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## Comparative thermodynamic studies of the micellization of amphiphilic block copolymers before and after cyclization

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**ABSTRACT:** The enthalpy and entropy of micellization in water,  $\Delta H_{\text{mic}}$  and  $\Delta S_{\text{mic}}$ , respectively, of three linear amphiphilic BAB block copolymers consisting of either poly(methyl acrylate) ( $M_n \sim 1200$  and 700 Da) or poly(ethyl acrylate) ( $M_n \sim 800$  Da) as hydrophobic (B) segments and poly(ethylene oxide) (PEO) as the hydrophilic (A,  $M_n \sim 3000$  Da) segment were determined by isothermal titration calorimetry (ITC). The  $\Delta H_{\text{mic}}$  and  $\Delta S_{\text{mic}}$  of the cyclic AB block copolymers obtained by cyclization of the linear triblock copolymers were determined under the same conditions. The  $\Delta H_{\text{mic}}$  value of the cyclic copolymers was smaller than that of their linear precursors. The  $\Delta S_{\text{mic}}$  value showed the same trend, but the relative difference between the cyclized and linear copolymers was less pronounced. The hydrodynamic diameter ( $D_h$ ), critical micelle concentration (CMC), molecular weight ( $M_w$ ), and second virial coefficient ( $A_2$ ) of the micelles were determined. The  $D_h$  value of the cyclic copolymer micelles was smaller than the linear counterpart. On the other hand, the CMC value became larger, whereas the  $A_2$  value was comparable or increased by cyclization. Overall, the results suggest that in the unimer state, the hydrophobic segments of the cyclized copolymers form a tightly coiled structure to minimize contact with water, resulting to the smaller  $\Delta H_{\text{mic}}$  value. Contrary to the linear copolymer micelles, the cyclic copolymer micelles

have no “dangling chains”, which may explain the topology-driven slight difference in the  $\Delta S_{\text{mic}}$  value.

## INTRODUCTION

Polymer topology, known to affect the properties and functions of polymers, is a topic of great importance to theoreticians and industrial scientists.<sup>1</sup> The cyclic topology, which combines the constraints imposed by the ring architecture and the absence of end groups, is under intensive current investigation as described in several recent reviews.<sup>2,3</sup> The systematic study of cyclic diblock copolymers was initiated by Booth et al. who succeeded in preparing cyclic diblock amphiphilic copolymers of composition nearly identical to that of commercially available linear amphiphilic diblock and triblock polymers. They demonstrated that micelles of cyclic diblock copolymers consisting of a water soluble poly(ethylene oxide) (PEO) block and either poly(butylene oxide) (PBO) or poly(propylene oxide) (PPO) blocks are larger than micelles of the linear (PEO–PBO–PEO), but smaller than micelles of the linear (PEO–PBO).<sup>4,5</sup> This seminal work was followed by extensive studies worldwide, as block copolymers are used widely in consumer products and industrial fluids, including cosmetics, foods, pharmacological formulations, and coating formulations.<sup>6</sup> The effect of topology on the micellization of cyclic diblock copolymers is mainly due to the entropy penalty associated with the transformation from the unimer state to the micellar state.<sup>6-9</sup> The free energy of micellization ( $\Delta G_{\text{mic}}$ ) of BAB micelles in water, where A is the water-soluble block and B the water-insoluble block, is much smaller in absolute term than that of ABA micelles, as a consequence of the entropic penalty arising from the formation of loops by the BAB chains upon micellization into “flower-like” micelles.<sup>10</sup> Simulations of the thermodynamics of the micellization of the same triblock copolymers confirmed the experimental results.<sup>11,12</sup> The enthalpy of micellization ( $\Delta H_{\text{mic}}$ ) of cyclic PEO–PPO is much smaller than that of the linear ABA counterpart,<sup>4,5</sup> due to the reduced exposure of the hydrophobic block to water in the unimer state.<sup>13,14</sup>

Several techniques have been used to explore the micellization of diblock copolymers, including surface tension measurements,<sup>1</sup> <sup>1</sup>H NMR relaxation studies,<sup>15</sup> dynamic light scattering, fluorescence spectroscopy, and differential scanning calorimetry (DSC). DSC measurements yield  $\Delta H_{\text{mic}}$  by integration of the heat capacity versus temperature signal.<sup>16,17</sup> Isothermal titration calorimetry (ITC) directly measures the enthalpy changes upon mixing two chemical entities or the binding of a molecule to a receptor protein. It was

also used to determine the CMC and  $\Delta H_{\text{mic}}$  of surfactants or polymer micelles in a single measurement without the use of an extrinsic probe.<sup>18</sup> Additional thermodynamic parameters related to the micellization, including the Gibbs free energy of micellization ( $\Delta G_{\text{mic}}$ ), the entropy of micellization ( $\Delta S_{\text{mic}}$ ) and the heat capacity of micellization ( $\Delta C_{p \text{ mic}}$ ), can be derived from the experimental  $\Delta H_{\text{mic}}$  and CMC values. The interpretation of ITC data necessitates the use of models, such as the mass-action model<sup>19</sup> or the phase-separation model.<sup>10</sup> The micellization of surfactants or amphiphilic polymers is entropy-driven at room temperature. The array of structured water molecules surrounding the hydrophobic segments of an amphiphile molecularly dissolved in water is disrupted upon micellization, resulting in an increase of the entropy of the entire system.<sup>20</sup>

Our group carried out a systematic comparative study of micelles formed by amphiphilic cyclic diblock and linear triblock copolymers, including copolymers having a poly(ethylene oxide) (PEO) chain as the hydrophilic block and either a poly(methyl acrylate) (PMA) or a poly(ethyl acrylate) (PEA) as the water-insoluble blocks (Figure 1). We observed that the core and shell of micelles formed by cyclic block copolymers are more compact than those of linear triblock copolymers. We also determined the topology dependence of properties such as salt resistance,<sup>1</sup> X-ray structures,<sup>21, 22</sup> NMR relaxation,<sup>23</sup> and emulsion stabilizing properties.<sup>24</sup> Micelles of the cyclic amphiphiles were resistant against agglomeration up to temperatures  $\sim 40$  °C higher and salt concentrations  $\sim 30$ -times higher than the micelles of the corresponding linear amphiphiles.<sup>1, 25</sup> NMR relaxometry confirmed that the agglomeration of linear copolymer micelles involves bridging of micelles by escape of a chain's hydrophobic block from one micelle and its re-insertion in a second micelle as in the case of gelation.<sup>23</sup> Due to the absence of end groups, agglomeration through bridging cannot take place in the case of cyclic amphiphiles. It occurs at higher temperature via heat-induced dehydration of the PEO blocks and subsequent aggregation of the dehydrated segments.

The objective of this study was to determine by ITC  $\Delta H_{\text{mic}}$ ,  $\Delta G_{\text{mic}}$ , and  $\Delta S_{\text{mic}}$  of the micellization of cyclic amphiphilic diblock copolymers (PMA-PEO and PEA-PEO) and their linear precursors, the triblock copolymers (PMA-PEO-PMA and PEA-PEO-PEA). Micellar solutions of the copolymers were characterized first by SLS to determine the molar weight ( $M_{w \text{ mic}}$ ), aggregation number ( $N_{\text{agg}}$ ) and second virial coefficient ( $A_2$ ) of the micelles. Their  $D_h$  was measured by DLS, and CMC was determined by the average scattering intensity. ITC of micellar copolymer solutions into water were performed to determine the  $\Delta H_{\text{mic}}$  value

of the copolymers. We observed that  $\Delta H_{\text{mic}}$  of the cyclic copolymers are smaller than those of the linear prepolymers, whereas the CMC value is larger for the cyclic copolymers. Interpretation of the ITC results in view of the overall characteristics of the micelles is presented in order to determine the distinct effect of the cyclic topology on the micellization of amphiphilic block copolymers.

## EXPERIMENTAL SECTION

### Materials.

Unless otherwise stated, all reagents and chemicals were purchased from Sigma–Aldrich, Tokyo Chemical Industry, or Wako Pure Chemical Industry and used as received. Water was purified by an Advantec Automatic Water Distillation Apparatus. The copolymers employed were prepared and purified as described previously.<sup>23</sup> Their composition and characteristics are listed in Table 1.  $M_n$  and  $M_w/M_n$  was determined by NMR and SEC, respectively. The molecular weights of the hydrophilic and hydrophobic segments varied to some extent between the linear and cyclic forms. This was due to the purification process.

### Preparation of the copolymer solutions in water.

Water was added to a weighed amount of a copolymer sample. The mixture was sonicated for 5 minutes to form a uniform solution. The copolymer concentration was adjusted to either 1.0 or 4.0 mg/mL.

**CMC.** CMC measurements were performed on an ALV goniometric Dynamic and Static Light Scattering System. A He–Ne laser operating at a wavelength of  $\lambda_0 = 632.8$  nm was used as a light source. The experiments were performed at 20 °C. Before measurements, solutions were filtrated through 0.2  $\mu\text{m}$  pore size membranes. CMC was determined from the point of intersection of the intensities as shown on the plots (Figures S1–S6). The set of concentrations was prepared by sequential addition of stock polymer solution (2.5 g/L) to water.

**$M_{w\text{mic}}$ ,  $A_2$ , and  $D_h$ .** A Malvern Zetasizer Nano instrument equipped with a frequency doubled DPSS Nd:YAG laser ( $\lambda = 532$  nm) with a scattering angle fixed at 173 ° was employed. The measurements were performed at 25 °C.  $M_{w\text{mic}}$  and  $A_2$  were determined using Zimm plots with a fixed angle and equation (1):

$$\frac{Kc}{R_0} = \frac{1}{M_w \text{mic} P_0} + 2A_2 c \quad (1)$$

where  $R_0$  is the Rayleigh ratio,  $c$  is the concentration, and  $P_0$  is the angle dependent scattering intensity,  $K$  is defined by the equation (2):

$$K = \frac{4\pi^2}{\lambda_0^4 N_A} \left( n_0 \frac{dn}{dc} \right)^2 \quad (2)$$

where  $N_A$  is Avogadro's number,  $\lambda_0$  is the wavelength of the laser, and  $n_0$  is the refractive index of the solvent. The  $dn/dc$  values of the copolymers were calculated to be 0.13 mL/g based on the weight fractions of the homopolymers.<sup>26, 27</sup> The copolymer concentration was set at 2.5 mg/mL for the determination of  $D_h$ .

**Isothermal Titration Calorimetry.** Titrations were performed at 20 °C with a VP-ITC titration microcalorimeter (MicroCal) and a cell volume of 1.428 mL. Samples were degassed in a ThermoVac system (MicroCal) prior to use. The cells were filled with deionized water. A micellar copolymer solution (2.5 mg/mL) was introduced in the syringe and injected portionwise in the thermostatted cell filled with deionized water. Data analysis was carried out using the OriginLab ORIGIN software.

To determine the experimental  $\Delta H_{\text{mic}}$  values, we used the method devised previously for titrations that do not give a sigmoidal  $\Delta H$  vs. polymer concentration titration curve.<sup>28-30</sup> Linear fits of the lower and upper concentration domains of the raw data (heat release upon injection of the micellar solution as a function of time) were performed as indicated in Figure 2. The abscissa of the last (highest) value in the fitted raw data of the lower concentration range, i.e., the start of the transition, and the abscissa of the first (lowest) value in the fitted data of the higher concentration domain, i.e., the end of the transition, were taken as the copolymer concentrations corresponding to the start and end of micellization, respectively.<sup>18</sup>

The Gibbs free energy of micellization is calculated by equation (3):

$$\Delta G_{\text{mic}} = RT \ln X_{\text{CMC}} \quad (3)$$

where  $X_{\text{CMC}}$  is the critical micelle concentration in mole fraction units determined by average scattering intensity.  $\Delta S_{\text{mic}}$  was obtained using the following equation (4):<sup>29, 31</sup>

$$\Delta S_{\text{mic}} = \frac{\Delta H_{\text{mic}} - \Delta G_{\text{mic}}}{T} \quad (4)$$

## RESULTS AND DISCUSSION

### Preparation and structural characterization of the copolymer micelles.

Two linear poly(methyl acrylate)–poly(ethylene oxide)–poly(methyl acrylate), PMA–PEO–PMA triblock copolymers of different molecular weights and a poly(ethyl acrylate)–poly(ethylene oxide)–poly(ethyl acrylate), PEA–PEO–PEA, were cyclized following the conditions reported previously,<sup>1,25</sup> leading to cyclic PMA–PEO and PEA–PEO block copolymers (Figure 1a). The cyclization was performed through an olefin metathesis reaction, in which two terminal olefins turn into one internal olefin. This reaction does not likely significantly affect the hydrophobicity arising from the functional groups. The composition and molar mass of the copolymers are given in Table 1.<sup>32</sup> Note that there is a difference between the experimental  $M_n$ (NMR) values of the cyclic copolymers and the  $M_n$ (NMR) values of their linear precursors. The discrepancy is a consequence of the extensive purification of the cyclized products. We prepared two PMA–PEO pairs of copolymers to evaluate the influence of the relative hydrophobic/hydrophilic block length and a single PEA–PEO pair to assess the effect of the composition of the hydrophobic block. Important characteristics of the copolymer micelles, namely  $D_h$  by DLS, the hydrodynamic volume ( $V_h$ ) derived from  $D_h$ ,  $M_{w\text{ mic}}$  by SLS, density ( $M_{w\text{ mic}}/V_h$ ),  $A_2$ , and CMC by average scattering intensity, are listed in Tables 1 and 2.

### Determination of $D_h$ of the micelles by DLS and CMC values by the average scattering intensity

$D_h$  determined by DLS of the micelles from the cyclic block copolymers were smaller than those of their linear counterparts (Table 1).<sup>32</sup> For example,  $D_h$  of **L1**, where L indicates the linear topology, micelles was 19 nm, while that of **C1**, where C indicates the cyclic topology, was 15 nm. This trend agrees well with our past reports.<sup>21, 22</sup> The cyclic copolymers, obtained earlier by Booth et al, by cyclization of PEO–PPO–PEO and PEO–PBO–PEO form micelles of larger  $D_h$ , probably as a consequence of the position of the hydrophobic segments in the chain.<sup>4, 5</sup> We obtained CMC of the micelles by average scattering intensity, using a polymer concentration at which the intensity starts to increase (Figures S1–S6). The CMC of the cyclic block copolymers was larger than that of the linear block copolymers for the three cyclic/linear pairs (Table 2).<sup>32</sup>

$M_{w\text{ mic}}$ ,  $N_{\text{agg}}$ , and  $A_2$

$M_{w\text{ mic}}$  and  $A_2$  of the copolymer micelles, listed in Table 1, were obtained from SLS data and Zimm plots presented as supporting information (Figures S7–S9). At least five points were obtained to determine  $M_{w\text{ mic}}$ . However, fitting for **L1** seems to be relatively less accurate compared to the others. Moreover, the pair of **L1** and **C1** has a comparably large difference in the weight fraction of PEO (Table 1), arising from the purification process, and thus is excluded from the following discussion. In the pair of **L2** and **C2** as well as **L3** and **C3**,  $M_{w\text{ mic}}$  and  $N_{\text{agg}}$ , which was calculated by dividing  $M_{w\text{ mic}}$  by the molecular weight of the copolymer, show a trend towards higher values for the cyclic copolymers. The increase in  $A_2$  may be attributed to the higher stability of the cyclic copolymer micelles, versus the linear micelles.<sup>1</sup> Interestingly, the density values of the micelles estimated based on  $M_{w\text{ mic}}$  and  $V_h$  are two to three times larger for cyclic copolymers versus linear copolymers. Density values derived from SAXS data reported earlier followed the same trend.<sup>21, 22</sup> The higher density of the cyclic copolymer micelles indicates that the free volume of cyclic polymers micelles is smaller than the free volume of linear polymer micelles, possibly due to the absence of chain ends in the cyclic polymers.<sup>33</sup> The core of cyclic copolymer micelles will be more compact than that of their linear counterpart, which accounts for the smaller diameter of the cyclic polymer micelles observed experimentally.<sup>21, 22</sup>

## ITC

Aqueous micellar solutions of the copolymers ( $c > \text{CMC}$ ) were injected in water placed in the ITC sample cell. Initially, the polymer micelles injected dissociate into isolated polymer chains, or unimers, upon dilution in the water. Once the polymer concentration in the sample cell reaches the CMC, only a few injected micelles dissociate, most of them remain intact. The enthalpy evolved upon injection decreases until  $c > \text{CMC}$ , at which point it remains constant and equal to the heat of dilution of intact polymer micelles. This titration yields the *de-micellization* enthalpy or  $-\Delta H_{\text{mic}}$ . The transition that takes place around the CMC is not sharp as in the case of low molecular weight surfactants. It occurs over several concentration decades (Figure 2). To determine the  $\Delta H_{\text{mic}}$  value, we used the method recommended by Ponchel et al.<sup>18</sup> depicted in Figure 2 and the experimental section. Enthalpograms recorded for the three linear/cyclic copolymer pairs are presented in Figure 3. The CMC of the micelles, their  $\Delta H_{\text{mic}}$ ,  $\Delta G_{\text{mic}}$ , and  $\Delta S_{\text{mic}}$ , are listed in Table 2. Again, the pair of **L1** and **C1** has a comparably large difference in the weight fraction of PEO (Table 1) and is excluded from the following discussion. In the pair of **L2** and **C2** as well as **L3** and



**C3**,  $\Delta H_{\text{mic}}$  and  $\Delta H_{\text{mic}}$  per hydrophobic unit ( $\Delta H_{\text{mic}}/n$ ) of the cyclic copolymer were significantly smaller than that of the linear copolymer. This trend may be attributed to differences in the conformations taken by the cyclic and linear copolymers prior to micellization, when the copolymers are dispersed in water as unimers.<sup>31</sup> In this state, the hydrophobic segments of *cyclic* copolymers adopt a tightly coiled conformation in order to reduce the interactions between water and the hydrophobic block (Figure 1c). In contrast, the hydrophobic units of isolated *linear* copolymers in water adopt an extended conformation, which facilitates the interactions between the two hydrophobic units at the expense of the hydrophobic block/water interactions (Figure 1b). Moreover, for each copolymer pair, the hydrophobic segment of the cyclic copolymer is roughly twice as long as each hydrophobic segment of the linear copolymer. As a result, the hydrophobic segment of the cyclic copolymer in the unimer state is better shielded from contacts with water than the two shorter hydrophobic blocks of the linear copolymer, which is in good agreement with the experimental values of  $\Delta H_{\text{mic}}$  (Table 2). Furthermore, the  $\Delta H_{\text{mic}}/n$  values recorded for solutions of PEO–PEA copolymers are larger than in the case of PEO–PMA copolymers of similar molar mass. This effect is likely due to the PEA’s strong hydrophobic properties.

From equations (3) and (4) in the experimental section and the value of CMC obtained by average scattering intensity (Table 2),<sup>29, 31</sup>  $\Delta G_{\text{mic}} = -38 \sim -39$  kJ/mol and  $\Delta S_{\text{mic}} = 140 \sim 190$  J/mol·K were found. The small positive values in  $\Delta S_{\text{mic}}$  results mostly from the decreased hydrophobic effect upon micellization.  $\Delta H_{\text{mic}}$  results from a number of recognized contributions<sup>31, 34</sup> according to Equation 5:

$$\Delta H_{\text{mic}} = \Delta H_{\text{mic}}(\text{hydrophobic}) + \Delta H_{\text{mic}}(\text{interface}) + \Delta H_{\text{mic}}(\text{dispersion}) + \Delta H_{\text{tr}}(\text{PEO}) \quad (5)$$

where  $\Delta H_{\text{mic}}(\text{hydrophobic})$  is associated with the hydrophobic effect,  $\Delta H_{\text{mic}}(\text{interface})$  with the formation of the core–corona interface,  $\Delta H_{\text{mic}}(\text{dispersion})$  due to the enhanced van der Waals interactions between the units of the PMA or PEA block in the core, and  $\Delta H_{\text{tr}}(\text{PEO})$  associated with the transfer of the PEO block to a more concentrated solution within the micelle corona. It is equal and opposite to the enthalpy of dilution of PEO (2.5 g/L) in water,  $\Delta H_{\text{dil}}(\text{PEO}) = -2.1$  kJ/mol as determined by ITC (Figure S10).

Here, we discuss the change in the thermodynamic parameters of the system during the transformation from the unimer state to the micellar state based on the obtained results in the above. Given that the hydrophilic segment of an amphiphilic block copolymer is hydrated in both the unimer state and the micellar state, its energy levels hardly change. In general,  $\Delta H_{\text{mic}}$  is known to be temperature dependent; the value is positive (disfavor to form micelles)

at low temperature due to the presence of the interactions between hydrophobic segments and water molecules in its unimer state.<sup>20</sup> When the temperature is raised, the  $\Delta H_{\text{mic}}$  value becomes negative (favor to form micelles), likely due to the thermal breakage of the hydrophobic segments–water molecules interactions in its unimer state.

Furthermore, the larger  $\Delta S_{\text{mic}}$  for linear block copolymers (Table 2) can be explained by the formation of micelles with dangling chains.<sup>11, 12</sup> In the unimer state, the water molecules minimize their interface to circumvent contact with the hydrophobic segments. As a result, the water molecules around the hydrophobic segments are highly structured, reaching a state referred to as an iceberg.<sup>35, 36</sup> Because this is a low entropy state, entropy is increased by the formation of micelles and the release of structured water to bulk water. In most cases, disturbing the iceberg state is energetically favorable and to become the driving force for micellization regardless of the temperature. In addition, in the micellar state, dangling chains form in the case of the linear block copolymers (Figure 1b), but not in the case of cyclic copolymers (Figure 1c). The dangling chain ends can move freely to some extent, resulting in relatively larger  $\Delta S_{\text{mic}}$  (Table 2). This phenomenon was reported by comparison of linear ABA- and BAB-block copolymers, where BAB-copolymers have relatively larger  $\Delta S_{\text{mic}}$ . Kim and Jo performed grand canonical Monte Carlo (GCMC) simulations of the micellization of ABA- and BAB- block copolymers finding BAB-block copolymers have larger  $\Delta S_{\text{mic}}$  due to the less structured micelles with dangling chains, compared with the ABA counterparts, for which the micellization is similar to that of cyclic copolymers.<sup>11, 12</sup> In this context, the larger size of micelles from BAB-block copolymer compared to cyclic counterparts was previously reported by solution SAXS.<sup>21, 22</sup>

## CONCLUSIONS

We investigated the properties of amphiphilic block copolymers with a cyclic topology possessing PEO as the hydrophilic segment and either PMA or PEA as the hydrophobic segments by forming micelles. Parameters for micellization such as CMC,  $\Delta H_{\text{mic}}$ , and  $\Delta S_{\text{mic}}$  were determined for the dependence of the topology of the copolymers. Based on the ITC measurements, the cyclized copolymers were found to have smaller  $\Delta H_{\text{mic}}$  values, and thus in the unimer state, their hydrophobic segment were suggested to have more tightly coiled conformations to avoid contact with water. Moreover, the micelles from the cyclic block copolymers do not have dangling chains unlike micelles formed by their linear counterparts, leading to smaller  $\Delta S_{\text{mic}}$ . This thermodynamic analysis facilitates the design of

novel functional self-assembled molecular systems by precise control of polymer–polymer and polymer–solvent interactions by taking advantage of the polymer topology (i.e., linear and cyclic forms).

**Table 1. Properties of Linear and Cyclized Amphiphilic Block Copolymers (L1, C1, L2, C2, L3, and C3)<sup>32</sup>**

abbreviation topology chemical structure $M_n$ (NMR)	weight fraction of PEO	$M_w/M_n^a$	$D_h$ (nm)	$M_w^{mic}^b$ (kDa)	$M_w^{mic}/V_h$ (Da/nm <sup>3</sup> )	$N_{agg}$	$A_2$ (mL·mol/g <sup>2</sup> )
<b>L1</b> linear PMA-PEO-PMA 1200-2800-1200	0.54	1.20	19	380	110	71	$4.2 \times 10^{-4}$
<b>C1</b> cyclized PMA-PEO 1900-3100	0.62	1.16	15	350	200	67	$3.7 \times 10^{-4}$
<b>L2</b> linear PMA-PEO-PMA 700-3000-700	0.68	1.15	18	290	94	63	$4.8 \times 10^{-4}$
<b>C2</b> cyclized PMA-PEO 1300-3200	0.71	1.12	15	390	200	82	$28 \times 10^{-4}$
<b>L3</b> linear PEA-PEO-PEA 800-3500-800	0.69	1.26	14	250	180	46	$11 \times 10^{-4}$
<b>C3</b> cyclized PEA-PEO 1500-3100	0.67	1.28	11	320	490	68	$32 \times 10^{-4}$

<sup>a</sup>Determined by SEC.

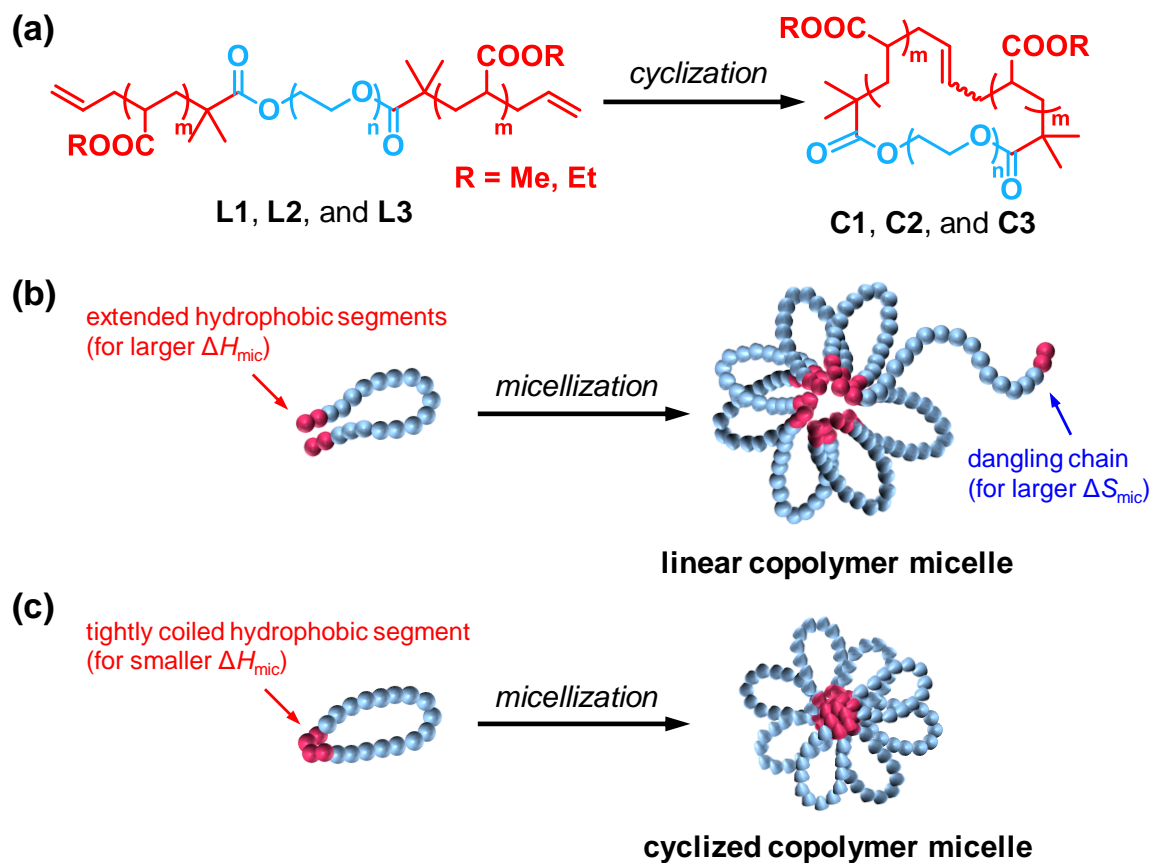
<sup>b</sup>Molecular weight of the micelles determined by SLS.

**Table 2. Thermodynamic Properties of Linear and Cyclized Amphiphilic Block Copolymers (L1, C1, L2, C2, L3, and C3) for Micellization<sup>32</sup>**

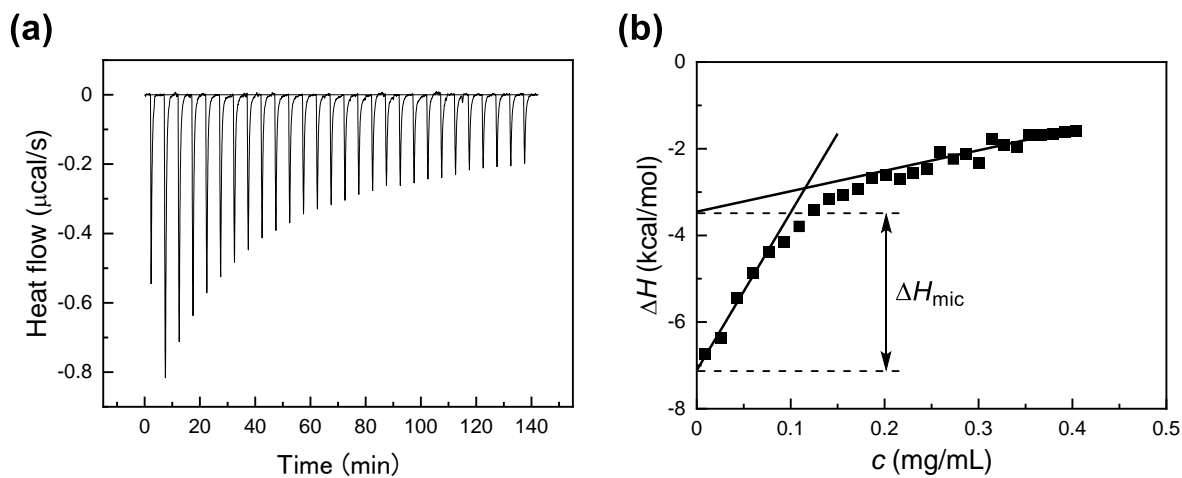
abbreviation topology chemical structure $M_n$ (NMR)	$\Delta H_{mic}$ (kJ/mol)	$\Delta H_{mic}/n^a$ (kJ/mol)	CMC <sup>b</sup> (mg/mL)	$\Delta G_{mic}$ (kJ/mol)	$\Delta S_{mic}$ (J/mol·K)
<b>L1</b> linear PMA-PEO-PMA 1200-2800-1200	5.4	0.20	0.049	-39	150
<b>C1</b> cyclized PMA-PEO 1900-3100	2.9	0.13	0.074	-38	140
<b>L2</b> linear PMA-PEO-PMA 700-3000-700	6.7	0.44	0.040	-39	150
<b>C2</b> cyclized PMA-PEO 1300-3200	2.9	0.19	0.044	-39	140
<b>L3</b> linear PEA-PEO-PEA 800-3500-800	19	1.1	0.042	-39	190
<b>C3</b> cyclized PEA-PEO 1500-3100	11	0.77	0.067	-38	160

<sup>a</sup> $\Delta H_{mic}$  per hydrophobic unit.

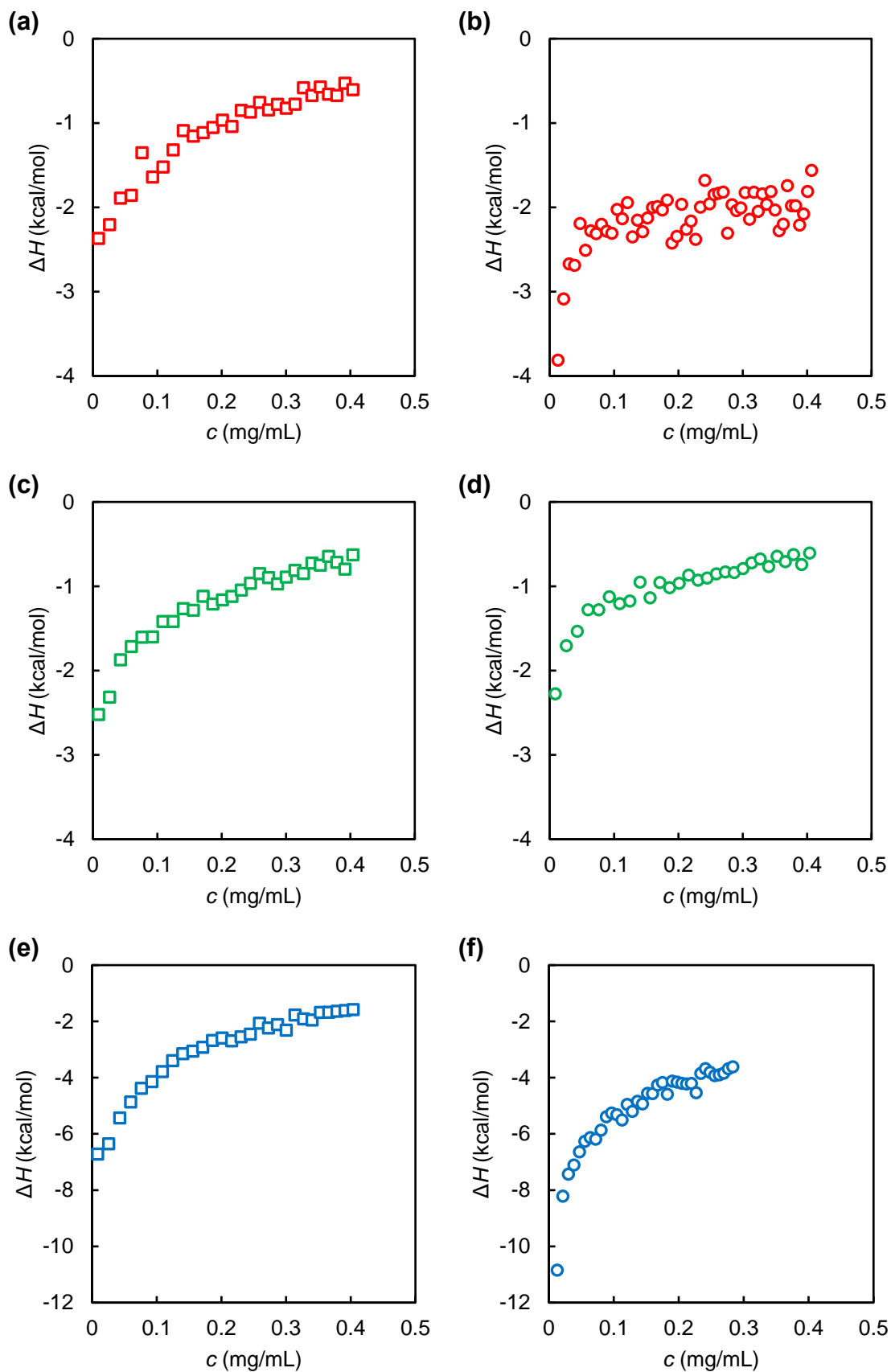
<sup>b</sup>Determined by average scattering intensity.



**Figure 1.** (a) Cyclization of linear amphiphilic block copolymers (L1, L2, and L3) to form cyclized amphiphilic block copolymers (C1, C2, and C3). Proposed unimer and micellized states of (b) L1, L2, and L3 and (c) C1, C2, and C3. The micelles from cyclized block copolymers are smaller in size and denser than those of the linear counterparts determined by SAXS.<sup>21, 22</sup>



**Figure 2.** (a) Exothermic heat released upon injection of **L3**. (b) Overall heat of reaction ( $\Delta H$ ) versus concentration of **L3**.



**Figure 3.** Overall heat of reaction ( $\Delta H$ ) versus concentration of (a) L1, (b) C1, (c) L2, (d) C2, (e) L3, and (f) C3 to determine  $\Delta H_{mic}$ .<sup>32</sup>



## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI:

Plots of average scattering intensity vs. copolymer concentration, Zimm plots, and plots of  $\Delta H_{dil}$  vs. PEO concentration (PDF)

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### Notes

The authors declare no competing financial interest.

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  32. In the present Table or Figure, the following symbols and colors are applied: square, linear copolymer; circle, cyclized copolymer; red, L1 and C1; green, L2 and C2; blue, L3 and C3.
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## TOC Graphic

