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ARTICLE *in* JOURNAL OF THE AMERICAN CHEMICAL SOCIETY · OCTOBER 2008

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Influence of Selectivity on the Supramolecular Polymerization of AB-Type Polymers Capable of Both A·A and A·B Interactions

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Abstract: The supramolecular polymerization of two AB-type monomers capable of hydrogen-bond-mediated A·B heterocoupling and A·A homocoupling is discussed. The AB-type supramolecular polymerization is based on the strong interaction between self-dimerizing 2-ureido-pyrimidinone (UPy) and 2,7-diamido-1,8-naphthyridine (NaPy). In an effort to reduce the "self-stoppered" effect that is inherently present in these supramolecular polymerizations we used a novel ureido-pyrimidinone substituted with a dibutylamino group at the pyrimidinone ring. As a result of the substitution, the dimerization constant of the novel UPy unit is lowered compared to the previous UPy unit while the heterodimerization strength is retained. Unexpectedly, the increased selectivity toward heteroassociation not only influences the concentration-dependent degree of polymerization due to reduction of the "self-stoppered" effect but also has a pronounced effect on the ring-chain equilibrium by increasing the tendency to cyclize. In order to quantitatively explain our results, a model was developed that accurately predicts the degree of polymerization by taking into account homo- and heterodimerization as well as cyclization. Finally, molecular weight distributions for noncyclizing AB supramolecular polymerizations with and without a reversible A·A interaction are calculated. It is found that the molecular weight distribution becomes narrower when A·A interactions are present.

1. Introduction

Combination of supramolecular chemistry and polymer science has led to development of supramolecular polymers in which the individual monomeric units are held together by strong, directional, and reversible noncovalent interactions.[1] Arrays of hydrogen bonds, being inherently dynamic and displaying tunable association strengths, constitute an important building block for supramolecular polymer-based materials.[2] The majority of supramolecular polymers has been constructed using a mixture of AA and BB ditopic molecules with complementary hydrogen-bonding functionalities.[3] In such systems, high molecular weight polymer is only obtained at the exact equivalence point ($c_{AA} = c_{BB}$) because a stoichiometric imbalance rapidly leads to a diminished degree of polymerization.[3a] In an attempt to avoid the need for stoichiometric balance we[4] and others[5] employed AA and BB ditopic monomers in which both A·A homodimerization and A·B heteroassociation can occur. For construction of the A·A interaction we made use of the very strong self-complementary quadruple hydrogen-bonding array based on the 2-ureido-4[1*H*]-pyrimidinone (UPy; $K_{dim} = 6 \times 10^7$ M^{-1} in $CHCl_3$) motif.[6] Conveniently, the UPy unit is able to selectively form strong heterodimers with 2,7-diamido-1,8-naphthyridine (UPy·NaPy, A·B interaction, $K_a = 6 \times 10^6$ M^{-1} in $CHCl_3$) in one of its tautomeric forms through a hydrogen-bonding acceptor−donor−donor−acceptor (**ADDA**) array (Scheme 1).[7] The dual complexation modes of UPy result in a concentration-dependent selectivity favoring UPy·NaPy het-

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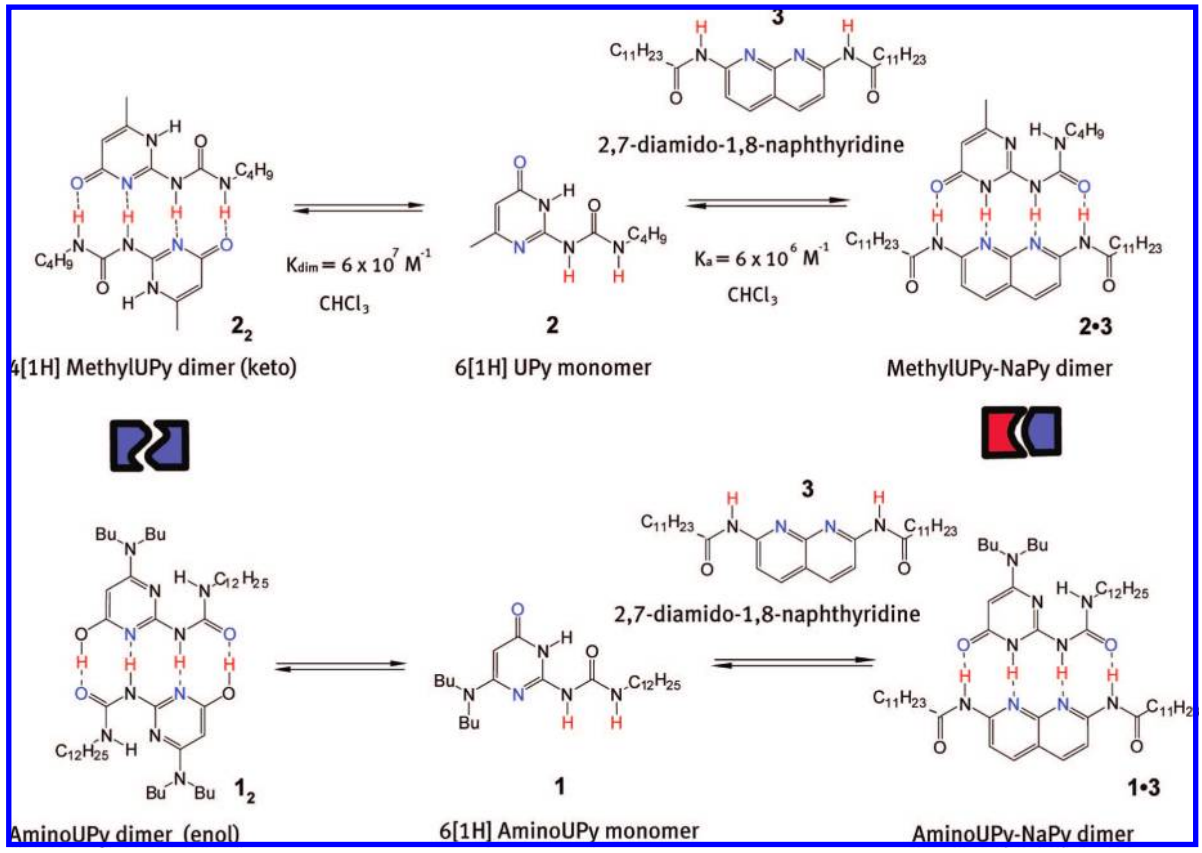
Scheme 1. Equilibrium between Methyl-Substituted UPy Dimer ($\mathbf{2}_2$) (Donor−Donor−Acceptor−Acceptor Hydrogen-Bonding Array) and 2,7-Diamido-1,8-naphthyridine (**3**) (top) and Equilibrium between Dibutylamino-Substituted UPy Dimer ($\mathbf{1}_2$) (Donor−Acceptor−Donor−Acceptor Hydrogen-Bonding Array) and 2,7-Diamido-1,8-naphthyridine (bottom)



erocomplexation over UPy homodimerization by a factor of >20:1 above a concentration of 0.1 M. Using this approach, high degrees of polymerization were obtained using mixtures of AA and BB ditopic monomers if $c_{AA} > c_{BB}$, while chain shortening occurs if $c_{AA} < c_{BB}$ because the excess of B units acts as a chain stopper.

An alternative way to address the problem of stoichiometric imbalance in supramolecular polymerizations is use of an AB-type monomer.[8] Recently an AB-type monomer was synthesized based on the UPy•NaPy motif using selective olefin-metathesis chemistry.[9] Concentration-dependent ^{1}H NMR and viscosity measurements indicated a transition from cyclic species at low concentrations to linear species at high concentrations.

Macrocyclization reactions play a fundamental role in covalent polymerizations in which they occur under both kinetic[10] as well as thermodynamic control.[11,12] In contrast to covalent polymerizations, macrocyclization reactions in noncovalent (supramolecular) polymerizations mostly occur under thermodynamic control. Theoretical distributions of cyclic and linear products in thermodynamically controlled macrocyclizations have been described by Jacobson and Stockmayer (JS),[13] who pointed out the existence of a critical concentration below which the system is composed of cyclic products only. This model was later extended by Flory[14] into a more realistic model, which also included end-to-end conformation effects. Successively, one of us (G.E.) remarked that the phenomenon of the critical concentration is not a universal feature of ring-chain equilibria because to manifest itself it requires a very large intermolecular association constant, say, larger than $10^5\ M^{-1}$.[15] Indeed, we have shown the existence of a critical concentration in solutions of bifunctional UPy derivatives indicating that the intermolecular association constant ($6 \times 10^7\ M^{-1}$) is sufficiently high.[16] Furthermore, the critical concentration in bifunctional UPy

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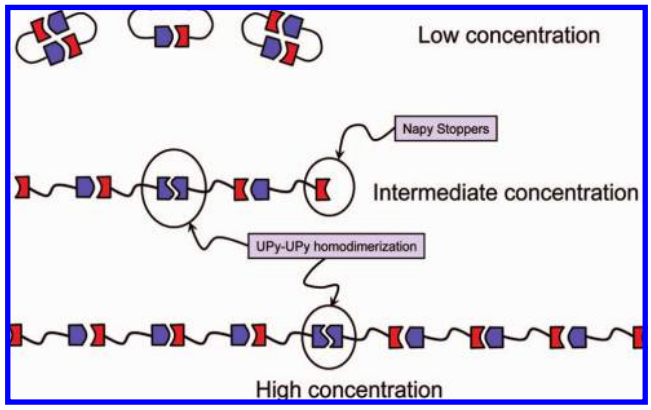
Scheme 2. Schematic Representation of the Supramolecular Polymerization of an UPy·NaPy AB-Type Monomer in Solution at Various Concentrations Illustrating the "Self-Stoppered" Effect[a]



[a] Due to the high dimerization constant of the methyl-substituted UPy unit a significant amount of chains containing free NaPy end groups are formed which limits the degree of polymerization.

derivatives could be readily controlled by proper conformational preorganization of the spacer unit.[17]

In supramolecular polymers based on the current UPy·NaPy system a major drawback is the incomplete selectivity of 2-ureido-4[1*H*]-pyrimidinone dimerization relative to association of 2-ureido-6[1*H*]-pyrimidinone with 2,7-diamido-1,8-naphthyridine because it results in self-stoppered[4,9] behavior in both AB and A_2-B_2 supramolecular polymerizations. The self-stoppered behavior in supramolecular AB polymerizations using the current UPy·NaPy system is a result of formation of free NaPy end groups (Scheme 2) due to formation of UPy·UPy bonds even at high concentrations. As the NaPy end groups hardly self-dimerize ($K_{dim} < 10\ M^{-1}$ in $CDCl_3$), chain growth is effectively limited at high concentrations.[28]

An approach to reduce the self-stoppered effect in A_2-B_2 supramolecular polymerizations introduced by Zimmerman is use of a guanosine urea derivative (UG) which only weakly self-associates ($K_{dim} = 200\ M^{-1}$) but has a high association constant with 2,7-diamido-1,8-naphthyridine ($\sim 5 \times 10^7\ M^{-1}$).[5,18] Recently, we have shown that dibutylamino-substituted UPy **1** (Scheme 1) also is able to form a stable heterocomplex with 2,7-diamido-1,8-naphthyridine.[19] Using a combination of X-ray crystallography, NOESY experiments, and FT-IR spectroscopy the existence of an **DADA** array of **1** in its pyrimidin-4-ol tautomeric form was verified both in solution (toluene-d_8 and $CDCl_3$) and in the solid state. Recent DFT calculations at the B3LYP/6-311++G(d,p) level have shown that the **DADA** hydrogen-bonding array is less stable than a **DDAA** hydrogen-bonding array.[20] This reduction in self-dimerization is caused by the fact that the individual hydrogen bonds in a **DADA** hydrogen-bonding array cannot simultaneously adopt their optimal geometrical arrangements. If the association constant of **1** with 2,7-diamido-1,8-naphthyridine (**3**) is comparable to the association constant of methyl-substituted UPy **2** (**DDAA** hydrogen-bonding array, $K_a = 6 \times 10^6\ M^{-1}$), the selectivity of heterocomplex formation will be increased due to the lower K_{dim} of $\mathbf{1}_2$. For an AB-type polymerization with both A·A homo- and A·B heterocoupling, the increased fidelity of heterocomplex formation will reduce the "self-stoppered" effect, thereby increasing the degree of polymerization.

In the first part of the paper the dimerization constant of $\mathbf{1}_2$ is investigated using the concentration-dependent excimer fluorescence of a pyrene-substituted derivative of **1**, while in the second part of the paper the supramolecular polymerization of two different AB monomers is studied using capillary viscometry, diffusion-ordered spectroscopy, and ^{1}H NMR spectroscopy. In the last part of the paper a theoretical model is presented that accurately explains the observed differences in the behavior of the two AB monomers as a function of concentration. Finally, we use our theoretical model to predict the polydispersity index at equilibrium for supramolecular polymers containing groups that can form reversible A·A and A·B interactions.

2. Results and Discussion

2.1. Dimerization Constant of Dibutylamino UPy Derivative and Association Constant with 2,7-Diamido-1,8-naphthyridine. Molecules **1**−**4** were synthesized following established routes (for details, see Supporting Information). The ^{1}H NMR spectrum of **1** (Scheme 1) in $CDCl_3$ at a concentration of 10 mM clearly shows three sharp resonances in the downfield region of the spectrum (12.60, 11.22, and 9.58 ppm) indicative of extensive hydrogen bonding. Dilution to a final concentration of 0.1 mM did not result in the appearance of new signals nor did any significant shift occur. Under the assumption that at least 10% dissociation is required to be observable at this concentration, a lower limit on the dimerization constant can be placed: $K_{dim} > 4.5 \times 10^5\ M^{-1}$. To more accurately establish the dimerization constant of dibutylamino-substituted 2-ureido-pyrimidinols, pyrene-labeled compound **4** was synthesized and studied by fluorescence spectroscopy. Pyrene is highly fluorescent and known to form an excimer species in solution with a fluorescence band well separated from the monomer fluorescence. By attachment of the pyrene probe to the ureido-pyrimidinol part excimer species within the dimerized complex can be followed as a function of concentration.[21] This method has been previously used to find accurate values of the dimerization strength of methyl-substituted 2-ureido-pyrimidinones,[6b] ureidodeazapterin,[22] and more recently to probe the dimerization constant of α,γ-cyclic peptides.[23] As a control experiment, a fluorescence spectrum was obtained at a concentration of 10^{-6} M **4** in the presence of a 1000-fold excess of nonpyrene-functionalized $\mathbf{1}_2$. The fluorescence spectrum did not show any emission bands corresponding to excimer or exciplex, indicating that intramolecular exciplex formation with the dibutylamino groups does not occur. The dimerization constant (K_{dim}) of $\mathbf{4}_2$ obtained from a freshly opened bottle ([water] = 10 mM) of $CHCl_3$ was determined to be 9 (±2) × $10^5\ M^{-1}$ (Figure 1), a value roughly 70 times lower than the value reported for the K_{dim} of UPy dimer $\mathbf{2}_2$.

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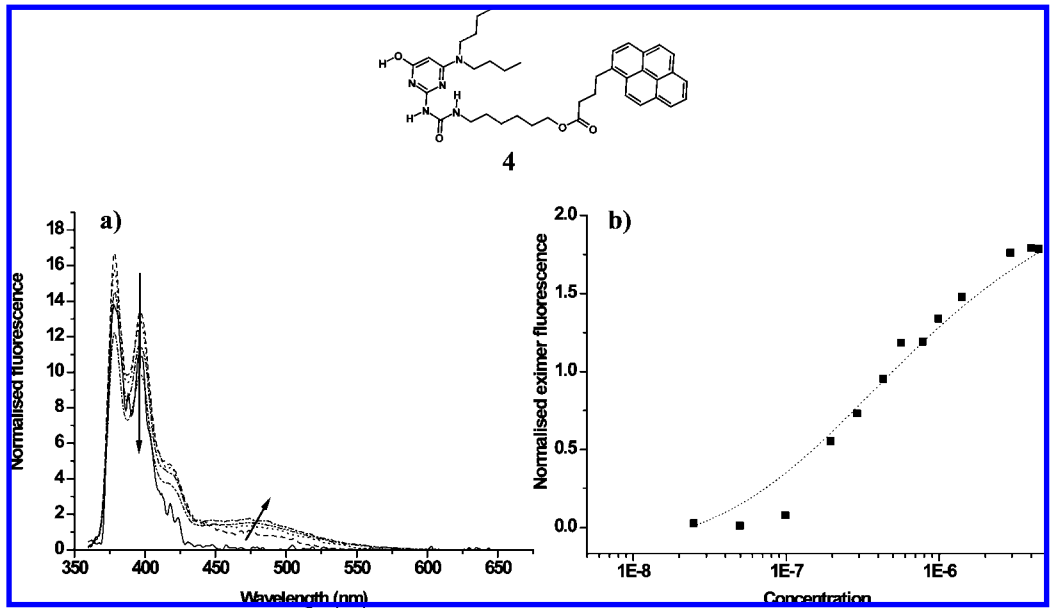

Figure 1. (a) Normalized excimer fluorescence (defined as the integrated intensity divided by the concentration of **4**) at several concentrations of **4** in $CHCl_3$. The arrow indicates an increase in concentration of **4** and hence an increase in intradimer excimer species. (b) Plot of the normalized excimer fluorescence as a function of concentration. The dashed line represents the best-fit ($R^2 = 0.98$) value of K_{dim} using a monomer−dimer binding isotherm.

The difference in the dimerization constant between $\mathbf{4_2}$ and a pyrene derivative of **2** is mainly caused by the greater number of repulsive secondary interactions in **DADA** dimers compared to **DDAA** dimers.[24] Using a recently published empirical model[25] a K_{dim} value of 1×10^6 M^{-1} was calculated for $\mathbf{4_2}$, in close agreement[26] with the experimentally determined value.

In order to determine the association constant of $\mathbf{1}_2$ with NaPy **3**, UV-spectrophotometric titrations were employed. Upon addition of $\mathbf{1}_2$ to a solution of NaPy **3** (2.5×10^{-5} M) in $CHCl_3$ the absorption intensity at 355 nm increased. A similar red shift upon formation of a hydrogen-bonded anthyridine-based **DDD-AAA** dimer has been recently reported by Leigh[27] and co-workers. The absorbance at 355 nm as a function of added **1** could be fit with a 1:1 binding model accompanied by dimerization of one of the components. Assuming a K_{dim} of 9×10^5 M^{-1} the association constant (K_a) of the UPy·NaPy heterodimer (as well as the extinction coefficient at the absorption maximum (ε_{nu})) was obtained.[19] Curve fitting gave a K_a of **1·3** of 6 ($\pm$0.5) $\times$ 10^6 M^{-1} in $CHCl_3$, a value close to the K_a of **2·3** (5 ($\pm$0.6) $\times$ 10^6 M^{-1}). To investigate the influence of the lowered K_{dim} of $\mathbf{1_2}$ on the fidelity of UPy·NaPy complex formation, the fraction of **1·3** in a 1:1 mixture was measured with ^{1}H NMR at several concentrations and compared with the concentration-dependent formation of **2·3**. As can be readily observed from Figure 2, the fraction of **1·3** at lower concentration is higher than the fraction of **2·3**, indicating that heteroassociation of $\mathbf{1}_2$ with **3** is more selective than heteroassociation of $\mathbf{2}_2$ with **3**. The calculated values, based on the experimentally determined values of K_{dim} and K_a, correspond well with the measured fractions as determined by ^{1}H NMR.

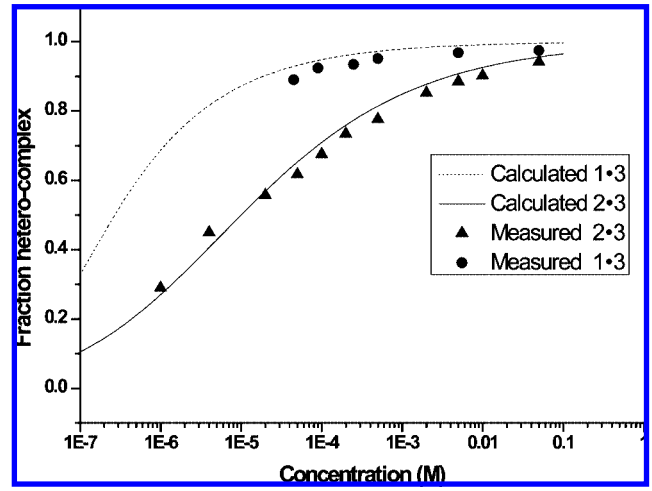

Figure 2. Measured value of the fraction of UPy·NaPy complex in a 1:1 mixture for **1·3** and **2·3**. Lines are calculated values from experimentally determined K_a and K_{dim} values.

2.2. Capillary Viscosity Measurements on AB Monomers. To investigate the influence of the increased fidelity on the supramolecular polymerization of an AB monomer in solution, two different AB monomers (**5** and **6**, see Figure 3) were synthesized (see Supporting Information). The two AB monomers differ in the nature of the UPy end groups but have the same NaPy unit incorporated. AB monomer **5** has a methyl-substituted UPy end group for which K_{dim} was previously determined to be 6×10^7 M^{-1} in $CHCl_3$. The second AB monomer **6** has a dibutylamino-substituted UPy end group with a K_{dim} of 9×10^5 M^{-1}. To ensure a fair comparison between the two different AB monomers it is of crucial importance to include the same linker between the hydrogen-bonding groups because conformational constraints in the linker can influence the equilibrium between cycles and linear species.[17]

A double-logarithmic plot of specific viscosity (η_{sp}) versus concentration of **5** and **6** in $CHCl_3$ yields a linear relationship well above the critical polymerization concentration (CPC).[15] The CPC

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(26) Because the model does not specifically consider OH···O hydrogen bonds the two OH···O hydrogen bonds in **1** were treated as NH···O hydrogen bonds.
(27) Djurdjevic, S.; Leigh, D. A.; McNab, H.; Parsons, S; Teobaldi, G.; Zerbetto, F. *J. Am. Chem. Soc.* **2007**, *129*, 476.

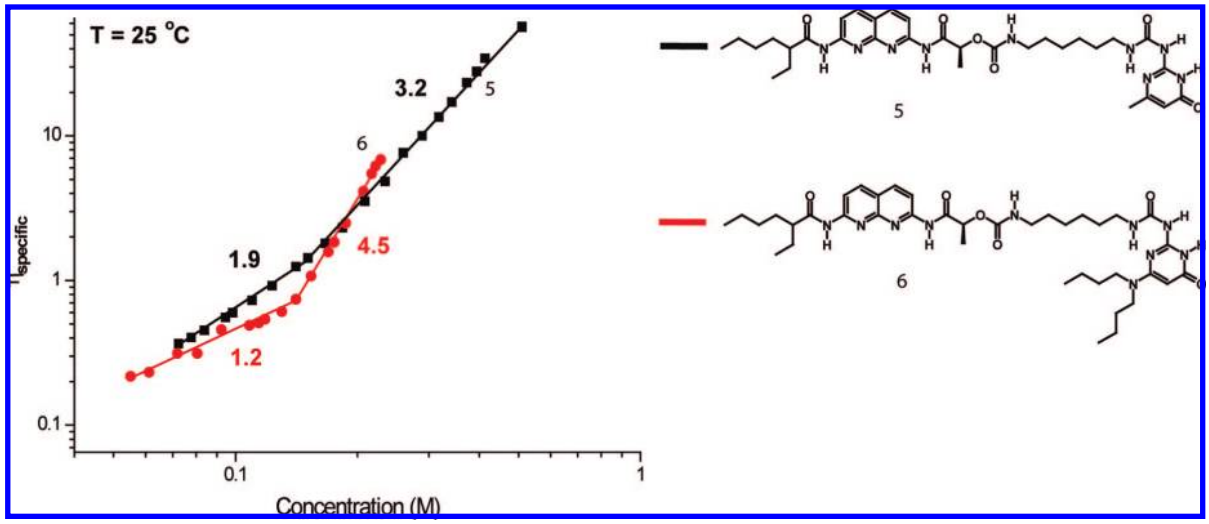


Figure 3. Solution viscosities of UPy·NaPy monomers **5** and **6** in $CHCl_3$ at 25 °C.

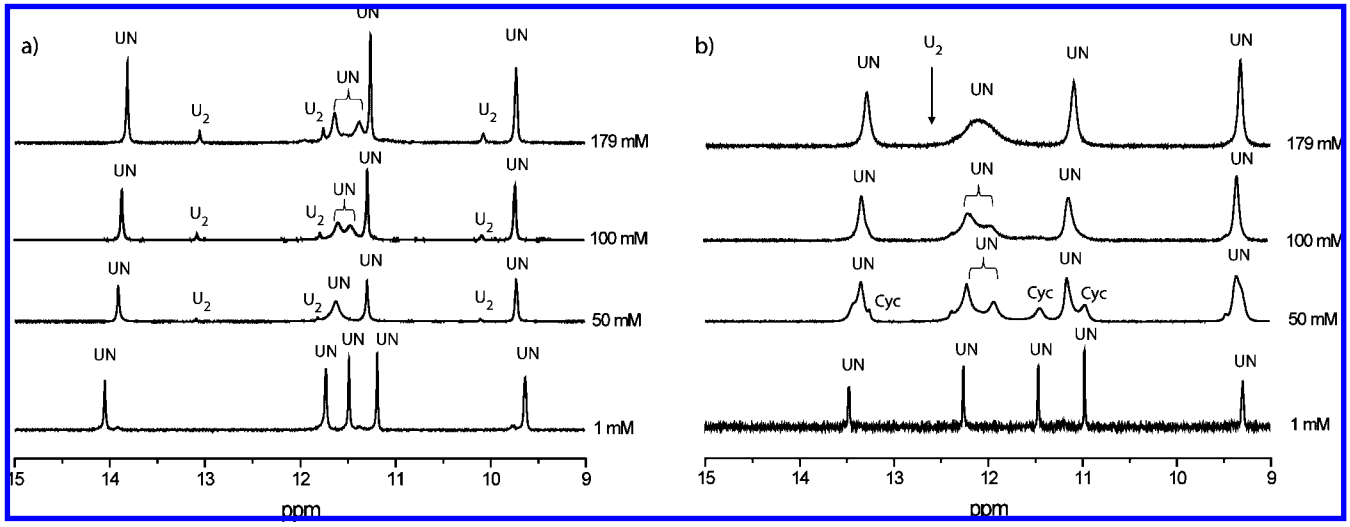


Figure 4. Partial ^{1}H NMR spectra of AB monomers at different concentrations in $CDCl_3$. (a) Methyl-substituted UPy·NaPy monomer **5**. (b) Dibutylamino-substituted UPy·NaPy monomer **6**. The abbreviations UN, U_2, and Cyc are used to denote signals arising from UPy·NaPy heterocomplex, UPy homodimer, and cyclic material, respectively. At the lowest concentration (1 mM) all monomers in solutions of **5** and **6** in $CDCl_3$ are incorporated in cycles.

for monomer **6** has a value of ~0.13 M in $CHCl_3$ as evidenced by the clear change of slope occurring at this concentration. In the case of monomer **5**, the change of slope is less sharp but approximately occurs in the same concentration region.

Surprisingly, up to concentrations well above the CPC the specific viscosity of **5** is higher than the specific viscosity of **6**. Hence, in this concentration region the system with the lowest selectivity displays the strongest effects of supramolecular polymerization. Only at concentrations above 0.2 M, the specific viscosity of **6** surpasses that of **5**. Furthermore, the slope of **6** above the CPC is higher than the slope of **5**, indicating a stronger concentration dependence of supramolecular polymerization of **6**. The lower specific viscosity of **6** just around the CPC and the higher slope above the CPC suggests that cycles are more abundant in solutions of **6** than in solutions of **5**. To find more evidence for this hypothesis we performed ^{1}H NMR dilution experiments and diffusion-ordered spectroscopy (DOSY) to probe the nature and sizes of the aggregates in solutions of **5** and **6** in $CDCl_3$ at various concentrations.

2.3. ^{1}H NMR and DOSY Measurements. ^{1}H NMR spectra at several concentrations of **5** and **6** were taken in $CDCl_3$. Figure 4 displays the partial ^{1}H NMR of **5** and **6** in the region where the hydrogen-bonding NH protons resonate. At low concentrations of **5** and **6** (1 mM) the downfield region clearly shows five sharp resonances, indicative of the five hydrogen bonds (four intermolecular and one intramolecular) being present in the UPy·NaPy **ADDA·DAAD** hydrogen-bonded complex. At higher concentrations of **5** (>50 mM, Figure 4a), additional signals corresponding to the hydrogen-bonding **DDAA** array (UPy·UPy dimer) are observed. Previously, the increase in fraction of UPy·UPy homodimer to UPy·NaPy heterodimer for a similar molecule was attributed to ring opening of small cyclic species at higher concentrations.[9] A further increase in the concentration of **5** only results in changes in the signals corresponding to the two naphthyridine amide protons (11.4 and 11.8 ppm) due to a concomitant change in exchange dynamics between homo- and hetero-hydrogen-bonding complexes at higher concentrations.

Due to the increased selectivity for heterocomplexation, no signals corresponding to dibutylamino-substituted UPy homodimer were detected at any concentration of **6** in $CDCl_3$.[29] At a concentration of 50 mM **6** in $CDCl_3$ (Figure 4b) the downfield region of the ^{1}H NMR spectrum displayed a large

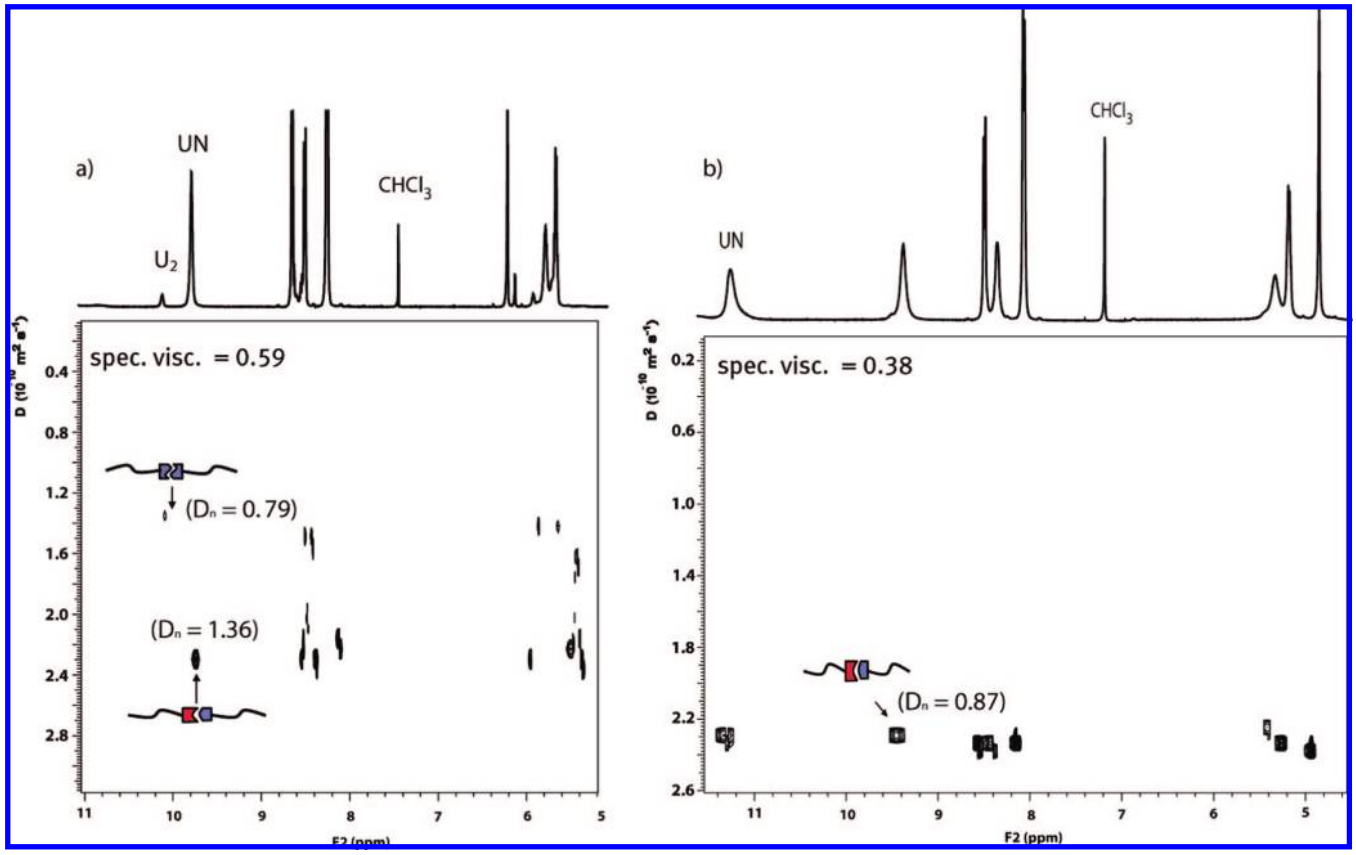


Figure 5. 2D-DOSY spectra at a concentration of 100 mM in $CDCl_3$ (T = 25 °C). (a) Methyl-substituted UPy·NaPy monomer **5**. (b) Dibutylamino-substituted UPy·NaPy monomer **6**. The values in parentheses are the viscosity-normalized diffusion constants.[33]

number of resonances, most probably originating from cyclic species. A further increase in concentration of **6** up to 179 mM resulted in four broad NH resonances due to the fast exchange of the two nonequivalent naphthyridine amide protons at high concentrations. This fast exchange results in a broad NH resonance centered at 12.0 ppm.

Diffusion-ordered ^{1}H NMR spectroscopy (DOSY) is a convenient method to probe the dimensions of polydisperse supramolecular aggregates provided that the chemical shifts of the different aggregates are in slow exchange both on the ^{1}H NMR as well as on the DOSY time scale.[30] The 2D DOSY spectrum of **5** at a concentration of 100 mM displays two sets of signals with different diffusion coefficients (Figure 5a). The diffusion coefficient of the signals originating from UPy·UPy homodimers is smaller than the diffusion constant of the UPy·NaPy, indicating that the UPy·UPy homodimers are part, on average, of an aggregate with a larger hydrodynamic radius. Because of the absence of signals belonging to UPy·UPy homodimer, all proton signals in the 2D DOSY spectrum of **6** (Figure 5b) have the same diffusion constant. Although accurate calculations on the sizes of the different aggregates are difficult to make due to the possibility of fast exchange on the DOSY time scale,[30e] the fact that the signals belonging to the UPy·UPy hydrogen bonds in **5** have a lower diffusion constant than the signals belonging to the UPy·NaPy hydrogen bonds is strong evidence that at this concentration cycle formation plays a dominant role (vide infra).

2.4. Theoretical Model and Simulations. Scheme 3 schematically displays the supramolecular polymerization of an AB monomer in solution capable of both reversible A·B heterocoupling (equilibrium constant K_a) and A·A homocoupling (equilibrium constant K_{dim}). Two different linear species can be formed: an *i*-meric linear chain with two NaPy chains ends and containing one reversible A·A (UPy·UPy) bond (chains M_i) and an *i*-meric linear chain with both a UPy (A) and a NaPy (B) chain end and containing only reversible A·B (UPy·NaPy) bonds (chains L_i). Due to the high association constant of heterobond formation (K_a) and the low dimerization constant of the NaPy chain ends,[28] only the linear chains with both an UPy and a NaPy chain end (L_i) are in direct equilibrium with cyclic species (equilibrium constant $K_{(intra)i}$). This model for the supramolecular polymerization of **5** and **6** in solution allows us to explain the lower diffusion constant of the UPy·UPy signals as measured with DOSY on the 100 mM solution of **5** in $CDCl_3$. At this concentration below the CPC the chains containing a single UPy·UPy bond (M_i-type chains) cannot

(28) Previously, the dimerization constant of 2,7-diamido-1,8-naphthyridine was determined to be <10 M^{-1} in $CDCl_3$, see: Corbin, P. S.; Zimmerman, S. C.; Thiessen, P. A.; Hawryluk, N. A.; Murray, T. J. *J. Am. Chem. Soc.* **2001**, *123*, 10475.

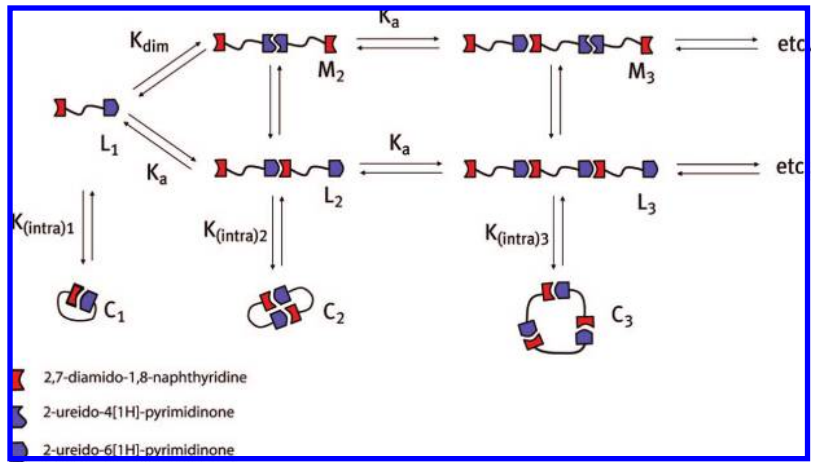
(29) A solution of 1.05 equiv of **1** and 1 equiv of **3** in $CDCl_3$ (total concentration 20 mM) revealed dibutylamino UPy homodimer $\mathbf{1}_2$ and dibutylamino-substituted UPy·NaPy heterodimer **1·3** to be in slow exchange on the ^{1}H NMR timescale. The signals of the three NH protons of the hydrogen-bonded dimer $\mathbf{1}_2$ resonate at 12.60, 11.22, and 9.58 ppm,

(30) (a) Brand, T.; Cabrita, E. J.; Berger, S. *Prog. Nucl. Magn. Reson. Spectrosc.* **2005**, *46*, 159. (b) Cohen, Y; Avram, L.; Frish, L. *Angew. Chem., Int. Ed.* **2005**, *44*, 520. (c) Johnson, C. S. *Prog. Nucl. Magn. Reson. Spectrosc.* **1999**, *34*, 203. (d) Johnson, C. S. *J. Magn. Reson., Ser. A* **1993**, *102*, 214. (e) Cabritta, E. J.; Berger, S.; Bräuer, P; Kärger, J. *J. Magn. Res.* **2002**, *157*, 124.

(31) Zhao, D.; Moore, J. S. *Org. Biomol. Chem.* **2003**, *1*, 3471.

(32) Schaefgen, J. R.; Flory, P. J. *J. Am. Chem. Soc.* **1948**, *70*, 2709.

Scheme 3. Linear (M_i- and L_i-type chains) vs Cyclic Species (C_i) Present in the Supramolecular Polymerization of an AB Monomer in Solution Capable of Both A·B Heterocoupling and A·A Homocoupling[a]



[a] Due to the nonassociating NaPy end groups, only linear species with one NaPy and one UPy end group (L_i-type chains) are able to form cycles. L_1 and all other L_i-type oligomers implicitly contain all tautomeric forms of the free UPy end group.

form cyclic species and hence will be much larger than the small cycles formed from the L_i-type chains.

Because the linker connecting the UPy and NaPy groups in both AB monomers **5** and **6** is equal and the association constants of **1**·**3** and **2**·**3** are nearly identical, it is straightforward to rationalize the influence of K_{dim} on the equilibrium between cycles and linear chains. Due to the higher K_{dim} of methyl-substituted UPy **2**, the fraction of linear chains with two NaPy chains ends (M_i) is higher in the supramolecular polymerization of **5** than **6**. As a result, the fraction of cyclic species of **5** at a given concentration below the CPC is lower compared to the fraction of cyclic species in the supramolecular polymerization of **6.** The higher fraction of cyclic species will result in a lower degree of polymerization of **6** below the CPC. Above the CPC, when additional monomer is added to linear species, the higher fraction of chains M_i in the supramolecular polymerization of **5** will result in a slower growth of the linear polymers due to the "self-stoppered" effect of the two NaPy chain ends. Hence, above the CPC, the degree of polymerization of **6** will increase faster than the degree of polymerization of **5** due to the higher fraction of M_i chains in the latter.

To gain a more quantitative insight into the effects of K_a, K_{dim}, and $K_{(intra)i}$ on the fraction of the various species and the degree of polymerization, a mathematical model was developed based on a previously published model for the ring-chain equilibrium of an AB monomer in solution capable of only A·B interactions.[15] The previous model was based on the concept of effective molarity which is a measure of the ease of formation of a given cyclic oligomer and is defined as $EM_i = K_{(intra)i}/K_a$. Under the assumption that all the rings, including the smaller ones, are strainless and follow the Jacobson−Stockmayer equation, i.e., $EM_i = EM_1 i^{-5/2}$, the following expression can be deduced (see Supporting Information) that links the total AB monomer concentration C and the equilibrium constants K_a, K_{dim}, and EM_1 to the structural characteristics of the system as schematically drawn in Scheme 3.

$$C = \underbrace{\frac{1}{K_a}\frac{x}{(1-x)^2}}_{L_i\text{-type chains}} + \underbrace{\frac{2K_{dim}}{K_a^2}\frac{x^2}{(1-x)^3}}_{M_i\text{-type chains}} + \underbrace{EM_1\sum_{i=1}^{\infty} i^{-3/2}x^i}_{\text{rings}} \qquad (1)$$

The three terms on the right-hand side of eq 1 represent the amount of monomer, in concentration units, that, at equilibrium, went into L_i chains, M_i chains, and rings, respectively. All of them are expressed as a function of x, namely, the extent of heterocoupling reaction in the linear fraction. To more quantitatively understand the development of the viscosity as a function of concentration, expressions for the weight and average degree of polymerization were also derived.

The number-average degree of polymerization (DP_n) is defined by eq 2

$$DP_n = \frac{\sum_{i=1}^{\infty} iN_i}{\sum_{i=1}^{\infty} N_i} \qquad (2)$$

where N_i is the number of molecules of a given i-mer. The numerator of eq 2 is proportional to the initial monomer concentration, C, whereas the denominator is proportional to the summation of the molar concentrations of all the i-mers. In other words, eq 2 can be rewritten as eq 3

$$DP_n = \frac{C}{\sum_{i=1}^{\infty}[L_i] + \sum_{i=2}^{\infty}[M_i] + \sum_{i=1}^{\infty}[C_i]} \qquad (3)$$

The first two sums in the denominator can be evaluated using standard expressions for infinite converging series, while the last sum can be numerically evaluated for finite-sized systems (see Supporting Information). The weight-average degree of polymerization (DP_w) is defined by eq 4

$$DP_w = \frac{\sum_{i=1}^{\infty} i^2N_i}{\sum_{i=1}^{\infty} iN_i} \qquad (4)$$

The numerator of eq 4 is proportional to the summation of the molar concentrations of all the i-mers multiplied by i^2, whereas the denominator is proportional to the initial monomer concentration, C. In other words, eq 4 can be rewritten as eq 5

$$DP_w = \frac{\sum_{i=1}^{\infty} i^2[L_i] + \sum_{i=2}^{\infty} i^2[M_i] + \sum_{i=1}^{\infty} i^2[C_i]}{C} \qquad (5)$$

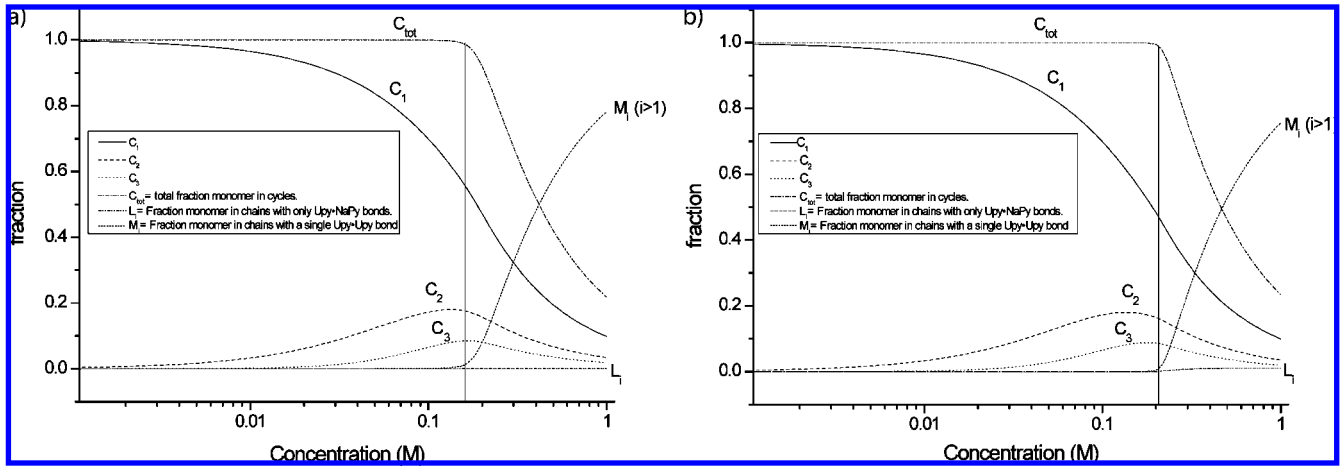


Figure 6. Calculations of the fraction of monomer in cyclic oligomers (C_1, C_2, and C_3), total fraction of monomer present in cycles (C_{tot}), and total fraction of monomer present in linear chains containing only UPy•NaPy bonds (L_i-type chains) or containing a single UPy•UPy bond (M_i-type chains) as a function of concentration for $EM_1 = 0.1$ M. (a) $K_a = 6 \times 10^6$ M^{-1} and $K_{dim} = 6 \times 10^7$ M^{-1} corresponding to the thermodynamic parameters of methyl-substituted UPy•NaPy monomer **5**. (b) $K_a = 6 \times 10^6$ M^{-1} and $K_{dim} = 9 \times 10^5$ M^{-1} corresponding to the thermodynamic parameters of dibutylamino-substituted UPy•NaPy monomer **6**.

Again, the first two sums can be evaluated using standard mathematical expression for infinite series (see Supporting Information), while the last sum can be approximated numerically. Finally, the polydispersity index is defined as

$$\mathrm{PDI} = \frac{\mathrm{DP_w}}{\mathrm{DP_n}} \tag{6}$$

Using the mass balance equation (eq 2) and the expressions for the weight-average degree of polymerization (eqs 3 and 5) the fraction of cycles, fraction of linear species, and the weight- and number-average degree of polymerization can be calculated given values of K_a, K_{dim}, and EM_1. Although the developed model assumes that all cycles are strainless, in reality the first few oligomeric rings will be strained. However, it is stressed that the goal of the numerical simulations is to reveal the differences in the supramolecular polymerizations of both AB monomers based on the difference in dimerization constant of the UPy•UPy interaction. The value for EM_1 was set to a value of 0.1 M to reproduce our experimental data.

Figure 6 displays the results of the calculations of the fraction of monomer incorporated in the various chains and rings as a function of the concentration of monomer using the experimentally determined thermodynamic parameters for **5** and **6**. As can be observed, there are some differences in the composition of the mixture between the high (**6**) and low (**5**) heteroselective system. For example, the concentration at which the fraction of cycles becomes significantly smaller than 1 is lower for the low heteroselective system due to the lower fraction of L_i chains, although this feature cannot be clearly detected from the plots in Figure 3. Further calculations on the fraction of M_i and L_i chains as a function of monomer concentration further show that the concentration of M_i-type chains is higher for the low heteroselective system at high concentrations (Figure S9, Supporting Information).

Simulations of the weight-average degree of polymerization vs concentration for both systems reveal large differences in the growth of supramolecular polymer as the concentration is increased. At concentrations slightly above the effective molarity of the first ring closure, the weight-average degree of polymerization for all *i*-mers of the low heteroselective system starts to increase while the weight-average degree of polymerization for the high heteroselective system is not increasing. Only at concentrations well above (>0.22 M) the effective molarity of the first cyclization, the weight-average degree of polymerization of the high heteroselective system starts to increase (Figure 7) and increases much faster compared to the low heteroselective system because of the higher fraction of L_i-type chains. In the intermediate concentration regime (between 0.15 and 0.25 M) the DP_w of the oligomeric and polymeric chains of the low heteroselective system is higher. These simulations illustrate, from a theoretical point of view,[35] the experimental results obtained from the capillary viscosity measurements where a similar crossover region is observed at roughly a concentration of 0.2 M (see Figure 3).

2.5. Effect of A·A Dimerization on Polydispersity. The mathematical model allows for determination of the polydispersity index at equilibrium. For an isodesmic equilibrium polymerization in the absence of cyclization, characterized by a single elongation constant (K_a), the polydispersity index approaches 2 as the concentration of AB becomes high.[32] Indeed, for $K_{dim} = 0$ M^{-1} our model predicts that the polydispersity index becomes 2 at high values of the dimensionless concentration K_aC (Figure 8a). However, if the AB monomer is also capable of A•A interactions the polydispersity drops to a limiting value of 1.5 (see Supporting Information for the derivation). The drop in polydispersity is accompanied with a lower weight-average degree of polymerization compared to the situation in which no A•A interaction is present (Figure 8b).

The first question that arises from these simulations is why homocoupling results in a lower limiting PDI value at high concentrations. This question can be answered by calculating the polydispersity index for the individual M_i- and L_i-type chains. For the L_i-type chains the following expression can be derived (see Supporting Information)

$$\mathrm{PDI} = 1 + x \tag{7}$$

Indeed, as x goes to 1, the polydispersity index goes to 2 in accordance with the standard theory for step polymerizations

(33) The normalized diffusion constantwas calculated using the measured specific viscosity of solutions of **5** and **6** and the measured value of the diffusion constant: $D_n = D_{meas}\eta_{mean}$.

(34) Todd, E. M.; Zimmerman, S. C. *J. Am. Chem. Soc.* **2007**, *129*, 14534.

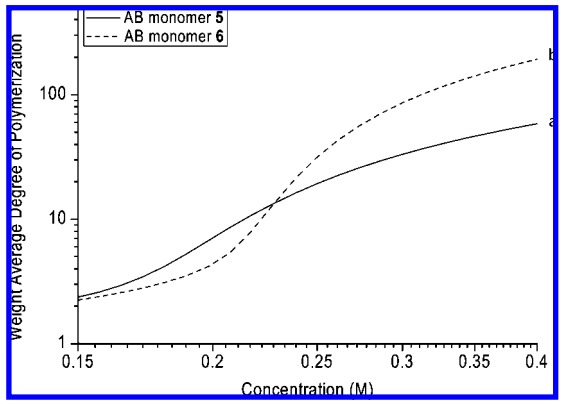


Figure 7. Simulation of the weight-average degree of polymerization vs total concentration of AB monomer for $EM_1 = 0.1$ M (a) $K_a = 6 \times 10^6$ M^{-1} and $K_{dim} = 6 \times 10^7$ M^{-1} corresponding to the thermodynamic parameters of methyl-substituted UPy·NaPy monomer **5**. (b) $K_a = 6 \times 10^6$ M^{-1} and $K_{dim} = 9 \times 10^5$ M^{-1} corresponding to the thermodynamic parameters of dibutylamino-substituted UPy·NaPy monomer **6**.

as derived by Flory.[36] For the M_i-type chains the following expression can be derived (see Supporting Information) that links the polydispersity index to the extent of the reaction (x)

$$\mathrm{PDI} = \frac{2+x}{2} \tag{8}$$

In contrast to the L_i-type chains, the polydispersity index for the M_i-type chains goes to 1.5 as $x \rightarrow 1$ in accordance with the limiting PDI for a multichain AB polycondensation containing a small amount of bifunctional initiator.[32] For the general case of an f-functional monomer ($R\text{-}A_f$) present in a low amount in a multichain AB polycondensation, Flory[32] derived the following approximate expression for the polydispersity index for high molecular weight chains in the limit $x \rightarrow 1$.

$$\mathrm{PDI} = 1 + \frac{1}{f} \tag{9}$$

The effect of the reversible AA interaction has an equivalent effect on the polydispersity as addition of a bifunctional RA_2 initiator in low amounts in a covalent multichain AB polymerization. Hence, the narrower distribution is the direct result of the linking of two statistically independent L_i polymer chains via the reversible A·A interaction.

Now that we analyzed the origin of the reduced polydispersity index in terms of the differences in the polydispersity index of the two different chains the question arises why the equilibrium shifts to M_i chains at the expense of L_i chains when the concentration is increased. This shift can be understood by further examination of eq . In this mass balance equation, the first and second terms represent the amount of monomer that has gone into the L_i- and M_i-type chains, respectively (the third term, representing the cyclic oligomers, is ignored because of the assumption that no rings are formed). The total concentration of L_i-type chains is proportional to $x/(1-x)^2$ whereas the M_i-type chains are proportional to $x^2/(1-x)^3$; thus, as x approaches 1 (or equivalently the concentration is increased), the concentration of M_i-type chains increases much more rapidly than that of the L_i-type chains. Hence, the change of PDI from 2 to 1.5 is a consequence of the shift of equilibrium in favor of the M_i-type oligomers. This fact is nicely illustrated by plots of the weight fractions of L_i- and M_i-type chains as a function of i for increasing values of x and $p > 0$ (see Figure S12, Supporting Information).

Although eqs 7 and 8 only apply for the case when cycle formation is neglected ($EM_1 = 0$) it has the advantage that they can be derived in a rather straightforward way. However, when cycle formation is taken into account it proved difficult to derive analytical expressions analogous to eqs 7 and 8. However, calculation of the polydispersity index as a function of monomer concentration, taking into account cycle formation,[37] shows that the molecular weight distribution becomes extremely broad around concentrations close to the effective molarity of first ring closure (EM_1). The broad distribution is the direct result of the fact that at these concentrations the solution consists of small cycles and long polymeric chains (see Figure S10, Supporting Information). Further examination of these graphs shows that the polydispersity index goes to 1.5 if $p > 0$ and $C \gg EM_1$, indicating that the above treatment is still valid when cycle formation is taken into account although only at high values of x.

3. Conclusions

The present study has analyzed formation of linear supramolecular polymers, in equilibrium with cyclic intermediates, through reversible recognition induced self-assembly of heteroditopic UPy·NaPy, AB-type monomers capable of complementary as well as self-complementary interactions. In our efforts to reduce the "self-stoppered" effect that is inherently present in these supramolecular polymerizations, two different UPy·NaPy monomers were synthesized and their concentration-dependent supramolecular polymerization studied using Ubbelohde viscometry, diffusion-ordered spectroscopy (DOSY), and ^{1}H NMR. Surprisingly, the UPy·NaPy monomer which was anticipated to exhibit the lowest amount of "self-stoppered" behavior showed the lowest degree of polymerization below the critical concentration, suggesting that cycle formation was enhanced by the increased fidelity for heterocomplexation. In order to theoretically illustrate our results a previous model for the ring-chain equilibrium of an AB monomer in solution was extended to include reversible A·A interaction. Simulations have shown that the value of K_{dim} significantly affects the extent of cyclization. For UPy·NaPy AB-type monomers, the fraction of cycles just above the critical polymerization concentration is lower when the dimerization constant of the UPy is increased. More importantly, growth of linear high molecular weight material far above the CPC has a stronger concentration dependence when the UPy dimerization constant is lower than K_a as in the case of UPy·NaPy monomer **6**, ultimately resulting in a higher degree of polymerization compared to UPy·NaPy monomer **5**.

Theoretical analysis of the polydispersity index at equilibrium when cyclization is negligible reveals that the presence of the reversible A·A interactions plays a crucial role in narrowing of the molecular weight distribution. The continuous quest to

(35) Previously, we have shown that the specific viscosity of supramolecular polymers scales with the degree of polymerization according to an empirical power law $\eta_{sp} = K^*DP^{\alpha}$. For UPy-based polymers, α was determined to be 0.78 (see ref 2). Therefore, the calculated plots of the weight-average degree of polymerization are a good representation of the development of the viscosity as a function of concentration.

(36) Flory, P. J. *Principles of Polymer Chemistry*; Cornell University Press: Ithaca, NY, 1953.

(37) In the calculations, only rings containing up to 100 monomeric units were included. Calculations including larger rings (up to 500) showed similar results.

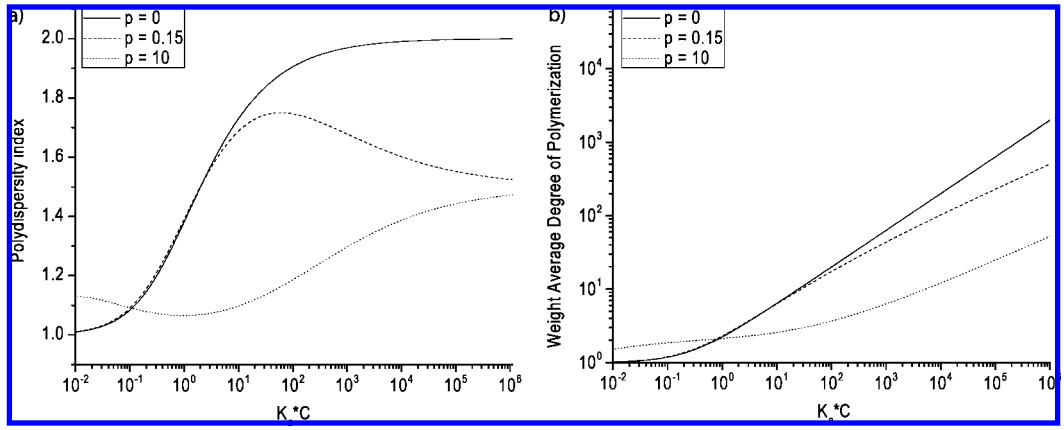


Figure 8. (a) Calculation of the polydispersity index vs dimensionless concentration (K_aC) for a supramolecular-type AB monomer for several values of the dimensionless binding constant p (defined as K_{dim}/K_a) and $EM_1 = 0$. (b) Calculation of the weight-average degree of polymerization vs dimensionless concentration for a supramolecular AB-type monomer for several values of the dimensionless binding constant p (defined as K_{dim}/K_a) and $EM_1 = 0$ M.

obtain polymeric architectures with low polydispersities in covalent polymerization has resulted in a wealth of novel living polymerization techniques in the last few decades (i.e., ATRP, RAFT, NMP). In sharp contrast, development of supramolecular polymeric architectures with low polydispersities has achieved much less attention with the exception of a few cases.[34]

Acknowledgment. The authors wish to acknowledge Mr. J. van Dongen, Dr. X. Lou, Mr. Ralf Bovee and Mr. H. Eding for technical assistance. Dr. O. Scherman (University of Cambridge) is acknowledged for help with the viscosity measurements. This work is supported by the Council for Chemical Sciences of The Netherlands Organization for Scientific Research (CW-NWO).

Supporting Information Available: Detailed experimental procedures; synthesis and characterization of each compound; derivation of ring-chain equilibria of a monomer A−B capable of both AB heterocoupling and AA homocoupling. This material is available free of charge via the Internet at http://pubs.acs.org.

JA8046409