

Poly(*N*-hydroxyethyl acrylamide)-*b*-Polystyrene by Combination of ATRP and Aminolysis Processes

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ABSTRACT: Block copolymers of very hydrophilic poly(*N*-hydroxyethyl acrylamide) (PHEAA) with polystyrene (PS) were successfully synthesized by sequential atom transfer radical polymerization of ethyl acrylate (EA) and styrene monomers and subsequent aminolysis of the acrylic block with ethanolamine. Quantitative aminolysis of poly(ethyl acrylate) (PEA) block yielded poly(*N*-hydroxyethyl acrylamide)-*b*-polystyrene in well-defined structures, as evidenced by Fourier transform infrared spectroscopy (FTIR) and ¹H-NMR spectroscopy techniques. Three copolymers with constant chain length of PHEAA (degree of polymerization: 80) and PS blocks with 21, 74, and 121 repeating units were prepared by this method. Among those, the block copolymer with 21 styrene repeating units showed excellent micellation behavior in water without phase inversion below 100°C, as inferred from dynamical light scattering, environmental scanning electron microscopy, and fluorescence measurements. © 2012 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* 000: 000–000, 2012

KEYWORDS: amphiphilic block copolymer; poly(*N*-hydroxyethyl acrylamide); ATRP; aminolysis

Received 4 May 2011; accepted 24 February 2012; published online

DOI: 10.1002/app.37604

INTRODUCTION

Synthesis of amphiphilic block copolymers has found great interest due to their self-assembling behavior in water or in organic solvents.^{1,2} Solubilization in aqueous or organic media,³ stabilization of nanoparticles,^{4,5} and their compatibilization with various polymer matrixes⁶ are some important applications of amphiphilic block copolymers. Assembling behaviors of the amphiphilic copolymers are closely related to the ratios of the block lengths.⁷ Therefore, synthesis of such copolymers with well-defined block-lengths is of special importance for application viewpoint.

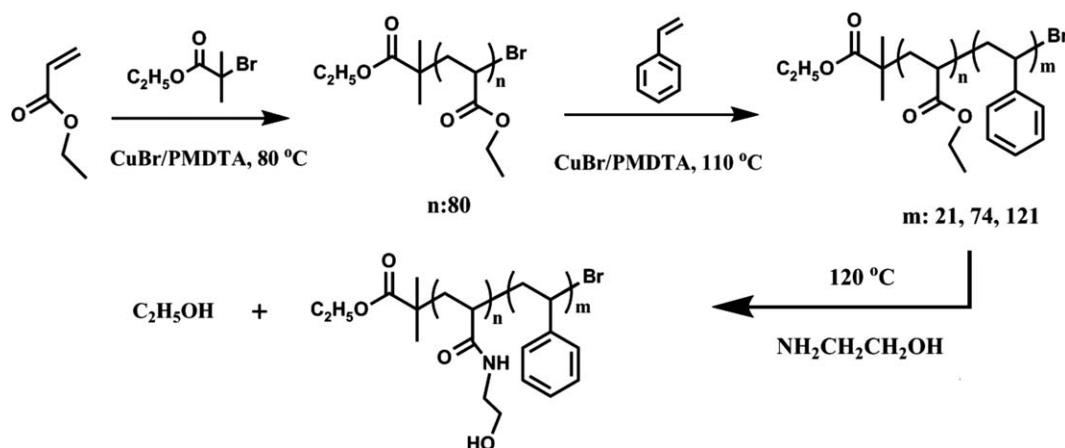
Block copolymers of styrene with ethylene oxide are most widely studied amphiphilic block copolymers,⁸ probably due to their phase inversion behavior. Solution- and micelle-forming behaviors of the block copolymers constituting with hydrophilic poly(ethylene oxide) and hydrophobic poly(propylene oxide) blocks have also been studied in detail.⁹ Self-assembling and nanocomposite formation of polystyrene-*b*-poly(4-vinyl pyridine),¹⁰ polystyrene-*b*-poly(acrylic acid),¹¹ and poly(ethylene oxide)-*b*-poly(butylene oxide)¹² have been investigated in various solvent systems.

Many combinations of hydrophobic and hydrophilic polymers can be considered to produce amphiphilic block copolymers. Controlled/living radical polymerization techniques such as

atom transfer radical polymerization (ATRP), radical addition-fragmentation chain transfer, and stable free radical polymerization techniques have made their preparation possible. However, still there appear many difficulties in syntheses of amphiphilic block copolymers directly from the monomers. Proper selection of a common solvent for the two blocks, applicability of the living technique to each monomer, and isolation of the copolymers are the main limitations in preparing such structures.

Synthesis of block copolymer by a well-known living polymerization technique and following hydrolysis or modification of one of the blocks is alternative strategy for preparing amphiphilic block copolymers.¹³ A number of physical,¹⁴ chemical,¹⁵ and enzymatic¹⁶ postmodification procedures have been reported to introduce various functional groups into prepolymers for diverse applications. Of course, these methods can also be considered for preparing amphiphilic block copolymers, but there is still solubility limitation in this case too.

The postmodification strategy has been used for preparation of star-shaped amphiphilic poly(caprolactone) block copolymers by debenzoylation¹⁷ and poly(vinyl alcohol-*b*-styrene) copolymers from poly(vinyl acetate)-*b*-polystyrene by hydrolysis.¹⁸ In a similar work, selective hydrolysis of the first block in poly(*t*-butyl acrylate)-*b*-poly(methyl methacrylate) has been used to prepare corresponding acrylic acid block copolymers.¹⁹ Recently,

Scheme 1. Preparation of PHEAA-*b*-PS.

Mahanthappa et al. described the synthesis of block copolymers of poly(vinyl alcohol) by selective hydrolysis of poly(vinyl chloroacetate)-*b*-poly(vinyl acetate).²⁰ This approach avoids the difficulties in finding proper solvent which is able to dissolve both of the blocks.

In this work, this strategy was used for preparation of poly(*N*-hydroxyethyl acrylamide)-*b*-polystyrene (PHEAA-*b*-PS).

Homopolymer of 2-hydroxyethyl acrylamide (HEAA) is very hydrophilic and has a hydration number of 4 (moles of water per repeating unit), which is the highest one ever known among water-soluble polymers.²¹ This polymer has been described as promising material as matrix in DNA separation in capillary electrophoresis due to its adhesion capability and good electroosmotic mobility in aqueous medium.²² Block copolymers of HEAA with various water soluble monomers such as *N*-acryloylmorpholine, *N,N*-dimethylacrylamide,²³ and *N*-isopropylacrylamide²⁴ have been prepared by ATRP method in aqueous solutions. There is yet no report on the synthesis of poly(*N*-hydroxyethyl acrylamide) (PHEAA) block copolymers by post-modification and combination of high hydrophilic PHEAA with hydrophobic polystyrene (PS) envisaged us to synthesize block copolymers.

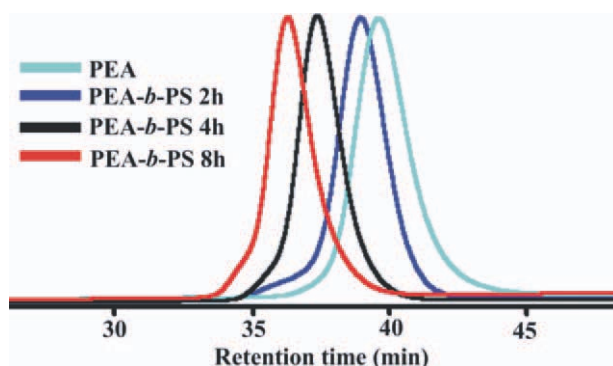


Figure 1. GPC traces of PEA and PEA-*b*-PS copolymers obtained at different time intervals. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

In this work, PHEAA-*b*-PS was synthesized in two steps, preparation of poly(ethyl acrylate)-*b*-polystyrene copolymers by ATRP and followed aminolysis of the acrylate block with

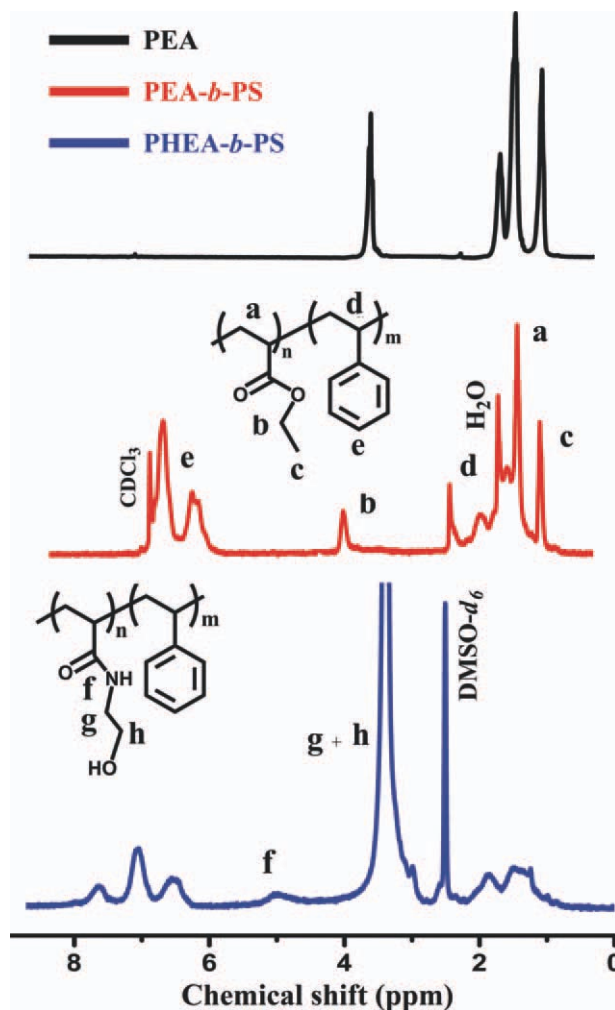


Figure 2. ¹H-NMR spectra of PEA, PEA-*b*-PS in CDCl₃, and PHEAA-*b*-PS in DMSO-*d*₆ (entry 2). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table I. Structures and Characteristics of EA Block Copolymers with Styrene and Their Aminolysis Products

Entries	M_n^a	PDI ^b	Composition	Aminolysis yield (%) ^c	CMC (mg L ⁻¹) ^d
1	10,200	1.10	PEA ₈₀ - <i>b</i> -PS ₂₁	100	38
2	15,700	1.11	PEA ₈₀ - <i>b</i> -PS ₇₄	100	Micelles were not stable
3	20,600	1.10	PEA ₈₀ - <i>b</i> -PS ₁₂₁	100	Water insoluble

^aAll the block copolymers were obtained by chain extension from bromo end groups of PEA prepolymer with $M_n = 8000$, $M_w = 8800$, $M_w/M_n = 1.10$, ^bPolydispersity index assigned by GPC, ^cEstimated by ¹H-NMR spectra, ^dAssigned by fluorescence method.

ethanolamine. The reaction conditions for the quantitative aminolysis were investigated, and the block structures were characterized by conventional analytical and spectroscopic techniques. Micelle-forming behaviors of the resulting copolymers were studied and correlated with the block ratios.

EXPERIMENTAL

Materials

Aldrich products; styrene, ethyl acrylate (EA), and ethanolamine were purified by distillation before use. All the other chemicals were analytical grade products; ethyl-2-bromoisobutyrate (EBIB), *N,N,N',N',N''*-pentamethyldiethylenetriamine (PMDETA), toluene, tetrahydrofuran (THF), pyrene (all from Merck), and these were used as purchased. CuBr was freshly prepared by the procedure described in the literature.²⁵

Instruments

Gel permeation chromatography (GPC) analyses of the polymer samples were performed in THF with a flow rate of 0.3 mL min⁻¹ using Agilent 1100 series instrument consisting of a pump, a refractive index-detector and Waters Styrogel (HR4, HR3, and HR2) columns. GPC trace of the aminolysis products were taken in dimethylformamide (DMF) solution with a

flow rate of 0.5 mL min⁻¹ using Viscotek TDA 302 equipped with a refractive index detector operating at 660 nm and OmniSEC 4.1 software. PS ($M_w = 99,878$ Da; PDI = 1.02) was the internal standard. ¹H-NMR spectra were recorded by a Bruker 250 MHz NMR spectrometer, using CDCl₃ and DMSO-*d*₆ as solvent. Fourier transform infrared spectroscopy (FTIR) spectra were recorded on a Perkin-Elmer FTIR Spectrum One B spectrometer. The micelle sizes and size distributions in the aqueous polymer solutions (5 g L⁻¹) were determined by dynamical light scattering (DLS) method, using a Brookhaven 90 Zeta-plus particle sizing instrument. Shapes and sizes of the micelles were assigned by environmental scanning electron microscopy (ESEM) technique, using Philips-FEI XL30, ESEM-FEG instrument operating at 5.00 kV in STEM mode. The critical micelle concentrations (CMC) were assigned by Hitachi F-4500 fluorescence spectrophotometer using pyrene as fluorescing probe.

Preparation of PEA by ATRP

In a 100 mL volume of three-necked flask, there was added 61.65 g (616.5 mmol) EA, 0.884 g (6.16 mmol) CuBr, and 1.086 g (6.16 mmol) PMDETA under nitrogen flow. The flask equipped with a reflux condenser and a nitrogen inlet was placed in a thermostated silicone bath. The temperature of the bath was adjusted to 80°C, and 1.208 g (6.16 mmol) EBIB was introduced to the mixture while stirring. The nitrogen flow was stopped, and reaction was conducted for 20 min at this temperature.

The resulting ATRP mixture was diluted with THF and passed through neutral alumina column to remove the copper catalyst. After evaporating the excess of THF, poly(ethyl acrylate) (PEA) was precipitated in *n*-heptane. The product was dried at 40°C for 8 h under vacuum. The yield was 22.7%.

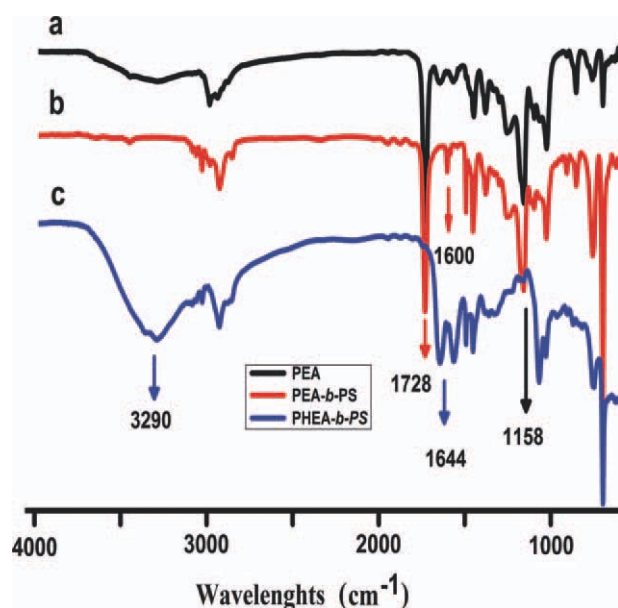


Figure 3. FTIR spectra of (a) PEA, (b) PEA-*b*-PS, and (c) PHEAA-*b*-PS. [Color figure can be viewed in the online issue, which is available at www.onlinelibrary.com.]

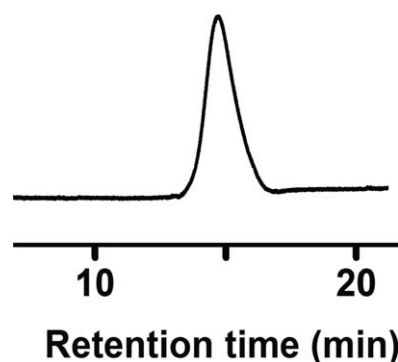


Figure 4. GPC trace of the aminolysis product of PEA₈₀-*b*-PS₁₂₁ (entry 3) in DMF solution.

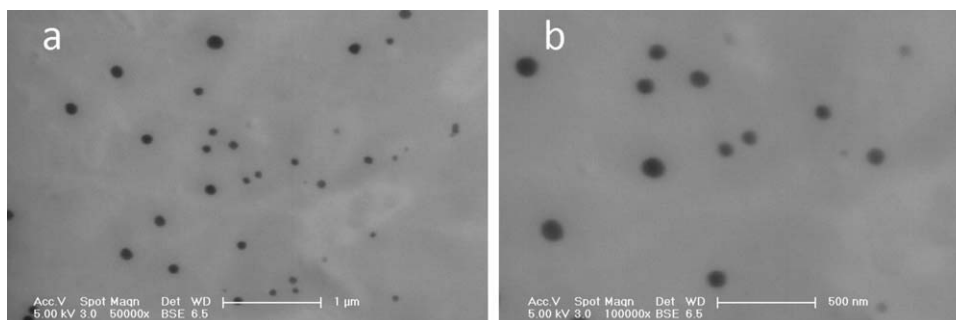


Figure 5. Representative ESEM micrographs of the micelles taken in the solution of PHEAA₈₀-*b*-PS₂₁ copolymer (5 g L⁻¹), (magnification: 50,000× on the left side, 100,000× on the right side).

Block Copolymerization with Styrene

Four grams of PEA (0.5 mmol) dissolved in a mixture of 10 mL toluene and 10 g (96 mmol) styrene in a canonical flask equipped with a reflux condenser and a nitrogen inlet. Under nitrogen atmosphere, 0.072 g (0.5 mmol) CuBr and 0.087 g (0.5 mmol) PMDETA were introduced to the mixture, and the reaction was conducted at 110°C. Approximately one-thirds of the polymerization mixtures were withdrawn at appropriate time intervals (2, 4, and 8 h), and the block copolymers were isolated similarly.

Aminolysis of the PEA-*b*-PS Block Copolymers

To the canonical flask, 0.7 g of the PEA-*b*-PS and 7 g of ethanolamine were added, and the flask was placed in thermostated silicone bath at 110°C. The reaction was continued until the homogeneous solution was observed (24–48 h). The excess of the ethanolamine was removed by rotary evaporator, and the polymer precipitated in excess of acetone. Weights of the final products were in 1.0–1.08 g range.

Determination of CMC of the Polymer

CMC was assigned by fluorescence method using pyrene as probe. For this purpose, a series of aqueous PHEAA-*b*-PS solutions (1.7–3.3 × 10⁻⁴ g L⁻¹) containing pyrene (in 2.5 × 10⁻⁸ M concentrations) was prepared. This was performed by adding acetone solution of pyrene (10 mg/100 mL, 5 × 10⁻⁷ M) after appropriate dilution. Fluorescence intensities were measured at two emission maxima of pyrene emerged at 374 and 393 nm by excitation 338 nm. To assign CMC of the polymer solution, the ratio, I_1/I_3 was plotted against logarithm of the polymer concentration, where I_1 and I_3 refer to the emission intensities at 374 and 393 nm wavelengths, respectively.

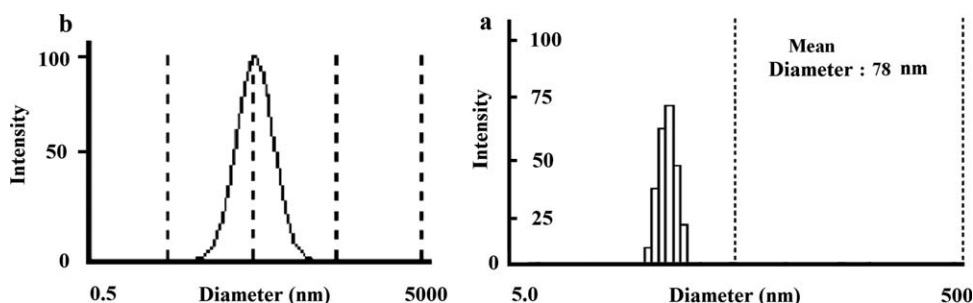


Figure 6. DLS trace of PHEAA₈₀-*b*-PS₂₁ in aqueous solution (5.0 g L⁻¹) (a) and histogram of its hydrodynamic diameter.

RESULTS AND DISCUSSION

The block copolymer, PHEAA-*b*-PS was prepared by the reaction sequences outlined in Scheme 1. The ATRP of EA in the first step was carried out in bulk at 80°C using molar ratio of [EA]/[CuBr]/[EBIB]: 100/1/1. GPC traces of the resulting polymer (Figure 1) revealed a number-average molecular weight (M_n) of 8000. The polymer with polydispersity index (PDI) of 1.1 was used as macroinitiator in ATRP of styrene at 110°C in toluene to attain block copolymers.

Three block copolymers with different chain lengths of PS were prepared by chain extension of PEA ($M_n = 8000$). GPC traces of the block copolymers (Figure 1) represent almost unimodal curves with small shoulder. The latter might be attributed to well known radical combination of the growing radicals in the styrene polymerization. Polydispersity indexes (PDI) of the block copolymers retain around 1.10, indicating highly controlled fashion of the chain extension with styrene monomer. As PDIs are satisfactorily narrow, we did not need to make further purification. The number-average molecular weights of the copolymers assigned by GPC imply 21, 74, and 121 repeating units for the PS blocks connected to PEA block with 80 EA repeating units.

¹H-NMR spectrum of the block copolymer sample (entry 2) in Figure 2 shows typical signals of the both blocks. Thus, aromatic proton signals appear in 6.8–7.6 ppm range. Methylenoxy group protons of PEA segment yield a broad signal centered at 4.1 ppm. The signals of remaining aliphatic protons lie in 0.9–2.4 ppm range.

Integral ratio of the aromatic protons to that of the aliphatic proton peaks in 0.8–2.5 ppm range is around 0.86, which means 68.8 styrene repeating units bearing chain extension is obtained

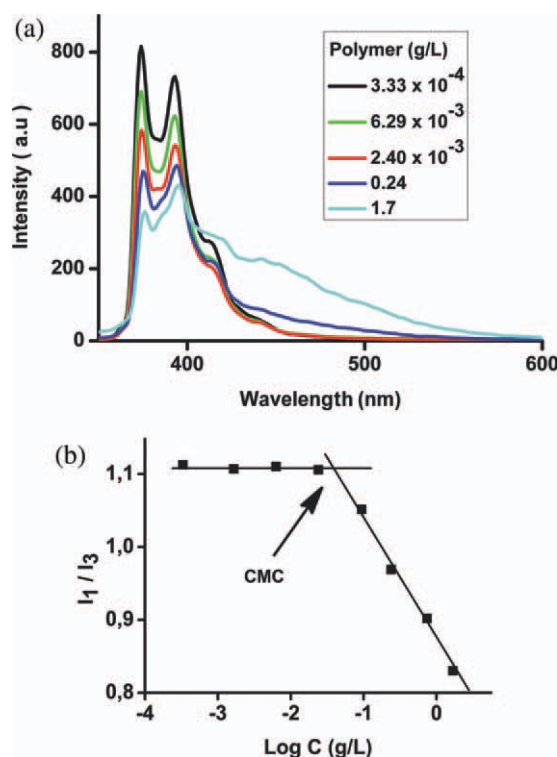


Figure 7. (a) Variation of the fluorescence emission spectra of pyrene (5×10^{-7} M) in aqueous PHEAA-*b*-PS solutions. (b) Fluorescence intensity ratio I_1/I_3 versus $\text{Log } C$ (g L^{-1}) for PHEAA₈₀-*b*-PS₂₁. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

according to 80 repeating units of EA. This implies a molecular weight of 15,150 which is well agreement with that assigned by GPC (15700). Structural characteristics of the copolymer samples and their aminolysis products are given in the Table I.

Heating the block copolymers in ethanolamine gave homogeneous solutions and no precipitations were observed on cooling, indicating the aminolysis had been completed. As ester aminolysis is a general reaction, the reaction of EA segments with ethanolamine does not take place via hydroxyl group to form another ester function in the presence of the amino group. Moreover, aminolysis reaction of esters with ethanolamine to give amide compound has already been described in the literature.^{26,27}

Figure 3 shows FTIR spectra of the polymers obtained in each step. In Figure 3(a), characteristic carbonyl vibration of the starting PEA appears at 1728 cm^{-1} . The other typical peaks observed at 1220 and 1158 cm^{-1} are associated with stretching vibrations of OC—O and O—CH₂ bonds, respectively. After the block copolymerization with styrene those peaks remain at the same positions [Figure 3(b)] and new peaks of the PS block appear in the spectrum. Typical skeletal vibrations of benzene ring of this block are observed at 1590 and 1600 cm^{-1} .

Aminolysis in the third step results in complete disappearance of carbonyl band of PEA segment at 1728 cm^{-1} [Figure 3(c)] and a new peak associated with the amide carbonyl emerges at 1644 cm^{-1} , which indicates quantitative aminolysis of the ester function with ethanolamine. The broad band in $3300\text{--}3650 \text{ cm}^{-1}$

range can be ascribed to stretching vibration of O—H group. Stretching vibration of N—H bond of the amide group expected in the same range must be embedded in the broad band of OH group. The plane bending vibration of the amide group expected around 1600 cm^{-1} is invisible most probably due to its broadening with the bands present at the same position.

In ¹H-NMR spectrum of the aminolysis product (in Figure 2 at the bottom), the signals at 4.1 and 0.9 ppm originating from ethoxy group of PEA segment disappears and a new strong signal associated with four protons of N—CH₂ and —CH₂—O groups emerges at 3.4 ppm. The broad singlet at 5.0 ppm can be assigned to the proton of the N—H group. These results imply a complete aminolysis of PEA segment of the block copolymer. To check any degradation occurs in the main chain while reacting with ethanolamine, GPC trace of the polymer sample derived from PEA₈₀-*b*-PS₁₂₁ (entry 3) was taken in DMF solution. As seen in Figure 4, the aminolysis product represents a unimodal curve and even lower PDI (1.04). The molecular weights, $M_n = 24,400$ and $M_w = 25,400$ Da are in consistent with the molecular weight of starting polymer ($M_n = 20,600$). This result clearly indicates that no degradation takes place in the aminolysis process.

The overall result revealed formation of the amphiphilic block copolymers, PHEAA-*b*-PS with three different PS chain lengths, due to quantitative aminolysis of PEA block of the precursor copolymer.

Regarding with high hydrophilicity of PHEAA, its block copolymers with comparable repeating units of the block sequences were considered to form stable micelles in water. By contrast, the block copolymer with 80 PHEAA and 21 PS repeating units (entry 1) was the only sample, forming stable micelles in water.

The copolymer, PS/PHEAA: 121/80 was completely insoluble in water and did not show any sign of micellation in different conditions. The micelles obtained by drop wise addition of DMF solution of the copolymer (entry 2) with nearly equal lengths of hydrophobic and hydrophilic blocks (PS/PHEAA: 74/80) into water were not stable and precipitated within 2 h at room temperature. DLS measurement indicated large particles with a mean diameter of 1280 nm for its slightly turbid dispersion.

ESEM micrographs of stable micellar solution of the first sample (entry 1) showed nearly spherical micelles (Figure 5). No phase separation was observed on standing 3 days or by heating up to 100°C for 1 h, indicating stability of the micelles.

DLS traces of this solution (Figure 6) implied a mean diameter of 78 nm for the stable micelles. The polydispersity was found 0.292. These results revealed that to attain stable micelles by this block copolymer system, the hydrophilic/hydrophobic block ratio must be far more than unity.

CMC of the micellar solution was estimated by fluorescence method, in which emission intensities of pyrene at 374 and 393 nm wavelengths were monitored in varying polymer concentrations, during excitation at 338 nm [Figure 7(a)].

The intensity ratio of these two bands was plotted against logarithm of the polymer concentration and the point at which

sharp decrease of the curve was assigned as CMC [Figure 7(b)]. The CMC value found 38 mg L^{-1} is consistent with those given for the polymer surfactants in the literature.

CONCLUSIONS

The procedure comprising controlled synthesis of block copolymers, PEA-*b*-PS by ATRP, and followed aminolysis of the PEA block by ethanolamine allows preparing well-defined amphiphilic block copolymers with controllable block sequences. The block copolymer with the short PS chain forms stable micelles in o/w emulsions.

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