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Thermothickening in Solutions of Telechelic Associating Polymers and Cyclodextrins

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Telechelic associating polymers (hydrophilic ethoxylated backbone, hydrophobic *n*-alkyl end-groups) form viscous solutions in water due to associations between the hydrophobes. The addition of α-, β-, or γ-cyclodextrin (CD) substantially reduces the solution viscosity because the CD molecules envelop and sequester the hydrophobes in their hydrophobic cavities. The present paper explores the variation in polymer−CD solution viscosity with temperature. We find that, in the case of α-CD alone, the solutions show "thermothickening", i.e., the viscosity *increases* from 25 to ca. 60 °C whereupon it reaches a peak value and then drops. In contrast, solutions with β- and γ-CD show monotonic drops in viscosity upon heating. At a fixed polymer content, the thermothickening is higher for higher α-CD concentrations. We have also studied how surfactants and lipids impact the thermothickening. Addition of single-tailed micelle-forming surfactants causes the viscosity to revert to the more typical decreasing trend with temperature. However, addition of double-tailed lipids to a polymer/α-CD solution accentuates the thermothickening behavior. The thermothickening is explained by the propensity of α-CDs to unbind from the hydrophobes and form inclusion complexes with the polymer backbone as the temperature is raised.

1. Introduction

The term "associating polymer" generally refers to a water-soluble polymer bearing hydrophobic groups either on its ends or along the backbone.[1,2] When the hydrophobes are present on the chain ends, the structure is called telechelic.[2] An example is the hydrophobic ethoxylated urethane (HEUR) architecture, where the backbone is composed of poly(ethylene oxide) (PEO) and this is linked to hydrophobic end-caps (typically *n*-alkyl moieties) through urethane spacers (Figure 1).[2] As their name indicates, associating polymers associate in aqueous solution through their hydrophobes. This results in "flower micelles" that have a hydrophobic core surrounded by a corona of looping PEO segments.[1,2] Adjacent flower micelles also get connected through bridging PEO segments, and this leads to a transient network of such micelles.[2] In turn, the viscosity of the solution is appreciably enhanced. The ability to thicken water at low concentrations makes associating polymers the rheology modifiers of choice in a variety of applications including paints and coatings, consumer products etc.[2]

Cyclodextrins (CDs) are a class of supramolecules known for their ability to modulate hydrophobic interactions between associating polymers.[3,4] These molecules are doughnut-shaped cyclic oligomers of glucose with the inner cavity of the doughnut being hydrophobic while the exterior is hydrophilic.[3] Three types of CDs commonly occur in nature: α-, β- and γ-CD, and these correspond to six-, seven- and eight-membered glucose rings, respectively (Figure 1).[3] When CD molecules are added to an aqueous solution of associating polymers, the hydrophobic cavities of the CDs envelop and sequester the hydrophobes on the polymer chains.[4−12] The hydrophobes are thereby prevented from associating with each other, and in turn, the solution viscosity is drastically reduced. Subsequent addition of surfactants to the above solutions can restore the viscosity: this is because the surfactants compete with the polymer hydrophobes for complexation with the CDs.[7,11,12]

The focus of this paper is the effect of temperature on solution viscosity. In the case of associating polymers, the viscosity typically drops exponentially upon heating.[1,8,10] The variation of the zero-shear viscosity η_0 with temperature can then be depicted on an Arrhenius plot, which is a semilog plot of η_0 vs $1/T$, where T is the absolute temperature.[1,8] The slope of the straight line on this plot can be used to estimate the flow-activation energy E_a for the system. Mixtures of associating polymers and CDs, which tend to exhibit lower viscosities than the polymer alone, have also been studied as functions of temperature.[8,10,12] In those cases also, a further drop in viscosity or other rheological properties is generally found upon heating, and again the data follow the Arrhenius relationship (with one exception,[10] see below).

In this paper, we report that mixtures of telechelic associating polymers (HEURs) and CDs can show *increases* in viscosity upon heating over a wide range of temperatures. As discussed above, this trend is unusual in the case of associating polymers. Indeed, an increase in viscosity upon heating (also called "thermothickening" or "thermogelling") is observed in only a few classes of

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(1) Annable, T.; Buscall, R.; Ettelaie, R.; Whittlestone, D. *J. Rheol.* **1993**, *37*, 695.
(2) Winnik, M. A.; Yekta, A. *Curr. Opin. Colloid Interface Sci.* **1997**, *2*, 424.
(3) Szejtli, J. *Chem. Rev.* **1998**, *98*, 1743.
(4) Tonelli, A. E. *Polymer* **2008**, *49*, 1725.
(5) Islam, M. F.; Jenkins, R. D.; Bassett, D. R.; Lau, W.; Ou-Yang, H. D. *Macromolecules* **2000**, *33*, 2480.
(6) Karlson, L.; Thuresson, K.; Lindman, B. *Langmuir* **2002**, *18*, 9028.
(7) Abdala, A. A.; Tonelli, A. E.; Khan, S. A. *Macromolecules* **2003**, *36*, 7833.
(8) Liao, D.; Dai, S.; Tam, K. C. *Polymer* **2004**, *45*, 8339.
(9) Burckbuchler, V.; Kjoniksen, A. L.; Galant, C.; Lund, R.; Amiel, C.; Knudsen, K. D.; Nystrom, B. *Biomacromolecules* **2006**, *7*, 1871.
(10) Liao, D. S.; Dai, S.; Tam, K. C. *J. Phys. Chem. B* **2007**, *111*, 371.
(11) Talwar, S.; Harding, J.; Oleson, K. R.; Khan, S. A. *Langmuir* **2009**, *25*, 794.
(12) Liao, D. S.; Dai, S.; Tam, K. C. *J. Rheol.* **2009**, *53*, 293.

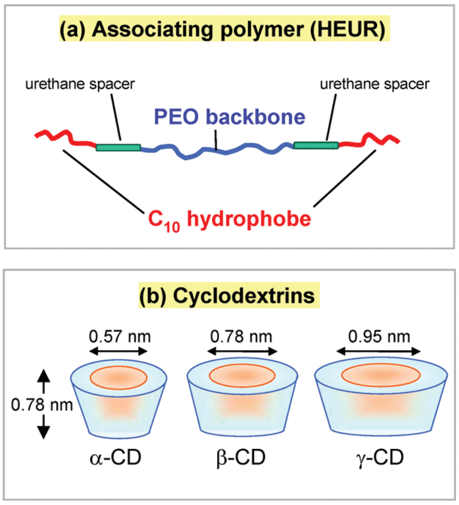

Figure 1. Schematics of (a) the RM825 associating polymer and (b) the cyclodextrins (CDs) studied.

complex fluids, whether based on polymers,[13−17] surfactants,[18,19] or other hybrid supramolecules.[20] The majority of complex, structured fluids decrease in viscosity upon heating. Thus, thermothickening in HEUR/CD fluids is definitely worthy of study. Interestingly, we observe this behavior only with α-CDs and not with *β*- and *γ*-CDs. We have also investigated the effect of amphiphiles (single-tailed surfactants and double-tailed lipids) on the thermothickening. Strikingly, we find that the addition of lipids accentuates the thermothickening behavior whereas single-tailed surfactants have the opposite effect.

To our knowledge, there is only one other study that has reported comparable results, and that is a recent one by Tam et al.[10] These authors studied mixtures of telechelic associating polymers and α-CDs and found that, depending on the concentration of α-CD, the solution viscosity either decreased monotonically with temperature or showed a modest increase over a range of temperatures. These results were explained in terms of a competition between the hydrophobic end-caps and the hydrophilic backbone of the polymer for complexation with α-CD molecules. In the present study, we explore thermothickening in HEUR/α-CD mixtures in more detail using both rheological techniques and small-angle neutron scattering (SANS). We also explain how lipids accentuate this effect by virtue of their self-assembly into vesicle structures.

2. Experimental Section

Polymers. The associating polymer (HEUR) used in most of the studies was a gift from the Rohm & Haas Co. and is denoted by RM-825. It was supplied as a purified wax and was used as received. The polymer has an overall molecular weight of about 25,000, and the hydrophobic end-caps are linear C_{10} alkyl chains. The same polymer has been employed in several previous studies in the literature.[21−23] Note that, in such samples, not all the chains (only ∼70%) are expected to have hydrophobic caps at both ends.[10,12]

In addition to RM-825, a few studies were also done with commercial associating polymers manufactured by OMG Borchers GmbH. One such polymer is denoted by BorchiGel PW25, and this was supplied as a solution of ∼25 wt % polymer in a 4:6 mixture of water:propylene glycol. The polymer was dried to constant weight in a vacuum oven for 48 h, and the resulting solid material was used for making samples. While the BorchiGel polymers are known to be HEURs, no further information on molecular weight or hydrophobe length was provided by the manufacturer.

Cyclodextrins and Amphiphiles. α-, *β*-, and *γ*-CDs (>98% purity) were purchased from TCI America. The surfactants, cetyl trimethylammonium bromide (CTAB) and sodium dodecyl sulfate (SDS) (both >99% purity), were purchased from Sigma-Aldrich. Lecithin (>98% purity) was obtained from Avanti Polar Lipids.

Sample Preparation. Ultrapure deionized water from a Millipore water-purification system was used in preparing samples for rheological characterization, while D_2O (99.95% deuteration, from Cambridge Isotopes) was used for the SANS studies. The samples without lecithin were prepared by dissolving weighed amounts of polymer, cyclodextrins and/or CTAB in water. The samples were heated to ∼65 °C under continuous stirring for about an hour until the solutions became homogeneous. Samples were then stirred continuously for one day and then left to equilibrate overnight at room temperature before any experiments were conducted. For samples containing lecithin, solutions were prepared by adding the lecithin to water and subsequently vortex mixing for 10 min. A Branson 1510 sonicator was then used for 2 h at 40 kHz to make vesicles. Weighed quantities of polymer and cyclodextrins were then added to the vesicle solutions, and the mixture was stirred for one hour using a magnetic stirrer bar at ∼65 °C. Thereafter, samples were stirred continuously overnight at room temperature to ensure that the final sample was completely homogeneous.

Rheological Studies. Steady and dynamic rheological experiments were performed on an AR2000 stress controlled rheometer (TA Instruments, Newark, DE). Samples were run on a cone-and-plate geometry (40 mm diameter, 4° cone angle) or a Couette geometry (rotor of radius 14 mm and height 42 mm, and cup of radius 15 mm). A solvent trap was used to minimize solvent evaporation. For temperature sweeps, a heating rate of 1 °C/min was used at a constant frequency of 10 s^{-1} and a strain of 1%. For experiments at distinct temperatures, the loaded sample was equilibrated for 1 h at that temperature prior to running the experiment. Dynamic frequency spectra were obtained in the linear viscoelastic regime of each sample as determined by dynamic strain-sweep experiments.

Small Angle Neutron Scattering (SANS). SANS measurements were made on the NG-7 and NG-3 (30 m) beamlines at NIST in Gaithersburg, MD. Neutrons with a wavelength of 6 Å were selected. Three sample−detector distances were used to obtain data over a range of wave vectors from 0.004 to 0.4 $Å^{-1}$. Samples were studied in 2 mm quartz cells at 25 and 50 °C. Scattering spectra were corrected and placed on an absolute scale using NIST calibration standards. The data are shown as plots of the absolute intensity I versus the wave vector $q = 4\pi \sin(\theta/2)/\lambda$, where λ is the wavelength of incident neutrons and θ the scattering angle.

3. Results and Discussion

HEUR + CD: Rheological Studies. First we present data on mixtures of a telechelic HEUR and different CDs at room temperature (25 °C). The HEUR is RM-825 with a molecular weight around 25,000 and with linear C_{10} alkyl chains as the hydrophobic end-caps.[22,23] A 5 wt % solution of RM-825 in

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[13] Kjoniksen, A. L.; Nystrom, B.; Lindman, B. *Macromolecules* **1998**, *31*, 1852.
[14] Kobayashi, K.; Huang, C. I.; Lodge, T. P. *Macromolecules* **1999**, *32*, 7070.
[15] Jeong, B.; Kibbey, M. R.; Birnbaum, J. C.; Won, Y. Y.; Gutowska, A. *Macromolecules* **2000**, *33*, 8317.
[16] Bossard, F.; Tsitsilianis, C.; Yannopoulos, S. N.; Petekidis, G.; Sfika, V. *Macromolecules* **2005**, *38*, 2883.
[17] Nair, L. S.; Starnes, T.; Ko, J. W. K.; Laurencin, C. T. *Biomacromolecules* **2007**, *8*, 3779.
[18] Kalur, G. C.; Frounfelker, B. D.; Cipriano, B. H.; Norman, A. I.; Raghavan, S. R. *Langmuir* **2005**, *21*, 10998.
[19] Davies, T. S.; Ketner, A. M.; Raghavan, S. R. *J. Am. Chem. Soc.* **2006**, *128*, 6669.
[20] Kidowaki, M.; Zhao, C. M.; Kataoka, T.; Ito, K. *Chem. Commun.* **2006**, 4102.
[21] Sadeghy, K.; James, D. F. *J. Non-Newtonian Fluid Mech.* **2000**, *90*, 127.
[22] Kamibayashi, M.; Ogura, H.; Otsubo, Y. *J. Colloid Interface Sci.* **2005**, *290*, 592.
[23] Kamibayashi, M.; Ogura, H.; Otsubo, Y. *J. Rheol.* **2006**, *50*, 1009.

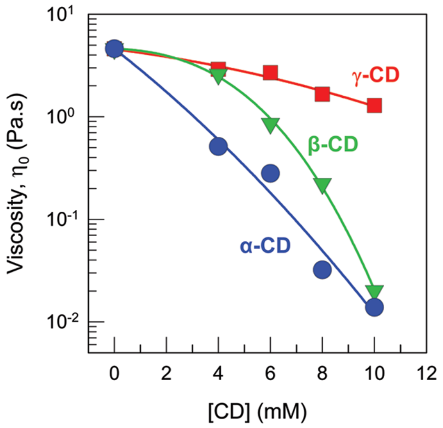

Figure 2. Zero-shear viscosity η_0 at room temperature (25 °C) for 5% RM825 + CD mixtures as a function of the CD concentration. Data are shown for α-, β-, and γ-CD. In all cases, the viscosity drops with increasing [CD].

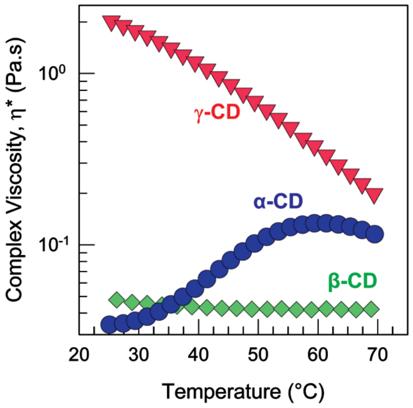

Figure 3. Viscosity as a function of temperature for solutions containing 7% RM825 and 14 mM of α-, β-, or γ-CD. The complex viscosity η^* is shown; similar results are available for the steady-shear viscosity. The viscosity decreases with temperature for the β- and γ-CD samples whereas the sample with α-CD shows an increase in viscosity with temperature (thermothickening).

deionized water showed a moderate viscosity. Under steady-shear rheology, the solution exhibited a Newtonian (shear-invariant) response with a constant viscosity of ~5 Pa·s over a range of shear-rates from 0.01 to 200 s^{-1}. The addition of all three CDs (α, β, and γ) lowered the viscosity while the response remained Newtonian. The rheology of each sample can therefore be represented by a single value of the viscosity, denoted by η_0, and this is shown in Figure 2 as a function of the CD concentration (note that the viscosity-axis is on a logarithmic scale).

Figure 2 shows that the sharpest decrease in η_0 is caused by α-CD, with η_0 dropping by a factor of about 500 on addition of 10 mM α-CD. A much smaller drop in η_0 (factor of ~5) is observed upon addition of 10 mM of γ-CD. For both α- and γ-CD, the drop in η_0 with increasing CD concentration ([CD]) is approximately exponential (straight line on the semilog plot). In the case of the β-CD, the magnitude of the viscosity drop is intermediate between that for α- and γ-CD, while the η_0 vs [CD] relationship is nonexponential. Incidentally, for all these Newtonian liquids, the viscosity η_0 under steady shear and the complex viscosity η^* under oscillatory shear are nearly identical. For experimental convenience, we prefer to focus on η^* over the rest of this paper; analogous results are available for η.

As mentioned in the Introduction, the CD-induced decrease in the room-temperature viscosity of HEUR solutions is not surprising and has been observed before by several groups.[6,8,10,12] The unusual result is that shown by Figure 3, which plots the complex viscosity η^* of RM-825/CD solutions as a function of temperature. Results are compared for three samples, each with 7% RM-825 and 14 mM each of the three different CDs. The β-CD and γ-CD samples both show a decreasing viscosity with increasing temperature, i.e., these solutions become thinner upon heating. In contrast, the combination of RM-825 and α-CD shows a significant increase in viscosity over a range of temperatures ("thermothickening"). The above behavior of HEUR/α-CD mixtures is rather unusual and is the focus of this paper.

Figure 4 further describes the temperature-dependent rheology of RM-825/α-CD solutions over a range of polymer and α-CD concentrations. First, in Figure 4a, we study solutions with varying α-CD concentrations while the RM-825 concentration is fixed at 5 wt %. For all samples, the viscosity η^* increases over a range of temperatures followed by a drop in η^* at even higher temperatures. The higher the [α-CD], the lower the η^* at room temperature; correspondingly, the greater the extent of thermothickening (defined as the ratio of peak:initial η^*). Also, the peak in η^* is reached at a lower temperature for a lower [α-CD]: e.g., the peak occurs at 45 °C for 6 mM α-CD, 55 °C for 8 mM α-CD and 62 °C for 10 mM α-CD. Next, in Figure 4b, we show data for solutions over a range of RM-825 concentrations and with the α-CD content being proportionately higher. This allows us to compare solutions with similar initial viscosities at room temperature (around 20−30 mPa·s). All samples exhibit thermothickening, with its extent being higher for higher polymer concentrations. The greatest increase in viscosity is for the 7% RM825 + 14 mM α-CD sample for which η^* increases from 33 mPa·s at 25 °C to 132 mPa·s at 62 °C, which is a net increase by a factor of 4. The peak temperature is approximately the same (~60 °C) for all these samples.

HEUR + α-CD: SANS Studies. The above data provide clear evidence for thermothickening in certain HEUR/α-CD solutions. To probe the underlying mechanism for these unusual results, we conducted SANS experiments on selected samples. Samples were made in D_2O to achieve the necessary contrast between the microstructure and the solvent; these samples were rheologically identical to those in H_2O. Figure 5 shows SANS spectra (I vs q) for four solutions, each containing 5% RM-825 and with α-CD concentrations of 3, 5, 7, and 10 mM. Data are provided at room temperature (25 °C) and at a temperature of 50 °C, with the latter corresponding to the thermothickened state. Together the data reveal a number of systematic trends. First, consider the 3 mM α-CD sample that shows negligible thermothickening: in this case, the curves at 25 and 50 °C are nearly identical. In contrast, the remaining samples, which have higher [α-CD], show increasing differences between their 25 and 50 °C spectra. The differences mainly occur at intermediate q (0.01 to 0.1 $Å^{-1}$) whereas the curves are almost identical at lower and higher q. Also, with increasing [α-CD] at a constant temperature of 25 °C, the intensity at intermediate q drops and a plateau appears, with the plateau being more pronounced at higher [α-CD]. In other words, increasing [α-CD] lowers the intensity at intermediate q whereas increasing temperature restores this intensity. An obvious interpretation would be that the drop in intensity upon addition of [α-CD] corresponds to a *suppression of hydrophobic clustering* (due to complexation of the α-CD with the hydrophobes on the ends of the HEUR chains) while the increase in intensity with temperature occurs because the *hydrophobic clusters are restored.*

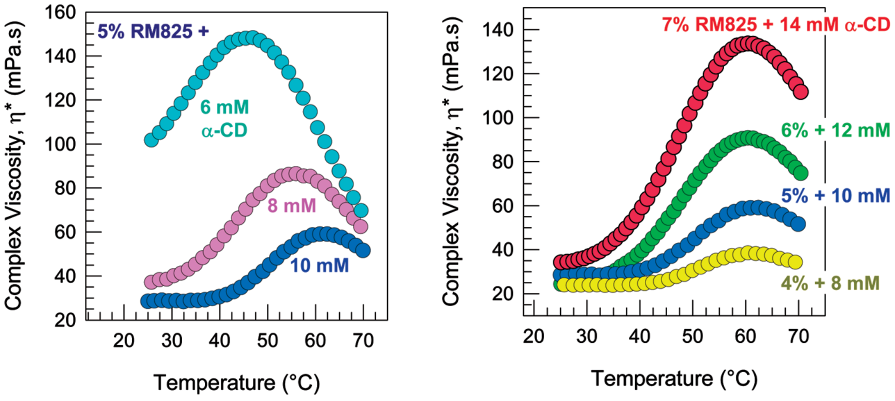

Figure 4. Thermothickening responses for different compositions of RM825 and α-CD. (a) Constant polymer concentration (5%), varying [α-CD]. (b) Different [polymer] and [α-CD] such that the solutions have approximately the same viscosity at room temperature.

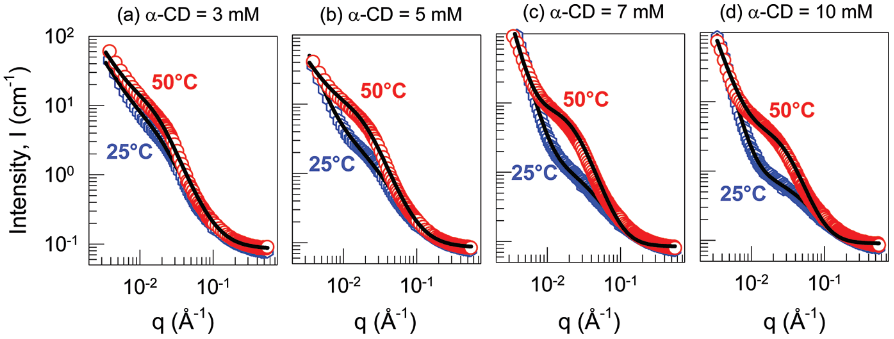

Figure 5. SANS data at low (25 °C) and high (50 °C) temperatures for solutions containing 5% RM825 and different concentrations of α-CD. The solid lines through each curve are fits to eq 1.

To obtain further insight, we modeled the SANS data using the following functional form suggested by Hammouda et al.:[24,25]

$$I(q) = \frac{A}{q^n} + \frac{B}{1+(q\xi)^m} \qquad (1)$$

Here, A and B are constants, n and m are power-law indices, and ξ is a correlation length. The model fits the curves in Figure 5 very well (fits shown as solid black lines through the data). The above model was originally developed to describe the SANS response from aqueous solutions of PEO.[24,25] More recently, it has also been applied to SANS data from mixtures of CDs with a class of associating polymers (hydrophobically modified alginate).[9] The first term in the model (A/q^n) corresponds to Porod-like scattering from large clusters while the second term is a Lorentzian function to describe scattering from individual polymer chains.[25] Thus, the first term describes features in the data at low q, specifically the upturn in intensity, which in our case occurs similarly for all samples and temperatures. It is the second Lorentzian term that accounts for the plateau at intermediate q, and the key parameter here is the correlation length ξ.

Figure 6 plots the correlation length ξ as a function of [α-CD] and for the two temperatures of 25 and 50 °C. We interpret ξ as an average size of local heterogeneities (hydrophobic clusters); thus, the larger the ξ the greater the clustering.[9,25] As expected, ξ decreases with increasing [α-CD], implying a suppression of hydrophobic clustering. This is consistent with the complexation of polymer hydrophobes by α-CD molecules. Moreover, the ξ values at 50 °C are higher than those at 25 °C for all solutions, suggesting that hydrophobe−hydrophobe interactions are reactivated by heat (which in turn implies a heat-induced weakening of hydrophobe−CD complexes). This result confirms the qualitative arguments put forward above, and we will return to this point shortly when we further discuss the mechanism for thermothickening.

HEUR + α-CD + Amphiphile: Rheological Studies. We now describe the effects of adding a surfactant or lipid to HEUR/α-CD solutions. First, we consider a typical cationic surfactant, CTAB. The term surfactant is used here to imply a *single-tailed* amphiphile that usually forms micelles in water above its critical micelle concentration (cmc). In the case of CTAB, its cmc in deionized water is 0.92 mM.[26] As shown by Figure 7, adding CTAB at a concentration above its cmc reversed the CD-induced reduction in room-temperature viscosity as well as the thermothickening. The control sample for this experiment was a mixture of 6% RM-825 and 12 mM α-CD: its η^* vs temperature data is shown for reference. Adding just 5 mM of CTAB increased the η^* at 25 °C about 100-fold and η^* decreased monotonically upon heating. Increasing the CTAB content to 20 mM further increased the η^* at 25 °C and again the η^* decreased upon heating. These results are to be expected: the added surfactant molecules should competitively bind with the α-CD, thereby liberating a large fraction of the polymer hydrophobes and restoring their associations.[7,11,12] In addition to CTAB, we have tested other surfactants, including anionic ones like sodium dodecyl sulfate (SDS), and in all cases the surfactant eliminated the thermothickening.

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(24) Hammouda, B.; Ho, D.; Kline, S. *Macromolecules* **2002**, *35*, 8578.
(25) Hammouda, B.; Ho, D. L.; Kline, S. *Macromolecules* **2004**, *37*, 6932.
(26) Brackman, J. C.; Engberts, J. *Langmuir* **1991**, *7*, 2097.

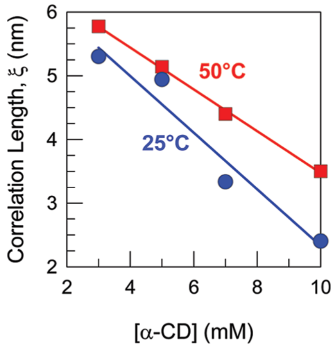

Figure 6. Correlation lengths ξ obtained from fits of eq 1 to the SANS data in Figure 5. The values are shown as functions of the α-CD concentration and for the two different temperatures. Lines through the data are guides for the eye.

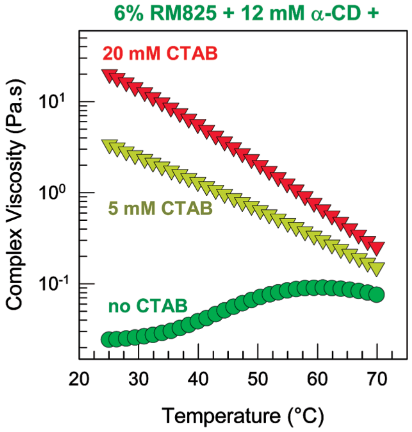

Figure 7. Viscosity vs temperature for solutions of 6% RM825 + 12 mM α-CD in the absence and presence of the cationic surfactant, CTAB. In the presence of CTAB, the response shifts from thermothickening to thermothinning.

A different result was obtained, however, upon addition of lipids to HEUR/α-CD solutions. The term lipid refers to *two-tailed* amphiphiles that assemble into vesicles (liposomes) in water. The typical lipid we have studied is lecithin, and we have used a standard procedure to make vesicles of lecithin (see Experimental Section). We then combined lecithin vesicles with the HEUR and the α-CD. The control sample again is 6% RM-825 + 12 mM α-CD, and as seen by Figure 8, it shows considerable thermothickening (factor of 3.4 increase in η^* with temperature). Adding 10 mM of lecithin vesicles to this sample has negligible effect on the room-temperature viscosity, but the thermothickening is enhanced. Further increase in lecithin concentration to 20 mM accentuates the thermothickening even more. The overall extent of thermothickening, i.e., the ratio of peak:initial η^* is by a factor of 4.6 for the 20 mM lecithin sample. Thus, the addition of lipid vesicles enhances thermothickening.

Thermothickening in solutions of HEUR polymers and α-CD is reproducible, as is the enhancement of this effect by addition of lipids. As an example of the robustness of this result, we show data for a different HEUR polymer from a different vendor. This polymer is a commercial, unpurified product from OMG Borchers GmbH and is denoted by BorchiGel PW25. Figure 9 presents rheological data for a 5% solution of this polymer combined with 10 mM of α-CD: the data again reveal substantial thermothickening. Additionally, we present data for the above sample combined with 10 mM of lecithin vesicles and once again we find that the vesicles accentuate the thermothickening. Based on these data, we can generalize the above trends to hold for a range of HEUR polymers.

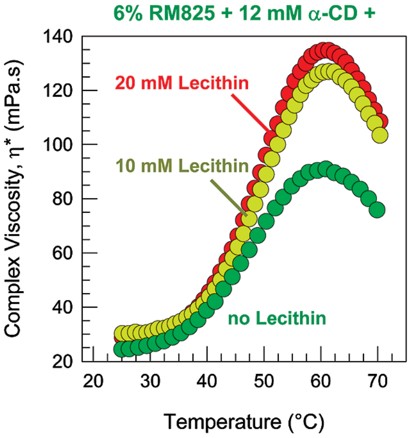

Figure 8. Viscosity vs temperature for solutions of 6% RM825 + 12 mM α-CD in the absence and presence of vesicles of the lipid, lecithin. The presence of lecithin vesicles accentuates the thermothickening response.

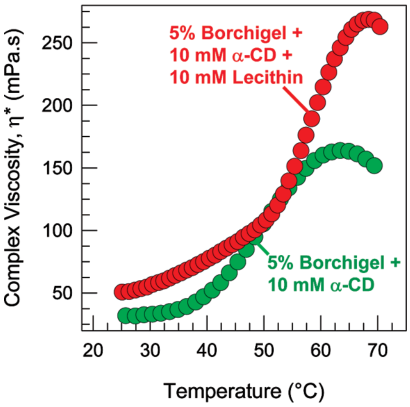

Figure 9. Viscosity vs temperature for solutions of 5% Borchigel PW25 + 10 mM α-CD in the absence and presence of 10 mM lecithin vesicles. This HEUR/α-CD mixture also shows thermothickening and lecithin vesicles again enhance the effect.

Mechanism for Thermothickening. We now attempt to provide sensible explanations for the results described above. Our first result (Figure 2) showed that the room-temperature viscosity of HEUR solutions was lowered by all three CDs. This is an expected result and is clearly due to complexation of the hydrophobes on HEUR chain ends by CD molecules. The extent of viscosity reduction follows the trend α-CD > β-CD > γ-CD (Figure 2), which is due to the size of the CD cavity relative to the size of the hydrophobic group.[4] For hydrophobes $\sim C_{10}$, as is the case here, the same trend has been observed in earlier studies as well.[4,7] Next, we come to our significant result, which is the observation of thermothickening in solutions of HEUR and α-CD, but not in solutions with β- or γ-CD (Figure 3). What causes thermothickening, and why does it occur only in the case of α-CD? We will now address these questions.

Our SANS data and its corresponding modeling (Figures 5 and 6) suggested that inclusion complexes between hydrophobes and α-CD molecules get disrupted by heat. The hydrophobes released from the α-CDs can then reassociate with each other, leading to a reactivation of hydrophobic clusters and thereby an increase in solution viscosity with temperature. But why does heat weaken hydrophobe/α-CD complexes alone and not those with β- or γ-CD?

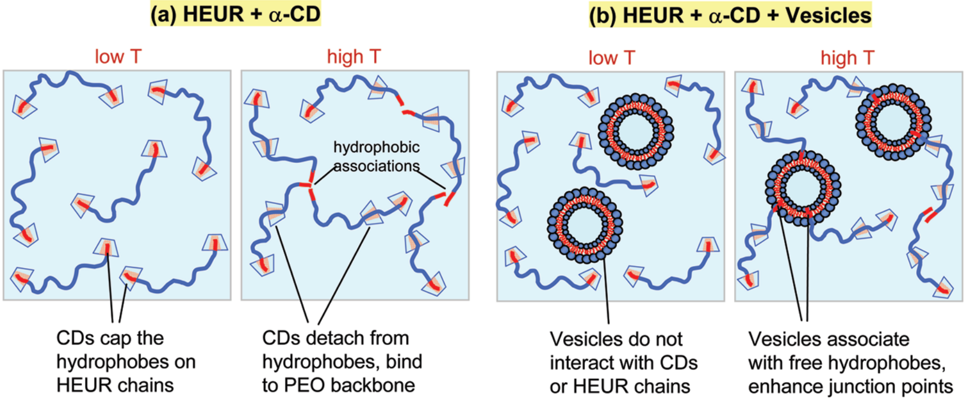

Figure 10. (a) Mechanism for thermothickening in HEUR/α-CD mixtures. At low *T*, the hydrophobes on HEUR chain ends are capped by α-CDs and the viscosity is hence low. Upon heating, some of the α-CDs detach from the hydrophobes and bind to the PEO backbone of the HEUR chains. The liberated hydrophobes associate with each other and thereby enhance the solution viscosity. (b) Mechanism for the enhancement of thermothickening by lipid vesicles. The vesicles do not bind to the α-CD and the solution has a low viscosity at low *T*. Upon heating, some hydrophobes get freed, and these can associate either with each other or with the bilayers of the vesicles. The vesicles, in effect, increase the connectivity of HEUR chains, and this further enhances the viscosity.

We believe that, at higher temperatures, the PEO *backbone* of the HEUR chains *competes* with the hydrophobic chain ends for forming inclusion complexes with α-CDs.[10] Complex formation between PEO and α-CD has been corroborated by a number of studies.[27−29] In contrast, β- and γ-CDs do not complex with PEO because their cavities are considerably larger than the cross-section of a PEO chain.[29] Complexation between PEO and α-CD is itself likely to be promoted at higher temperatures because the PEO backbone becomes more hydrophobic[24,25] and thereby more compatible with the hydrophobic cavity of the α-CD.

Taken together, we explain thermothickening by the schematic in Figure 10a. At low temperatures, the α-CD is bound to the hydrophobes on HEUR chain ends and the viscosity is low. At higher temperatures, some of the α-CDs will unbind from the hydrophobes and thread onto the PEO backbone of the HEUR chains. (Note: as stated in the Experimental Section, some HEUR chains will only have one end capped with the urethane spacer and hydrophobe. It is possible that the α-CDs preferentially thread onto the PEO backbone of these chains.) The unbinding of α-CDs will allow those liberated hydrophobes to associate with each other and thereby cause an increase in viscosity. This scenario continues up to the peak temperature. At even higher temperatures, the competing effect of thermal energy in terms of disrupting hydrophobic associations becomes dominant: i.e., more associations are broken than are formed. This explains why the viscosity attains a peak and thereafter decreases.

It is worth noting that the binding of α-CD with the polymer backbone occurs only in the case of PEO.[28] Other associating polymers such as hydrophobically modified derivatives of chitosan, alginate or hydroxyethyl cellulose (HEC), as well as hydrophobic alkali-soluble emulsion polymers (HASE) do not have backbones that can complex with α-CD;[7] as a result, no evidence for thermothickening has been reported in past studies (or detected in our laboratory) for mixtures of the above polymers with α-CD.

Next, we discuss why double-tailed lipids accentuate the thermothickening of HEUR/α-CD mixtures (Figure 8) whereas single-tailed surfactants revert the viscosity to the typical thermothinning trend (Figure 7). First, consider single-tailed surfactants. These are known to have high affinities for CDs: for example, the binding constants for CTAB and SDS with α-CD are 99,200 and 21,000 M^{-1} respectively.[30,31] These surfactants can therefore effectively displace polymer hydrophobes from the cavities of α-CD molecules. The liberated hydrophobes will then associate and give rise to a high solution viscosity at room temperature. As temperature is raised, the progressive disruption of hydrophobic associations leads to thermothinning, much like for neat HEUR solutions. In contrast to surfactants, the binding constants of lipids with CDs are very low, i.e., they have weak affinities for CDs. For example, a lipid with two C_7 tails is reported to have binding constants of 550, 1290, and 750 M^{-1} for α-, β-, and γ-CDs respectively.[32] The weaker binding of lipids is because the CDs can typically include only one alkyl chain in their cavities.[32] This explains why the HEUR/α-CD solution retains its low viscosity upon addition of lecithin, i.e., the hydrophobes remain bound to the α-CDs. In turn, the added lecithin will remain in solution in the form of nanosized unilamellar vesicles (Figure 10b).

Now, consider the effect of heating a lecithin/HEUR/α-CD mixture. As discussed above, the α-CD will tend to dissociate from the hydrophobes and instead bind to the PEO backbone of the HEUR. This will liberate several polymer hydrophobes, which will now be free to interact among each other as well as with the unilamellar lecithin vesicles. We hypothesize that some polymer hydrophobes will get embedded in the bilayers of vesicles (Figure 10b).[33−35] This will enhance the “cross-links” or junction points between the polymer chains, in turn enhancing the thermothickening effect. Support for this hypothesis comes from a number of studies on mixtures of associative polymers and vesicles, which have shown viscosity enhancement due to vesicles.[33−35] In this context, a higher volume fraction of vesicles will provide more junction points and will thereby permit a higher viscosity to be reached, which is quite consistent with the data in Figure 8.

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(27) Harada, A.; Kamachi, M. *Macromolecules* **1990**, *23*, 2821.
(28) Harada, A.; Li, J.; Kamachi, M. *Macromolecules* **1993**, *26*, 5698.
(29) Harada, A.; Takashima, Y.; Yamaguchi, H. *Chem. Soc. Rev.* **2009**, *38*, 875.
(30) Mwakibete, H.; Cristantino, R.; Bloor, D. M.; Wynjones, E.; Holzwarth, J. F. *Langmuir* **1995**, *11*, 57.
(31) Tsianou, M.; Alexandridis, P. *Langmuir* **1999**, *15*, 8105.
(32) Funasaki, N.; Ishikawa, S.; Neya, S. *Langmuir* **2002**, *18*, 1786.
(33) Meier, W.; Hotz, J.; GuntherAusborn, S. *Langmuir* **1996**, *12*, 5028.
(34) Ashbaugh, H. S.; Boon, K.; Prud’homme, R. K. *Colloid Polym. Sci.* **2002**, *280*, 783.
(35) Lee, J. H.; Gustin, J. P.; Chen, T. H.; Payne, G. F.; Raghavan, S. R. *Langmuir* **2005**, *21*, 26.

4. Conclusions

Aqueous mixtures of HEUR type associating polymers and α-CDs show thermothickening, i.e., an increase in viscosity with temperature. The solutions have a low viscosity at room temperature because the hydrophobic end-groups on HEUR chains are sequestered inside the cavities of the α-CDs. As temperature is increased, the increasing affinity of the α-CDs for the PEO backbone of the HEUR causes some of the hydrophobes to be liberated, and the association of these hydrophobes causes thermothickening. The effect is not observed with β- and γ-CDs because they do not form inclusion complexes with PEO. Thermothickening of HEUR/α-CD mixtures is accentuated by the addition of lipid vesicles. Lipids (two-tailed amphiphiles) do not bind with α-CD since the cavity in α-CD can accommodate only one hydrophobic tail. As a result, at room temperature, the α-CDs remain bound to the polymer hydrophobes, while the lipid vesicles are also left intact in solution. Upon heating, some of the polymer hydrophobes disengage from the α-CD as explained above. These free hydrophobes can either connect with each other or bind to vesicle bilayers. In effect, the vesicles enhance the connectivity of the hydrophobes, which explains why the thermothickening effect is enhanced.

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