DOI: 10.1002/masy.201100105

Synthesis and Characterization of Poly(*N*-isopropylacrylamide) and Poly(vinyl acetate) Diblock Copolymers via MADIX Process

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Summary: The synthesis of diblock copolymers of poly(*N*-isopropylacrylamide) (PNIPAM) and poly(vinyl acetate) (PVAc) was performed by macromolecular design via interchange of xanthates (MADIX) process. Following the preparation of methyl (isopropoxycarbonothioyl) sulfanyl acetate (MIPCTSA) as chain transfer agent, it was reacted with vinyl acetate to obtain PVAc macro-chain transfer agent. Then, block copolymerization was completed by successive addition of *N*-isopropylacrylamide (NIPAM). ^{1}H NMR spectroscopy confirmed the presence of both blocks in the copolymer structure, with the expected composition based on the feed ratio. Size Exclusion Chromatography (SEC) was used to investigate the relative values of molecular characteristics. Only 20% of PVAc was converted to block copolymer. The resultant block copolymer structures were further examined in terms of their morphologies as well as critical micelle concentration (CMC) by using ESEM and Fluorescence Excitation Spectroscopic techniques, respectively. Morphological characterization confirmed amphiphilic block copolymer formation with the existence of mainly ca. 100 nm well distributed micelles. The thermo responsive amphiphilic behavior of the block copolymer solutions were followed by Dynamic Light Scattering (DLS) technique.

Keywords: CMC; diblock copolymers; MADIX; morphology; poly(*N*-isopropylacrylamide); poly(vinyl acetate); thermo responsive behavior

Introduction

Poly(N-isopropylacrylamide) (PNIPAM) is one of the most widely investigated thermo responsive polymers. The thermo responsive behavior of PNIPAM has applications in fields such as surface modification, drug delivery, reaction catalysis, stabilization and functionalization of metal nanoparticles. [1–6] Many studies have been done concerning the effect of block copolymerization of NIPAM with suitable comonomers. The traditional way of preparing NIPAM copolymers by free radical polymerization leads to polymers with high polydispersity and with poorly defined end-group chemistries. These disadvantages limit the possibility of synthesizing well-defined and also end-functionalized block copolymers that may be used in further applications. Among the controlled radical polymerization methods, reversible addition-fragmentation chain transfer (RAFT) polymerization is an exceptionally versatile tool for the synthesis of polymers with narrow molecular weight distributions. [7] This technique has created also new possibilities for the synthesis of various NIPAM copolymers with poly(ethylene oxide) (PEO), [3,8,9] poly(acrylic acid) (PAA), [4] poly(N-vinylimidazole) (PVim), [5] poly(2-(diethylamino)ethylmethacrylate) (PDEAEMA) [10] and poly(2-vinylpyridine) (P2VP). [11] On the other hand, the controlled radical polymerization of vinyl acetate (VAc), yielding polymers having

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application areas ranging from adhesives, paints, and concrete additives to pharmaceuticals, [12] is a challenge since the monomer is deprived of any radical stabilizing substituent. Controlled polymerization of VAc via RAFT technique was found to be possible by using xanthates in macromolecular design via interchange of xanthates (MADIX) process [12–14] and also dithiocarbamates [15] as RAFT agents. Recently, for an aggregation-induced microgelation study of PVA-*b*-PNIPAM, a new difunctional initiator with an active halide group and xanthate group in the molecule was used to overcome abovementioned drawback in synthesis of PVAc-*b*-PNIPAM [16] which is the source of PVA-*b*-PNIPAM.

In the present work, the synthesis of diblock copolymers of PNIPAM and PVAc was performed by MADIX process. In the first stage, methyl (isopropoxycarbonothioyl) sulfanyl acetate (MIPCTSA) was used as chain transfer agent to obtain PVAc macro-chain transfer agent (macro-CTA). Then, block copolymerization was studied by addition of NIPAM to above mentioned macro-CTA.

Experimental Part

Materials

2-Propanol (Merck), carbon disulfide (Allied Chemical), methyl bromoacetate (Acros), and potassium hydroxide (Merck) were obtained at the highest purity available and used without further purification. Vinyl acetate (VAc) (Merck, 99%) was filtered through a column of basic aluminum oxide and distilled before utilization. *N*-Isopropylacrylamide (NIPAM) (Acros, 99%) was purified by recrystallization in a benzene/*n*-hexane mixture. 2, 2′-azobis (isobutyronitrile) (AIBN) obtained from Acros was recrystallized from methanol. All solvents were redistilled before use.

Polymer Synthesis

The synthesis and purification of MIPCTSA and Pac macro-CTA was done using a procedure previously outlined in literature. [16] The latter reaction was carried out at two different temperatures with the same molar ratios of monomer, CTA and initiator in order to investigate the effect of decomposition of AIBN on the molecular weight distribution. For the synthesis of block copolymers, PVAc macro-CTA2, NIPAM and AIBN were all dissolved in 1, 4-dioxane in a flask and degassed by three freeze–vacuum–thaw cycles. The flask was immersed into oil bath and polymerization was carried out for 24 h at 75 °C under nitrogen atmosphere. The product was dried by freeze-dry technique.

Characterization

^{1}H NMR was performed on a Varian Gemini 400 MHz nuclear magnetic resonance spectrometer at room temperature using $CDCl_3$ as the solvent. The number-average molecular weight (*M*n) and polydispersity (PDI) of the polymers were determined by SEC at 30 °C with a Waters 1525 chromatograph equipped with a Waters 2414 refractive index detector and three Waters Styragel columns (HT2, HT3, and HT4). Tetrahydrofuran (THF) was used as the mobile phase at a flow rate of 0.35 mL/min. Polystyrene standards were employed for calibration. The morphology of the polymer samples were examined by ESEM, ESEM-FEG/EDAX Philips XL-30 instrument, with dialyzed samples dropped on copper grids. Particle size analysis was conducted for determining micelle sizes in water with the Brookhaven Instruments Corporation 90Plus Dynamic Light Scattering Particle Size Analyzer (Nano-PSA). Fluorescence spectroscopy measurements for determining critical micelle concentration (CMC) were conducted using Varian-Cary Eclipse Fluorescence Spectrophotometer. Pyrene as the fluorescence probe and slit width of 2.5 nm settings were used in order to calculate CMC from data of excitation peaks at 339 nm and 334 nm with respect to emission wavelength of pyrene at 390 nm.

Table 1.
Conditions and Results of the Synthesis of PVAc macro-CTA

Sample	VAc^{a}:MIPCTSA:AIBN (Molar ratio)	T (°C)	Time (h)	$Conversion^{b}$ (%)	$M_{n(NMR)} \times 10^{-3}$	$M_{n(SEC)} \times 10^{-3}$	PDI
PVAc macro-CTA1	169.7: 2.2: 1.0	60	16	96	10.2	5.6	2.35
PVAc macro-CTA2	182.5: 2.4: 1.0	65	16	94	10.7	11.4	1.31

^{a}[VAc] $= 1.3 \times 10^{-2}$ M, ^{b}Determined by ^{1}H NMR.

Results and Discussion

Synthesis of PVAc macro-CTA

The polymerization conditions and expected reaction are given in Table 1 and Scheme 1, respectively.

The ^{1}H NMR spectrum of the above-mentioned PVAc macro-CTA shows methylene protons at $\delta = 1.6$–1.9 ppm, methyl protons both attached carbonyl at $\delta = 2.0$ ppm and xanthate group at $\delta = 1.4$ ppm as well as methine proton at $\delta = 4.8 - 5.0$ ppm (Figure 1).

Traces of unreacted monomer could be observed at $\delta = 4.6, 5.9$ and 7.2 ppm belonging to vinyl protons of VAc and the conversion was calculated as 94 and 96% for PVAc macro-CTA1 and PVAc macro-CTA2 samples, respectively.

The data obtained from SEC analysis given in Table 1 that for PVAc macro-CTA1, bimodal distribution was attained, with the presence of a second small peak at lower molecular weight region. The population of this low molecular weight species may be attributed to low decomposition rate of AIBN at 60 °C[18] leading to delayed radical formation which than results in smaller chains. In order to overcome this formation of low molecular weight product, the macro-CTA synthesis was repeated at 65 °C, termed as PVAc macro-CTA2 with the reaction conditions given in Table 1. Figure 2 shows the SEC data of PVAc macro-CTA2, which presents unimodal molecular weight distribution.

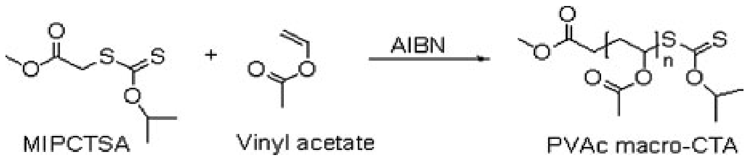
The molecular weights of the two PVAc macro-CTA's also calculated from the ^{1}H NMR data are given in Table 1, as M_n (NMR). The relative intensities of specific peaks belonging to PVAc (methine proton at 4.8–5.0 ppm) and CTA attached to PVAc (methine proton at 5.72 ppm) (Figure 1) were used in order to calculate the number average molecular weights. PVAc macro-CTA2 was observed to be in good agreement with the SEC analysis data (Table 1), whereas the presence of bimodal distribution and low molecular weight products in PVAc macro-CTA1 create divergence between the calculated and obtained number average molecular weights.

Synthesis of Block Copolymers of PVAc and PNIPAM

The synthesis of block copolymers was conducted by using PVAc macro-CTA2, NIPAM and AIBN via MADIX process as shown in Scheme 2.

The polymerization and characterization details are also given in Table 2.

^{1}H NMR spectrum of block copolymer C-AN1 Figure 3(a) does not only show the characteristic PVAc peaks but also the peaks belonging to PNIPAM; methyl protons of isopropyl group at $\delta = 1.1$ ppm (g),



Scheme 1.
Polymerization scheme for vinyl acetate via MADIX process.[17]

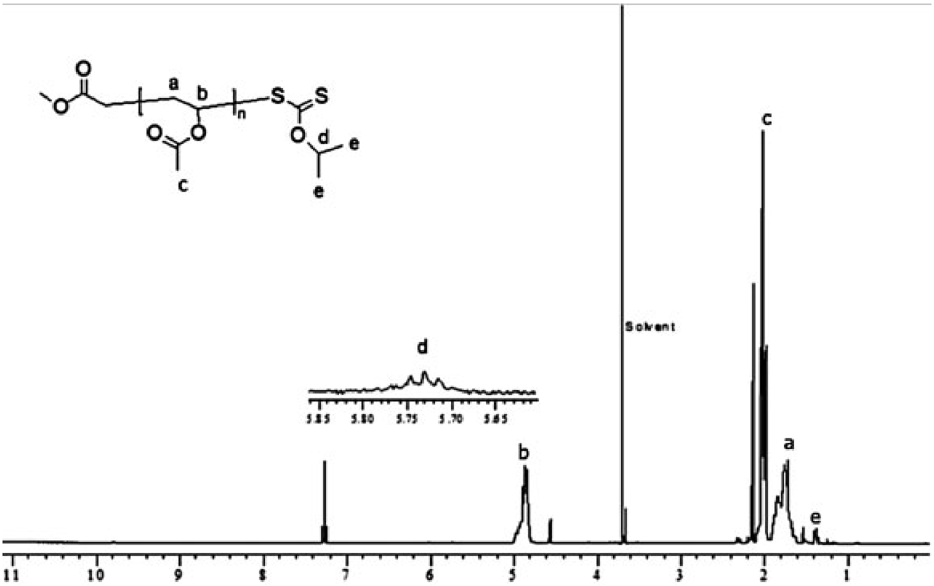


Figure 1.
^{1}H NMR Spectrum of PVAc macro-CTA2 taken in d-methanol.

methylene protons at $\delta = 1.6 - 1.9$ ppm (d), methine proton at $\delta = 2.3$ ppm (e) and methine proton of the isopropyl group at $\delta = 4.0$ ppm (f). The peak b at 4.8–5.0 ppm corresponding to the methine proton of PVAc and the peak of PNIPAM were chosen especially to investigate the presence of both PVAc and PNIPAM units in the copolymer structure.

Table 2 also includes the data for block copolymers C-AN2 and C-AN3 which were synthesized with different PVA: PNIPAM ratios. It is quite clear that block copolymerization can be conducted with similar conversions.

In order to investigate the possible homopolymer impurity, the product was precipitated several times from diethyl

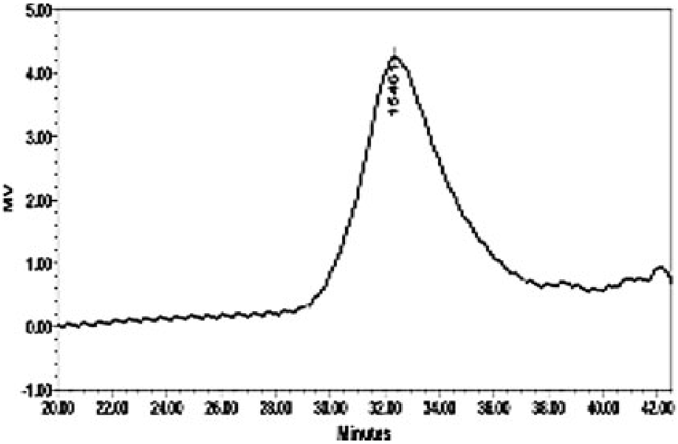
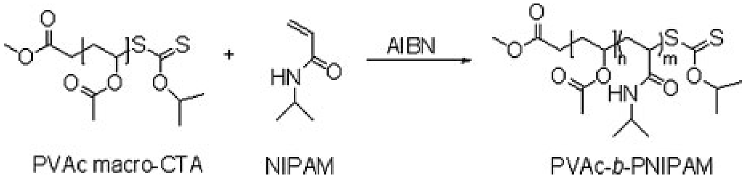


Figure 2.
SEC curve of PVAc macro-CTA2.



Scheme 2.
Block copolymerization reaction of PVAc with NIPAM.

ether which is non solvent for PNIPAM. The final precipitate was analyzed by using ^{1}H NMR (Figure 3 (b)) as well as SEC techniques.

In the NMR spectrum, the characteristic PVAc peak (b) decreases with respect to PNIPAM peak (f). These results show that precipitate contains block copolymer having high molecular weight PNIPAM sequences whereas PVAc mainly remains soluble as homopolymer in this solvent.

Further SEC chromatograms of the sample before and after selective precipitation are given in Figure 4 (a) and (b), respectively.

The bimodal and broad molecular weight distributions were observed for all products before selective precipitation (Figure 4 (a)). The disappearance of the peak corresponding to PVAc in former chromatogram also confirms the existence and successful separation of homopolymer of VAc from the product. Both gravimetric analyses of the fractions and integrations of characteristic peaks of PVAc and PNIPAM in NMR lead to the conclusion that approximately 20% of PVAc was converted to the block copolymer.

Although Desterac et al [19] reported RAFT/MADIX block copolymerization of N,N-Dimethylacrylamide (PDMA) with VAc by using PDMA macro CTA, in our study, a series of trials by using PNIPAM macro CTA (in-situ or successive addition) to obtain the block copolymer where PNIPAM as first block were all unsuccessful.

Further examinations of synthesized and dialyzed PVAc-*b*-PNIPAM structures were conducted in terms of their morphologies as well as critical micelle concentration (CMC).

Morphological characterization of C-AN1 sample via ESEM analysis is given in Figure 5. As it is clearly seen from the higher magnification image, the sample exhibits stable and perfect spherical micelle structures. It is known that diblock copolymers consisting of a PNIPAM block and a hydrophobic block can form core–shell micellar structures below the lower critical solution temperature (LCST).[20,21] This polymeric micellar structure forms a hydrophilic outer shell of hydrated PNIPAM blocks and a hydrophobic PVAc inner core. Moreover, the structure and abovementioned micellar structure dependent properties can be tuned by changing the temperature and the composition of the block copolymers.

The almost 80% of small micelles with ca. 100 nm size as well as 20% of bigger sized (ca 500 nm) micelles exhibit a uniform distribution. The observed micellar struc-

Table 2.
Block copolymerization^a details of PVAc macro-CTA with NIPAM

Sample	VAc:NIPAM (mol ratio)	Conversion (%)	M_nSEC X 10^{-3}	PDI
C-AN1	1:1	97.3	19.5	1.88
C-AN2	1:0.5	95.7	28.1	1.82
C-AN3	1:2	98.6	21.4	1.88

^{a}24 h at 75 °C.

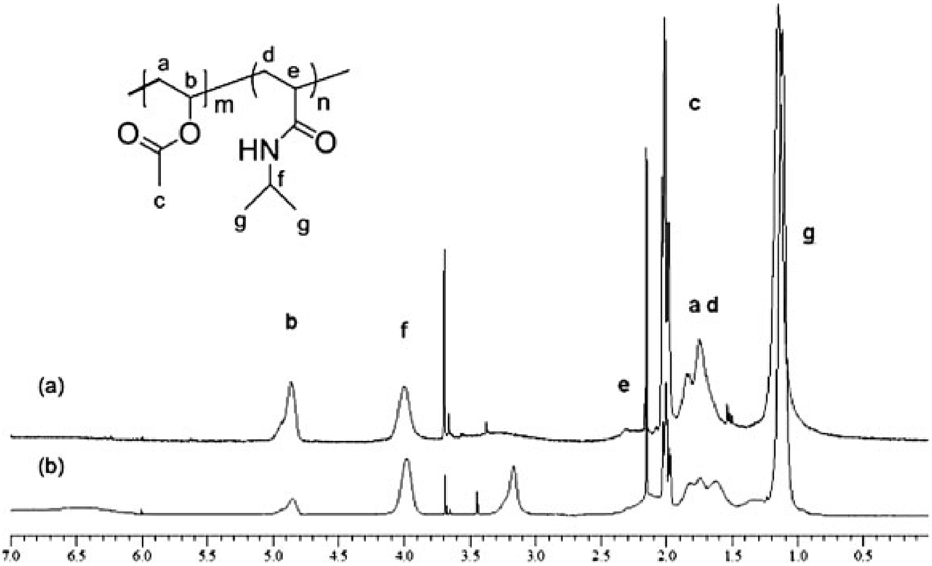


Figure 3.
^{1}H NMR spectra of product (C-AN1) before (a) and after (b) selective precipitation.

ture can be easily accepted as a confirmation of the abovementioned amphiphilic block copolymer formation.

The results of fluorescence spectroscopy analysis using pyrene as a fluorescence probe for determining CMC of C-AN1 micelles are given in Figure 6.

The data acquired with respect to emission wavelength at 390 nm, are also overlaid as shown in the figure. The calculation of CMC of PVAc-*b*-PNIPAM was found from the curve of ratios of intensities at 337 nm and 334 nm versus minus logarithm of concentrations. The convergence point of two tangent lines drawn on the curve indicated a –log C value which equals to 2.39. Further calculations using this value gave a concentration of 4.07×10^{-3} g/L which is the CMC of the PVAc-*b*-PNIPAM. The obtained low CMC value for the block copolymer is in well agreement with the fact that high molecular

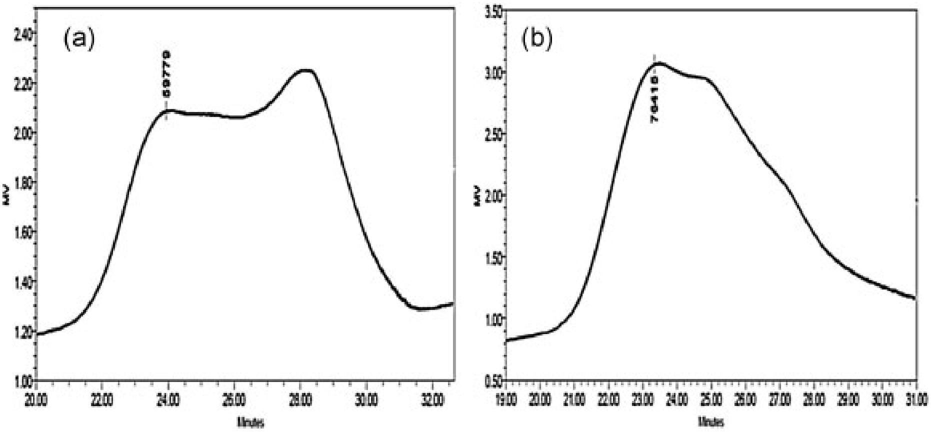


Figure 4.
SEC chromatograms of the sample before (a) and after (b) selective precipitation.

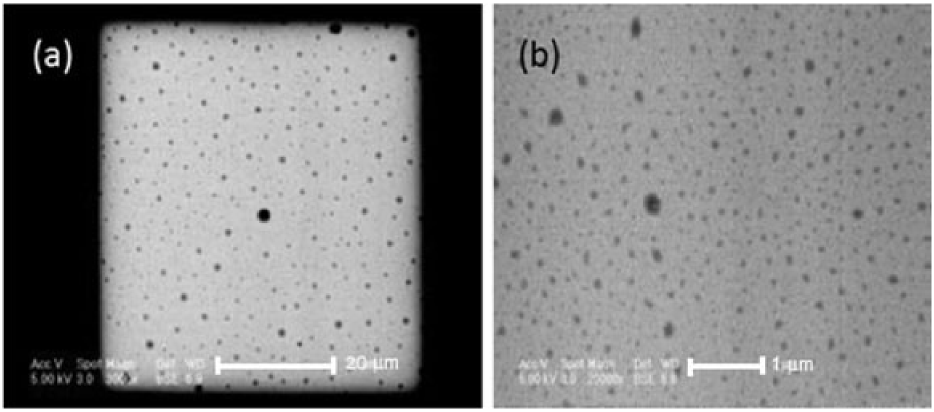


Figure 5.
Low (a) and high (b) magnifications of ESEM micrographs of C-AN1.

weight block copolymers exhibit low CMC's due to early start of significant micellar associations. Thus, formation of micellar structures occurs even in very dilute solutions.[22]

The temperature effect on the PVAc-*b*-PNIPAM self-assemblies was investigated by using dynamic light scattering technique.

The results given in Figure 7 indicate that the effe ctive diameter of micelles change from *ca.* 780 nm at 25 °C to *ca.* 380 nm at 40 °C which is thought to be well above LCST of PNIPAM. [23] This behavior of the micellar solution is due to the collapse of PNIPAM block and micelle size shrinkage occurring as temperature is increased.

Conclusion

PVAc-*b*-PNIPAM block copolymers were prepared via MADIX process, using MIPCTSA as chain transfer agent. The

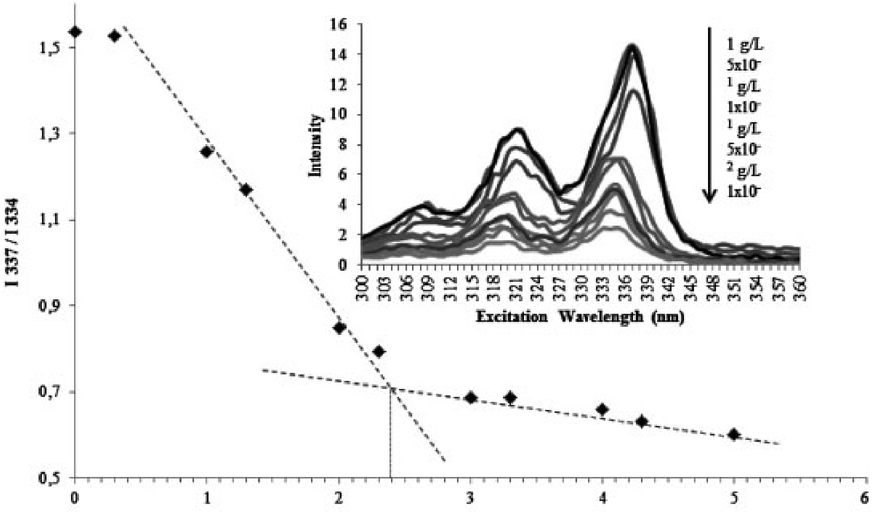


Figure 6.
Fluorescence excitation spectrum intensity ratios versus log of polymer concentration.

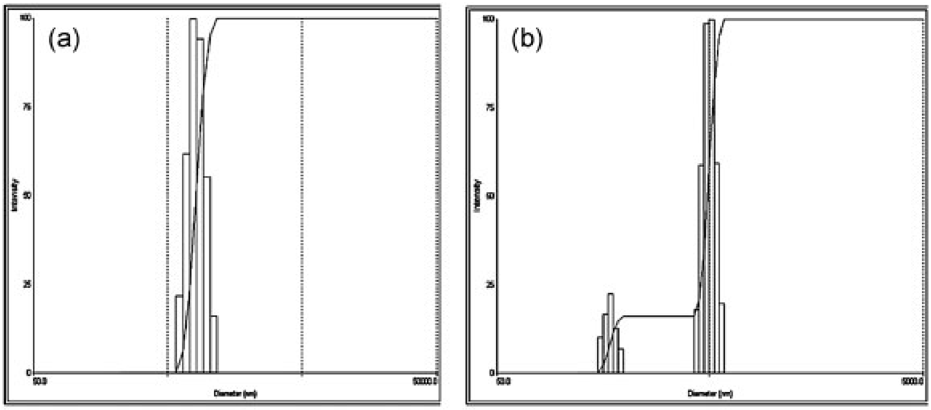


Figure 7.
DLS results for C-AN1 at (a) 25 °C and (b) 40 °C.

data showed only partial incorporation of PVAc segment in block copolymer structure. The existence of quite defined and well distributed micelles as well as their low CMC values can be accepted as a confirmation of block copolymer formation. The micelles were found to be responsive to the thermal changes especially beyond the LCST of PNIPAM block.

Acknowledgements: Support given by Bogaziçi University Research Foundation No. 10B5573 is gratefully acknowledged.

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