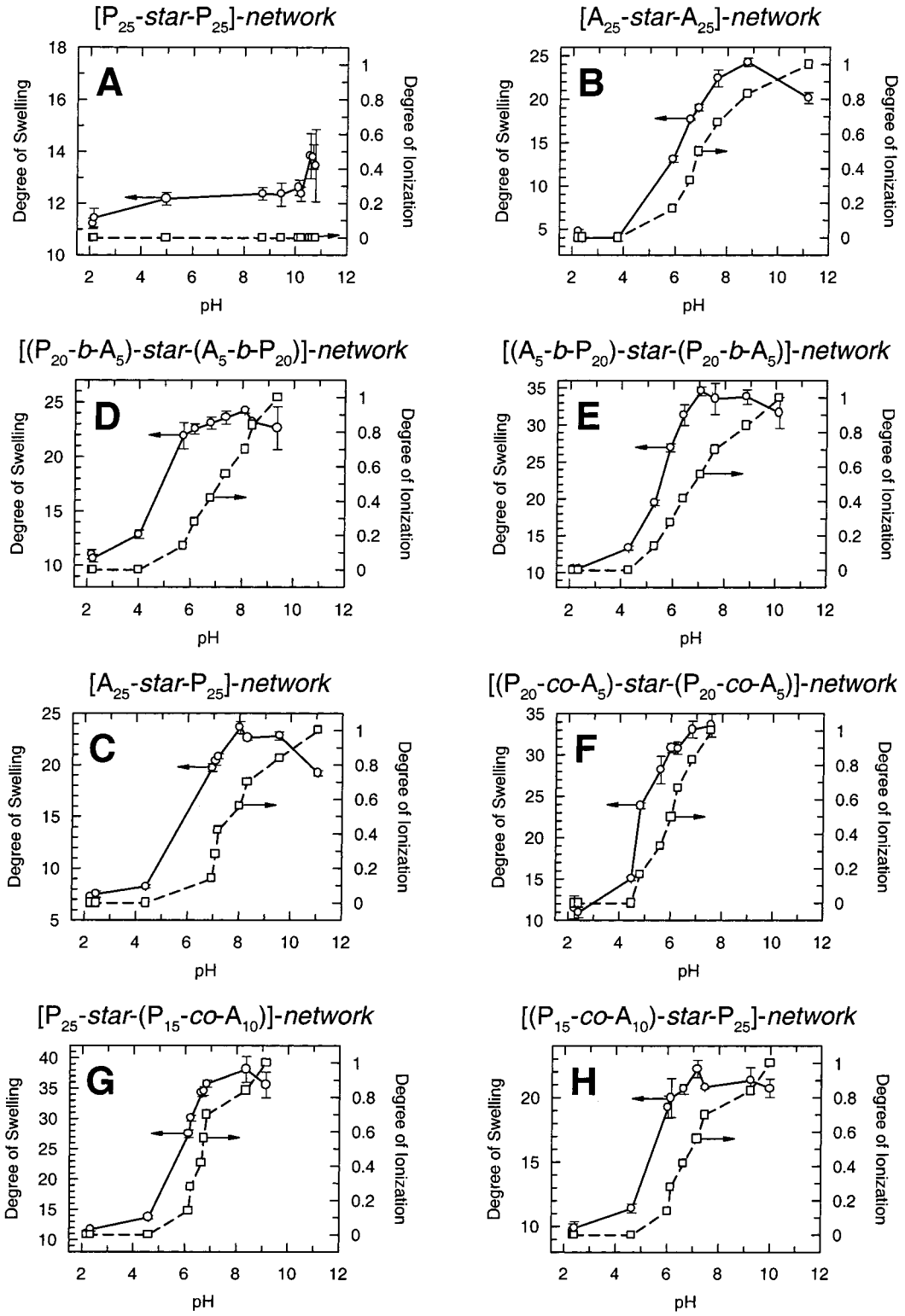

Figure 6. pH dependence of the aqueous degrees of swelling and the degrees of ionization of all the cross-linked star networks: P, methoxy poly(ethylene glycol) methacrylate (PEGMA); A, methacrylic acid (MAA).

their structure, suggesting that the location of the MAA units in the network structure does not affect their swelling properties at low pH.

In contrast, the DSs at high pH increase with the MAA content of the network and are strongly architecture-dependent. Thus, an increase of the high pH DS is observed following the order A < (D, H) ≈ C ≈ B corresponding to networks which contain 0, 20, 50, and 100% MAA, respectively. Under these conditions, the main contribution to swelling comes from the ionized MAA units since the high pH DSs are at least two times greater than the corresponding low pH DSs (2−3.5-fold increase from low to high pH for the heteroarm star network and the statistical and block copolymer star networks and 6-fold increase for the MAA homopolymer network) and much higher than the DS of the PEGMA homopolymer network. However, at high pH, apart from the composition, there is also a strong dependence of

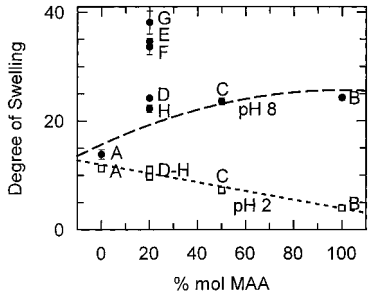

Figure 7. Low pH and high pH degrees of swelling of the networks as a function of the methacrylic acid (MAA) mol fraction. The curves are drawn to guide the eye.

the DS on the star architecture. This is also shown in Figure 7 where the five isomeric copolymer networks (D−H) exhibit a significant variation of their high pH DSs, which was not observed for the low pH DSs. The factors that affect the DS and result in these differences in the high pH DSs of the isomeric copolymer networks are, first, the MAA content of the elastic chains of the networks (secondary arms of the stars) and, second, the location of the MAA units within the star structure. Thus, network G, which has the highest MAA content in its elastic chains among the copolymer networks, exhibits the highest DS, while the lowest DS is obtained for network H, which has no MAA units in the secondary arms. This is consistent with the fact that the main contribution to swelling at high pH comes from the ionized MAA units, and it suggests that the elastic chains have a greater effect on the swelling behavior of the networks compared to the dangling chains, which has also been observed for homopolymer and amphiphilic copolymer-based cross-linked stars.[49,59] The effect of the location of the MAA units in the network structure on the swelling behavior of the networks is seen when comparing the high pH DS of the isomeric networks D, E, and F. Although all three networks have the same MAA content in both their elastic and dangling chains, network D exhibits the lowest DS at high pH. This is attributed to the fact that the ionized MAA units in network D are all located in blocks around the cores of the "in−out" stars. This initially high charge density may lead to significant counterion condensation and ultimately result in the weakest electrostatic repulsion and lowest increase in osmotic pressure.[70] Comparing networks D and E, the latter has a higher DS even though it also has MAA blocks around the secondary cores of the network (formed upon the inter-cross-linking of the "in−out" stars to obtain the polymer network). This seems surprising at a first glance but can be explained by the presence of MAA units at the end of the dangling chains of network E, which are not "locked" around a star core and can extend to a greater volume, thus reducing counterion condensation. On the other hand, networks E and F exhibit, within experimental error, the same DSs, consistent with the same composition of both their dangling and elastic chains. This result also suggests that the random distribution of the MAA units in network F, or their location in blocks around the secondary cores and at the end of the dangling chains in network E, has the same effect on the swelling behavior. A more effective counterion condensation would be expected to take place around the secondary cores of network E, which would result in a lower high pH DS compared to network F. However, this effect is counterbalanced by the stronger electrostatic repulsions developed between the charged MAA blocks, located at the end of the dangling chains of network E, which cause its expansion and ultimately result in statistically the same DS for the two networks. It is noteworthy that the effective pK of network F is slightly lower than that of network E.

Conclusions

We have used GTP to synthesize complex model network structures based on cross-linked "in−out" star polymers of PEGMA and MAA. These networks are new materials exhibiting interesting swelling behavior. Their degree of swelling was found to be affected by the solution pH, network composition and star architecture. Therefore, network design can be critical in controlling their swelling properties. Future work will focus on further investigation of the effects of polymer composition and molecular weight on the swelling behavior. Possible applications based on both the ionic and double-hydrophilic character of these networks will be also explored.

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