Synthesis and Characterization of Polyampholytic Model Networks: Effects of Polymer Composition and Architecture†

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ABSTRACT: Group transfer polymerization (GTP) was used for the preparation of seven ampholytic polymer networks based on 2-(dimethylamino)ethyl methacrylate (DMAEMA) and methacrylic acid (MAA). The MAA units were introduced via the polymerization of tetrahydropyranyl methacrylate (THPMA) and the acid hydrolysis of the latter after network formation. Ethylene glycol dimethacrylate (EGDMA) served as the cross-linker. Six of the networks had linear segments of accurate molecular weight between cross-links; i.e., they were model networks. In the seventh network the lengths of the segments between cross-links had a wide distribution of molecular weights (randomly cross-linked network) since the cross-linker was copolymerized at the same time with the monomers. Four of the six model networks were based on ABA triblock copolymers with DMAEMA mid-blocks and MAA (THPMA) end-blocks. In these networks the degree of polymerization of the DMAEMA mid-block was kept constant at 20, while the overall degrees of polymerization were 25, 30, 40, and 60. The fifth model network was based on an equimolar BAB triblock copolymer with an MAA (THPMA) mid-block and a total degree of polymerization 40. The sixth model network was based on an equimolar statistical copolymer with a total degree of polymerization 40. All linear precursors to the networks were analyzed by gel permeation chromatography and proton nuclear magnetic resonance spectroscopy to characterize their molecular weights, composition, and monomer conversion. The degrees of swelling (DSs) of all the polyampholytic networks were measured as a function of pH and were found to present a minimum at a pH value which was taken as the isoelectric point. The isoelectric point increased with the network content in DMAEMA basic units. The isoelectric DSs of most networks were constant at 5, independent of network composition and architecture. The DSs at basic pH (∼11) increased sharply with the network content in MAA units. It was also found that the DS depends on network architecture, with the statistical copolymer-based model network exhibiting higher basic and acidic DSs than its isomeric counterparts.

Introduction

Polyampholytes are polymers bearing groups which can acquire both positive and negative charges.[1,2] Proteins and nucleic acids are two examples of biological polyampholytes.[3] Polyampholytes have also been made synthetically, one example being polyampholytic latex[4] and the other example being linear random polyampholytes.[5] The latter type of synthetic polyampholytes was studied extensively during the 1950s and 1960s.[6] Recent work on random polyampholytes has been conducted by the groups of Candau[7−12] and McCormick.[13−16] Hahn et al.[17−21] prepared and characterized alternating polyampholytes. The synthesis and characterization of diblock polyampholytes was not accomplished until the 1970s.[22−24] Extension of this work was reported recently and involves both linear diblock[25−30] and linear ABC triblock polyampholytes.[25,31−39]

Contrary to linear polyampholytes, little attention has been paid to polyampholyte networks, comprising cross-linked polyampholyte structures.[1] Polyampholyte networks can be classified according to the strength of the constituting base and acid. Polyampholyte networks comprising strong base and strong acid groups exhibit properties, e.g., charge and degree of swelling, which are pH independent but acid−base composition dependent.[40−45] When either the basic or the acidic groups,[46−49] or both,[50,51] are weak electrolytes, the behavior of the polyampholyte network becomes pH dependent. With the exception of charge-mosaic membranes[52] and cross-linked proteins,[53] all polyampholyte networks studied to date[40−51] have been prepared by free radical polymerization,[54−56] leading to poor structural control, with the random placement of the cross-links along the chains and with the random distribution of the acidic and basic units.

Improvement of the structure of polyampholyte networks can yield materials with novel properties and potentially new applications. This was the aim of the present study in which a "living" polymerization technique, group transfer polymerization (GTP),[57−60] was used to prepare block copolymers (of precise molecular weight and composition) based on acidic and basic units and interlink those copolymers from their chain ends to form model networks.[61] The present polyampholytes are based on weak base and weak acid repeat units and, in particular, 2-(dimethylamino)ethyl methacrylate (DMAEMA) and methacrylic acid (MAA), respectively. The latter was introduced via a protected ester monomer, tetrahydropyranyl methacrylate (THPMA), which was readily hydrolyzed to the acid after network formation. The chemical formulas of these three monomers along with those of the ethylene glycol dimethacrylate (EGDMA) cross-linker and the 1,4-bis(methoxytrimethylsiloxymethylene)cyclohexane (MTSMC) GTP bifunctional initiator are presented in Figure 1. The flexibility

† This work is dedicated to the memory of Professor Toyoichi Tanaka, formerly of the Physics Department of the Massachusetts Institute of Technology (MIT), who introduced one of the authors (C.S.P.) to the science of hydrogels.

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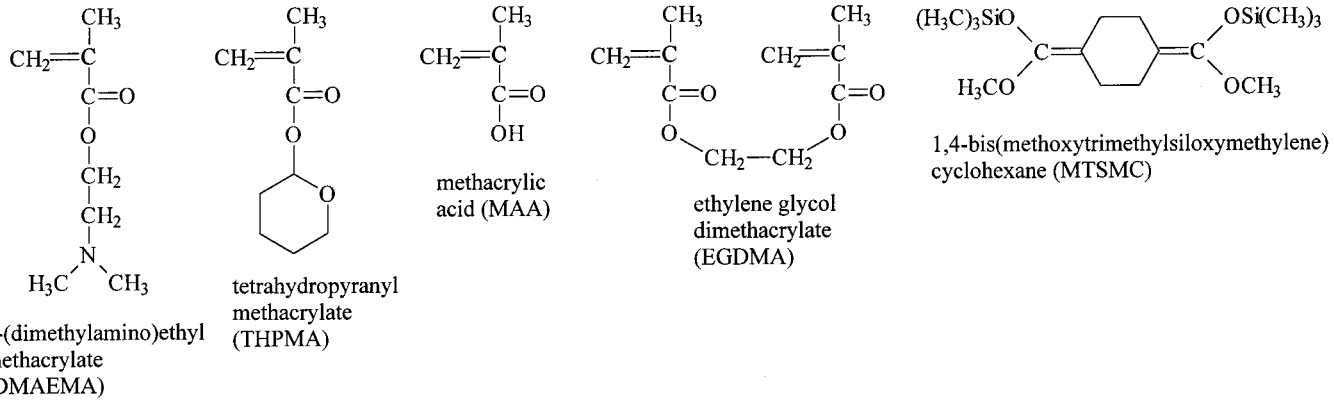

Figure 1. Chemical structures and names of the monomers, the cross-linker, and the initiator used for the preparation of the networks.

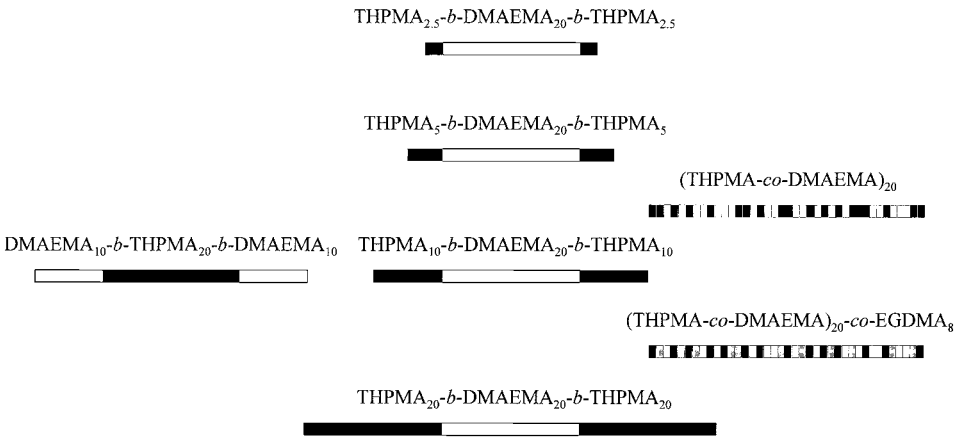

Figure 2. Schematic representation of the structures of the linear segments between the cross-links of the networks in this study. The white color represents the DMAEMA units, the black color the THPMA/MAA units, and the gray color the EGDMA (cross-linker) units.

of GTP allowed the variation of both the composition and the architecture of the networks. The linear precursors to the networks are shown schematically in Figure 2. Four ABA triblock copolymer-based networks, with DMAEMA mid-blocks, were prepared in which the DMAEMA/THPMA ratio was varied systematically, and their linear precursors are illustrated schematically in the central column of Figure 2. The central row of the same figure depicts the four equimolar isomers, which comprise the BAB and ABA triblocks, the statistical copolymer, and the randomly cross-linked statistical copolymer in which the units of the EGDMA cross-linker are colored gray.

Experimental Section

Materials and Methods. All chemicals were purchased from Aldrich, Germany. While DMAEMA and EGDMA are commercially available, THPMA and the MTSMC initiator are not and were thus in-house synthesized. The former was synthesized by the catalytic esterification of MAA with 100% excess 3,4-dihydro-2*H*-pyran at 55 °C[62] using a modification of the procedure reported by Hertler.[63] Thus, sulfuric acid, rather than cross-linked poly(4-vinylpyridine hydrochloride), was used as the acid catalyst. The latter was synthesized by the silylation of dimethyl 1,4-cyclohexanedicarboxylate, accomplished in a two-step procedure:[64] the reaction of dimethyl 1,4-cyclohexanedicarboxylate with diisopropylamine and butyllithium in absolute tetrahydrofuran (THF) at −78 °C, followed by the reaction of the mixture with trimethylsilyl chloride under the same conditions. The polymerization catalyst was tetrabutylammonium bibenzoate (TBABB), and it was prepared by the method described by Dicker and co-workers.[59] It was stored under vacuum until use. THF served as the polymerization solvent. It was dried by refluxing it over a sodium/potassium alloy for 3 days, and it was freshly distilled prior to the polymerization. The monomers DMAEMA and THPMA and the cross-linker were passed through basic alumina columns to remove protonic impurities and inhibitors. They were stirred overnight over calcium hydride to remove the last traces of moisture and protonic impurities. This was done in the presence of an added free radical inhibitor, 2,2-diphenyl-1-picrylhydrazyl hydrate (DPPH), to avoid thermal polymerization. DMAEMA, THPMA, EGDMA, and MTSMC were freshly distilled prior to the polymerization.

Polymerizations. All the networks of this study were prepared by GTP at room temperature in 30 mL cylindrical glass vials sealed by a rubber septum. The amount of the EGDMA cross-linker used was 8 times the number of moles of the MTSMC initiator, as determined in preliminary investigations in which the synthesis of DMAEMA star homopolymers (with the use of a monofunctional rather than a bifunctional initiator) was optimized.[65] Networks of different compositions were prepared by varying the relative amounts of the two comonomers, DMAEMA and THPMA. Different network architectures were obtained by varying the order of addition of the reagents. Figure 3 presents the four addition sequences necessary for preparing the four different network architectures. Model network synthesis requires the sequential addition of the monomers, in the appropriate order, to an initiator/catalyst solution, completed by the addition of the cross-linker. Synthesis of randomly cross-linked networks is accomplished by the addition of the initiator to a solution of monomers, cross-linker, and catalyst.

We illustrate the synthetic procedure below by detailing the preparation of the equimolar ABA triblock copolymer-based

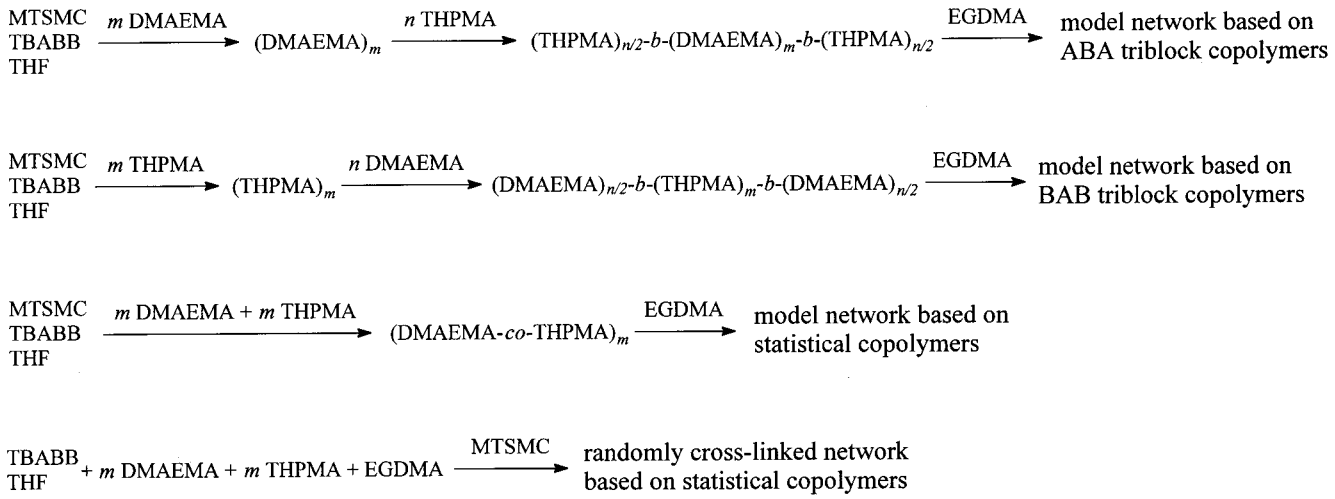

Figure 3. Synthetic routes followed for the preparation of the four different network architectures.

model network. This comprises a three-step sequential addition, starting with the preparation of the DMAEMA mid-block, followed by the growth of the THPMA end-blocks, and completed with the incorporation of the dimethacrylate cross-linker. A 30 mL cylindrical glass vial, kept under a dry nitrogen atmosphere and containing a small amount of TBABB and 14 mL of freshly distilled THF, was charged with 0.12 mL (0.15 g, 0.43 mmol, 0.024 M in final solution) of MTSMC initiator and subsequently with 1.43 mL (1.33 g, 8.5 mmol, 0.48 M) of DMAEMA, under stirring. The polymerization exotherm (25.6−34.5 °C) abated within 5 min, a sample was extracted for gel permeation chromatography (GPC) and proton nuclear magnetic resonance (^{1}H NMR) spectroscopy analyses, and 1.44 mL (1.44 g, 8.5 mmol, 0.48 M) of THPMA was added. After the completion of the polymerization of this monomer (exotherm 34.0−42.0 °C) and sampling for GPC and ^{1}H NMR, 0.64 mL (0.67 g, 3.4 mmol, 0.19 M) of EGDMA cross-linker was added (exotherm 36.5−39.7 °C), which led to the gelation of the solution within seconds. The BAB triblock copolymer-based network (with an THPMA mid-block) was also obtained using a similar procedure in which the order of addition of the two comonomers was reversed, whereas the statistical copolymer model network was synthesized by the simultaneous addition of the two comonomers. The randomly cross-linked network of the statistical copolymer was prepared by the addition of the MTSMC initiator to the THF solution of the monomers, cross-linker, and catalyst.

Characterization by GPC and ^{1}H NMR. Linear homopolymer and copolymer samples were obtained before cross-linking and were characterized in terms of their molecular weight, composition, and monomer conversion using GPC and ^{1}H NMR. GPC was performed on a Polymer Laboratories system equipped with a PL-LC1120 isocratic pump, an ERC-7515A refractive index detector, and a PL mixed "E" column. The eluent was THF, and it was pumped at 1 mL min^{-1}. The molecular weight (MW) calibration was based on six narrow MW (630, 1400, 4250, 7600, 13 000, and 28 900 g mol^{-1}) polyMMA standards also supplied by Polymer Laboratories. The ^{1}H NMR spectra of polymer solutions in deuterated chloroform were recorded using a 300 MHz AVANCE Bruker spectrometer equipped with an Ultrashield magnet.

Hydrolysis of the THPMA Units. The networks were first taken out of the polymerization vials, which were incised using a diamond knife and broken by the application of a hot glass rod. They were then transferred to 1 L glass jars, which contained 400 mL of water plus 50 mL of HCl (2 M) aqueous solution whose number of moles in HCl was more than 5 times the number of THPMA plus DMAEMA (DMAEMA does not get hydrolyzed but captures HCl to get ionized) equivalents in the network. The system was allowed to hydrolyze for 1 week, followed by washing with distilled water for another 4 weeks to remove THF and the excess of HCl. The water was changed every 3−4 days. Before each water change, the pH of the supernatant solution and the gel mass were measured. Both stabilized 2 weeks after the first washing with water. The pH of all networks was 3.4 ± 0.3. FTIR spectra of vacuum-dried network samples before and after the hydrolysis were obtained using a Bruker VECTOR 22 instrument.

Measurement of the Aqueous Degrees of Swelling. The degrees of swelling (DSs) of the networks were measured in water within the pH range between 2 and 12. First, the hydrolyzed and water-washed networks were cut into pieces of approximately cubic shape with edge 0.5−1 cm, and their DSs were measured at the present pH of ∼3.4. To this end, two samples of each network were dried in a vacuum oven at 40 °C for 24 h. The DS was calculated as the ratio of the water-swollen divided by the dry mass, both determined gravimetrically. An average of the two measurements was taken.

For the measurements of the DSs at different pHs, the appropriate number of drops of 0.1 or 0.5 M HCl and 0.1 or 0.5 M NaOH solutions were added to samples of the water-swollen gels to adjust the pH within the range between 2 and 12. For each different network, 11 samples were used, each adjusted to a different pH with degree of deprotonation increments of about 10%. The degree of deprotonation describes the cumulative ionization behavior of the weakly acidic and weakly basic units of the polyampholytes and is defined as follows:

$$\text{degree of deprotonation} = \frac{(\text{no. of deprot acidic units}) + (\text{no. of deprot basic units})}{(\text{total no. of acidic and basic units})} \quad (1)$$

The required amount of moles of HCl or NaOH in each case was calculated as the product of the desired degree of deprotonation times the total number of moles of DMAEMA plus MAA units present in the sample. The latter was calculated from the mass of the swollen (in pure water, pH of supernatant solution ∼ 3.4) sample, the known DS in pure water (measured earlier), and the polymerization stoichiometry. For the calculation of the former, a linear hydrogen ion titration curve was assumed, in which the degree of deprotonation changes from 0 to 1 within the pH range 2−12. This implied that the degree of deprotonation at the initial pH of 3.4 was 14%. Thus, different volumes of HCl solution were added to two samples, different volumes of NaOH solution were added to eight samples, while nothing was added to the eleventh sample.

The pH of the supernatant solution and wet network mass were measured every 3−4 days and stabilized in 2−3 weeks after the addition of HCl or NaOH. The DS under these conditions was calculated again as the ratio of the swollen divided by the dry mass. The latter was estimated from the mass of the hydrogel swollen in pure water and the known

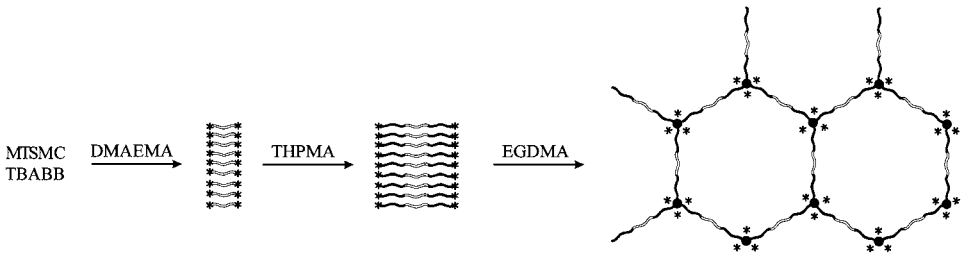

Figure 4. Schematic representation of the synthetic procedure followed for the preparation of the model network based on the triblock copolymer $THPMA_{20}$-*b*-$DMAEMA_{20}$-*b*-$THPMA_{20}$. The DMAEMA units are shown in white, while the THPMA units are painted black. The "*" symbols indicate the active sites of the polymerization.

Table 1. Molecular Weights, Polydispersity Indices, and Composition of the Homopolymer and Copolymer Precursors to the Networks As Measured by GPC and ^{1}H NMR

					% mol THPMA	
name	chemical structure	theor MW[a]	M_n by GPC	M_w/M_n by GPC	theory	^{1}H NMR
gel 1	$DMAEMA_{20}$	3336	5580	1.15		
	$THPMA_{2.5}$-*b*-$DMAEMA_{20}$-*b*-$THPMA_{2.5}$	4186	7340	1.15	20.0	17.5
gel 2	$DMAEMA_{20}$	3336	5270	1.16		
	$THPMA_5$-*b*-$DMAEMA_{20}$-*b*-$THPMA_5$	5036	7880	1.18	33.3	30.6
gel 3	$DMAEMA_{20}$	3336	5550	1.16		
	$THPMA_{10}$-*b*-$DMAEMA_{20}$-*b*-$THPMA_{10}$	6736	10600	1.16	50.0	46.5
gel 3a	$THPMA_{20}$	3596	6920	1.18		
	$DMAEMA_{10}$-*b*-$THPMA_{20}$-*b*-$DMAEMA_{10}$	6736	13200	1.18	50.0	48.8
gel 3b	(DMAEMA-*co*-THPMA)$_{20}$	6736	9210	1.16	50.0	45.9
gel 4	$DMAEMA_{20}$	3336	6060	1.15		
	$THPMA_{20}$-*b*-$DMAEMA_{20}$-*b*-$THPMA_{20}$	10136	17200	1.18	66.7	62.9

[a] Weight from the initiator fragment (196 g mol^{-1}) included.

DS in pure water of the same gel measured according to the first paragraph of this section. Three measurements were taken at equilibrium, and their average is presented.

Results and Discussion

Polymerization Methodology. The synthetic procedure for the preparation of the model networks is presented schematically in Figure 4, where the synthesis of the gel based on the $THPMA_{20}$-*b*-$DMAEMA_{20}$-*b*-$THPMA_{20}$ triblock copolymer is shown. The synthesis involves sequential monomer and cross-linker addition. The first step in Figure 4 results in the preparation of linear DMAEMA homopolymer with both active ends (indicated by asterisks) due to the use of the bifunctional initiator. The second step leads to the synthesis of the THPMA−DMAEMA−THPMA triblock copolymer with two active ends. The synthesis is completed by the addition of EGDMA cross-linker, which effects the interconnection of the polymer active ends, providing a three-dimensional network. The number of arms at the cross-links is not three, as indicated in the figure, but higher, probably between 20[66] and 50,[67] similar to the number of arms in star polymers also prepared by GTP.

There are several advantages of the present GTP network synthesis over the conventional free radical polymerization synthesis.[54,55] GTP secures a fast polymerization reaction at room temperature, with quantitative polymerization yields (confirmed by GPC and ^{1}H NMR on linear precursors: absence of monomer peak in GPC and absence of olefinic proton peaks in ^{1}H NMR), control over molecular weight, composition, cross-link density, and architecture. In free radically made polyampholyte gels, the reaction time can be more than 30 min and the temperature may need to be as high as 60 °C, especially when such initiators as 2,2′-azobis(isobutyronitrile) (AIBN) are used. Moreover, the monomer conversion is never complete, and no attempt is made to determine the amount of unreacted monomers and cross-linker. Finally, there is no ability to taylor network architecture. One disadvantage of the present method is the requirement for the protected form of the MAA monomer, THPMA, and its hydrolysis after network formation. However, it is not unlikely that the relatively reactive carboxylic acid group of MAA participates in some side reactions during its direct free radical polymerization.

Removal of the Tetrahydropyranyl Protecting Groups. The THPMA units were converted to MAA units via acid hydrolysis[62] rather than by thermolysis[62,68] due to the tendency of the latter to produce anhydride rather than carboxylic acid.[26,27,36] The conversion to MAA units was confirmed qualitatively by FTIR with the appearance of a double peak at 3000−2750 cm^{-1} due to the stretching vibration of the OH group of MAA. Quantitative confirmation was provided from hydrogen ion titrations on the hydrolyzed network samples, which indicated the presence of a concentration of carboxylic acid (and tertiary amine) groups close to the stoichiometrically expected.

Molecular Weights and Composition. Table 1 shows the molecular weights (MWs) and composition of the linear precursors to the networks as measured by GPC and ^{1}H NMR, respectively. The number-average MWs, M_ns, were found to be reasonably close to those predicted by theory, from the ratio of monomer to initiator. They were, however, systematically slightly higher than the theoretically predicted MWs, probably due to partial deactivation of the initiator. Molecular weight distributions (MWDs) were found to be narrow, and the polydispersity indices (M_w/M_n) were calculated $\leq$1.2. This confirms the homogeneity of the lengths of the segments between the cross-links in the networks. The copolymer composition was determined from the ^{1}H NMR spectra (not shown) of the copolymers, by ratioing the signal from the ester acetal proton (5.9 ppm) in THPMA to the six protons in the two azamethyl groups

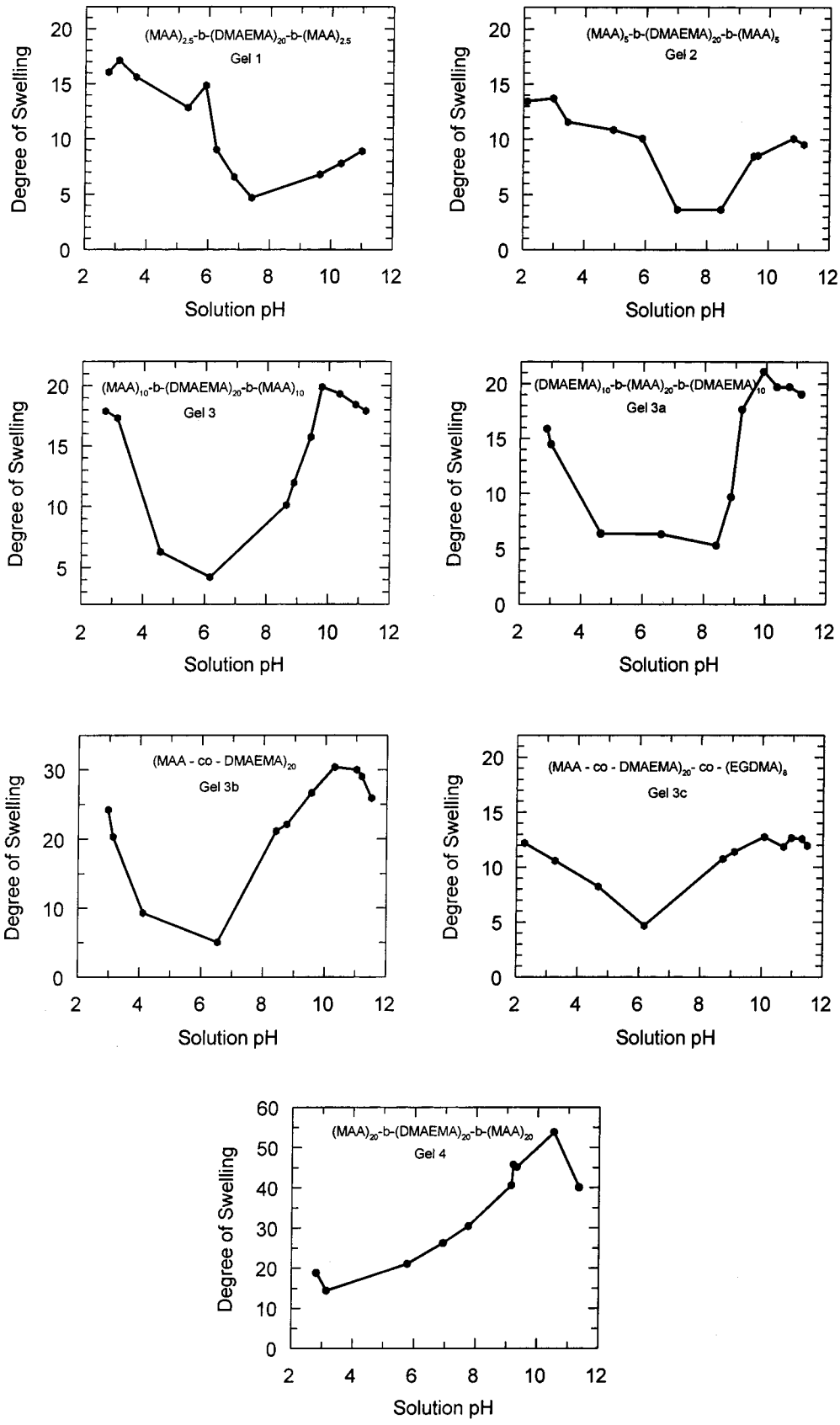

Figure 5. Degrees of swelling as a function of pH for all the polyampholytic networks of this study.

(2.3 ppm) in DMAEMA.[36] The percentages of THPMA determined by ^{1}H NMR were found to be close to the theoretically calculated percentages of THPMA, albeit systematically slightly lower.

Aqueous Degrees of Swelling. The experimentally measured aqueous degrees of swelling (DSs) of all the networks are plotted against the pH of the supernatant solution in Figure 5. The number and structure of each

network (gel) are indicated above each plot. The networks present a characteristic minimum in their DSs at intermediate pH values, while they expand again at acidic and basic pHs. This behavior is characteristic for polyampholytes, which have an isoelectric point, p*I*, that is a pH of zero net charge. Similar to polyampholyte networks, proteins[69,70] and linear synthetic polyampholytes[25] present solubility minima around their p*I*s. Around the p*I*, the van der Waals and hydrophobic attractive forces contribute significantly to the polyampholyte collapse. Moreover, around the p*I*, all counterions to the charged groups are "dialyzed out" of the gel,[1] while Coulombic attractions replace Coulombic repulsions. Therefore, the contribution of electrostatic forces to swelling at the p*I* is not only annihilated but also negative due to the Coulombic attractions between the equal in number positively and negatively charged units, thus further contributing to the polyampholyte collapse. It is reminded that for the present polyampholyte system, and with the effective p*K*s of the basic and acidic units of approximately 8 and 5,[71] respectively, a great percentage of the ionizable groups is charged at the isoelectric point.[72] It is noteworthy that, for the equimolar materials with p*I*s around 6.5, most basic and acidic units are ionized.

At the pH extremes the behavior of the polyampholyte networks is dominated by that of the corresponding ionized units. Thus, the high DSs at low pH are due to the ionization of the DMAEMA basic units, while the high DSs at alkaline pH are due the ionization of the MAA acidic units. The polyampholyte network swelling behavior at the pH extremes is therefore similar to that of simple polyelectrolyte networks, in which the ionized units create an osmotic pressure in the network, promoting swelling, and also the charges on the ionized units cause electrostatic repulsive forces between the polymer chains, leading to further swelling of the network.[73−75] The slight decrease in the DSs at very extreme pHs in some networks is due to the increase in the ionic strength, effected by the relatively high concentrations of HCl or NaOH under these conditions, which cause charge screening. The plots in Figure 5 were used to extract the p*I*s and the aqueous DSs at low, isoelectric, and high pH of the networks, which are presented and discussed in the following sections.

It is noteworthy that, in their study on the pH dependence of the DS of polyampholyte networks based on strong base and weak acid prepared by free radical polymerization, Annaka and Tanaka observed multiple phases.[46] More specifically, their polyampholyte hydrogels would reproducibly expand or shrink discontinuously between states (phases) of different DSs, depending on the pH path. For one of their polyampholyte networks, seven such states were observed. A search for such multiple phases in our polyampholyte networks was beyond the scope of the present investigation, but it would be worth pursuing at a future stage.

Isoelectric Points of the Networks. The p*I*s of the networks, taken as the pHs at the minima of the swelling curves in Figure 5, are plotted in Figure 6 as a function of the molar ratio of the basic to the acidic units. As expected, the p*I*s increase with the DMAEMA/MAA molar ratio. The four equimolar networks have similar p*I*s, which, however, span a range of values from 6.1 to 6.8. This is due to the sensitivity of p*I* to basic/acidic composition, suggested by the theoretical curve[25,72,76] shown by the dashed line in the

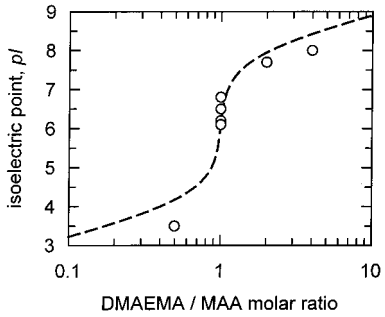

Figure 6. Dependence of the isoelectric points (open circles) on the DMAEMA/MAA molar ratio of the ampholytic networks. The dashed line represents a theoretical prediction.

figure. The theoretical curve is derived by considering that the charge of the basic and acidic units changes around the corresponding effective p*K*s according to simple Henderson−Hasselbach equilibria, the two effective p*K*s are constant (composition and pH independent), and the net charge is equal to zero.[72] The analytical form of the theoretical curve is

$$\mathrm{p}I = \mathrm{p}K_{\mathrm{DMAEMA}} + \log\left[\frac{R-1}{2} + \sqrt{\left(\frac{R-1}{2}\right)^2 + R \times 10^{\mathrm{p}K_{\mathrm{MAA}} - \mathrm{p}K_{\mathrm{DMAEMA}}}}\right] \quad (2)$$

where $\mathrm{p}K_{\mathrm{DMAEMA}}$ and $\mathrm{p}K_{\mathrm{MAA}}$ are the effective p*K*s of the basic and acidic units, respectively, and R is the DMAEMA/MAA molar ratio. The curve indicates that, around $R = 1$, differences in composition of the order of 10% can cause differences in the p*I* of about 1 pH unit. The effective p*K*s used for plotting the curve were those obtained by nonlinear regression on the data and were $\mathrm{p}K_{\mathrm{DMAEMA}} = 7.9 \pm 0.3$ and $\mathrm{p}K_{\mathrm{MAA}} = 4.2 \pm 0.4$, which compare favorably with those reported in an independent potentiometric study: $\mathrm{p}K_{\mathrm{DMAEMA}} = 8.0$ and $\mathrm{p}K_{\mathrm{MAA}} = 5.4$.[71]

Aqueous DSs at Low, Isoelectric, and High pH. The DSs at low pH (pH around 3), isoelectric pH (p*I*), and alkaline pH (pH around 11) for each network, along with the corresponding 95% confidence intervals on three measurements, are presented in Figure 7a,b. Figure 7a presents the effect of polymer composition while Figure 7b focuses on the effect of polymer architecture. Figure 7a plots the aqueous DSs against the number of acidic MAA units. The choice of this *x*-axis (as opposed to, for example, the ratio of the MAA to DMAEMA units) is justified by the fact that all networks have a constant number of 20 DMAEMA units between cross-links and because the overall degree of polymerization between cross-links increases with the number of MAA units. Thus, the present *x*-axis will capture effects of both composition and MW. The figure shows that, with the exception of the acidic network, the isoelectric DSs of the networks are constant and around 5, indicating that they are in a rather collapsed state due to the absence of counterions and repulsive forces. A DS of 5 does not represent a fully collapsed state, for which DSs between 1 and 2 would be more appropriate as in the case of amphiphilic (hydrophobic/hydrophilic) networks.[77] The higher isoelectric DS of the acidic network of about 14 can be attributed to the greater hydrophilicity of MAA units than that of the DMAEMA units, the longer chains between cross-links in this network (see Figure 2), and the concomitant lower content in hydrophobic cross-linker. PolyMAA is

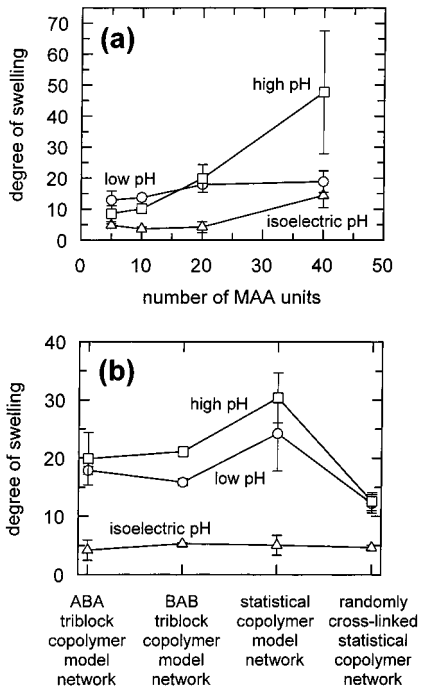

Figure 7. Degrees of swelling of the networks at low, high, and isoelectric pH, along with the 95% confidence intervals on three measurements: **(**a**)** effect of polymer composition; **(**b**)** effect of polymer architecture.

somewhat hydrophobic but is definitely more hydrophilic than polyDMAEMA: linear homopolymers of uncharged DMAEMA have cloud points in water of about 40 °C,[78] whereas linear homopolymers of uncharged MAA have cloud points near 60 °C.[79] Figure 7a also shows that the aqueous DSs at both acidic and alkaline pH increase as the number of acidic MAA units increases. Again, this is due to the MAA relative hydrophilicity and the increase of the chain length between cross-links with MAA content. The ionization of the MAA units at high pH is the reason for the much more rapid increase in the DSs under these conditions compared to low pH. While for the equimolar polyampholyte network the high pH and low pH DSs are the same (within experimental error), for the basic networks (5 and 10 MAA units between cross-links) the low pH DSs are higher than the high pH DSs, and for the acidic network (40 MAA units between cross-links) the reverse is true. This highlights the importance of the repulsive electrostatic forces with respect to the swelling of these systems at extreme pH values. Figure 8 illustrates schematically the conformations of the acidic polyampholyte network at low, isoelectric, and high pH. At high pH, the MAA blocks (in black) are ionized and expanded, while the DMAEMA blocks (in white) are neutral and rather shrunk. At low pH, the reverse is true, with the MAA blocks neutral and rather collapsed and the DMAEMA blocks ionized and expanded. However, because there are more ionized units at high pH than at low pH for the acidic network, the DS is higher under the former than the latter conditions. At the isoelectric pH, both blocks are rather collapsed and the DS is lowest.

Figure 7b illustrates the effect of polymer architecture on the DSs. At the p*I*s, all four isomeric networks are rather collapsed, exhibiting the same DSs, around 5. At high pH, the DSs of the ABA and BAB triblock copolymer-based polyampholyte model networks are the same, approximately 20, suggesting no architecture effect in this case. The DS at alkaline pH of the statistical copolymer-based polyampholyte model network is more than 50% higher than those of the two previously mentioned networks. The lower DSs in the latter case may be attributed to the aggregation of the neutral DMAEMA blocks in domains stabilized by hydrophobic or/and hydrogen-bonding forces. This aggregation reduces the effective chain length between cross-links, lowering the DSs, and it is similar to that proposed for amphiphilic model networks.[77,80] Such an aggregation is not possible within the statistical polyampholyte model network due to the random distribution of charged (MAA, at high pH) and neutral (DMAEMA, at high pH) units. For this network, the effective chain length is not shortened as the charged MAA units drag along the DMAEMA uncharged units, which also contribute to swelling.[80] The high-pH DS of the randomly cross-linked statistical copolymer-based polyampholyte network is lower than those of the triblock copolymer based model networks and much lower than that of the model network based on the statistical copolymer. This is surprising because the present network cannot microphase separate, and therefore, it was expected to exhibit an equally high alkaline DS as the statistical copolymer based model network. It is possible, however, that the lower than expected alkaline DS of this network is due to the broad distribution of chain lengths between cross-links (contrary to the narrow size distribution of the chain lengths between cross-links in its three other model network isomeric counterparts). The presence of some (much) shorter than average chains may dominate the swelling behavior and result in the low DS observed. The trends in the DSs at low pH are similar to those at high pH, and analogous explanations can be given.

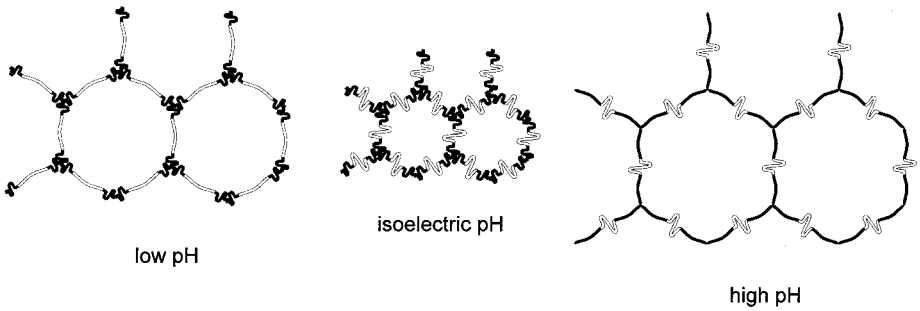

Figure 8. Schematic representation of the conformations adopted by the network based on the MAA_{20}-*b*-$DMAEMA_{20}$-*b*-MAA_{20} triblock polyampholyte at low, isoelectric, and high pH.

Conclusions

A "living" polymerization technique, GTP, was employed to prepare ampholytic hydrogels covering a range of compositions and architectures. The DSs of all networks presented a minimum around the isoelectric point where the net charge is zero, while they increased at alkaline and acidic pHs, due to the ionization of the weak acid and weak base monomer repeat units, respectively. Although the DSs at both high and low pH increased with the number of units of weak acid between cross-links, the DSs of weak-base-rich polyampholyte networks were higher at low than at high pH, and the DS of the weak-acid-rich polyampholyte network was higher at high than at low pH. The high pH and low pH DSs of the statistical copolymer based polyampholyte model network were higher than those of its two triblock copolymer based counterparts due to some aggregation within the latter type of networks, while the alkaline and basic DSs of the randomly cross-linked statistical copolymer-based polyampholyte network were the lowest due to the existence of some very short elastic chains within this network. At the isoelectric point, all networks were in a semicollapsed state, with the DSs of most networks being composition and architecture independent.

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