Electronic Supplementary Material (ESI) for ChemComm.

Selenoamides modulate dipole-dipole interactions in hydrogen-bonded supramolecular polymers of 1,3,5-substituted benzenes†

José Augusto Berrocal,[a‡] Mathijs F.J. Mabesoone,[a‡] Miguel García Iglesias,[a, b, c] Alex Huizinga,[a] E. W. Meijer[a*] and Anja R. A. Palmans[a*]

---

[a] Institute for Complex Molecular Systems, Eindhoven University of Technology, P. O. Box 513, 5600 MB Eindhoven, The Netherlands. E-mail: e.w.meijer@tue.nl or a.palmans@tue.nl.[b] Department of Organic Chemistry, Universidad Autónoma de Madrid (UAM), Calle Francisco Tomás y Valiente, 7, 28049 Madrid, Spain. [c] IMDEA Nanociencia, c/ Faraday 9, Cantoblanco, Spain.

Supplementary information

Table of Contents

Experimental materials & methods **2**

Sample preparation and measurement CD samples ***2***

Synthesis of SeBTA ***3***

Details on the thermodynamic mass balance models for homopolymerization **11**

Supplementary references **17**

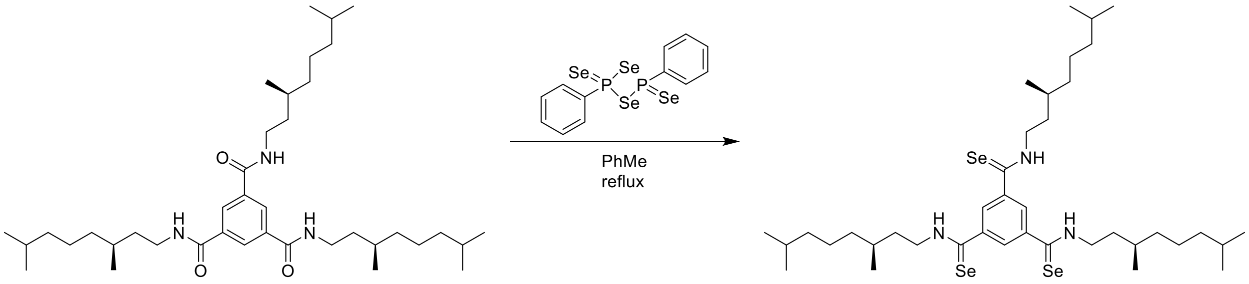
Experimental materials & methods

All other starting materials were obtained from commercial suppliers and used without prior purification. **OBTA** and **SBTA** were synthesized according to a previously reported procedure.[1,2] The MCH and $CHCl_3$ used in the CD and UV-Vis measurements were of spectroscopic grade and purchased from VWR and TCI respectively. ^1H and ^{13}C NMR spectra were measured on a Bruker Avance 3 HD NanoBay spectrometer (1H-NMR 400 MHz, 13C NMR 100 MHz). ^1H and ^{13}C shifts are reported relative to the residual d_6-acetone signals at 2.05 ppm and 29.84 ppm, respectively. CD spectroscopy was performed on a Jasco J-815 CD spectrometer equipped with an MPTC-490 multicell holder. UV-Vis results were obtained with the JASCO J-815 CD spectrometer or a Jasco V-650 UV-Vis spectrometer. IR spectra were recorded on a PerkinElmer Spectrum One spectrometer. Solution state IR was measured using 1 mm NaCl cells. AFM measurements were performed on an Asylum Research MFP-3D system in non-contact tapping mode. Processing of the AFM micrographs was done using Gwyddion 2.52.

Sample preparation and measurement CD samples:

SeBTA was dissolved in degassed MCH at room temperature in a volumetric flask. After dissolution, the solution was purged with Ar for a minimum of 30 minutes and equilibrated under Ar atmosphere overnight before measurement. Variable temperature measurements were conducted in screw-capped cuvettes. Cooling curves were measured at a cooling rate of 30 °C/h.

Synthesis of SeBTA:



Scheme S1 Synthesis of **c-SeBTA**.

NOTE: Selenides are highly toxic with a pungent smell and should be handled with appropriate safety precautions and in a well-ventilated fume hood.

c-OBTA (162.2 mg, 0.258 mmole) was dissolved in dry toluene (5 mL) under an argon atmosphere. Woollin's reagent (422.9 mg, 0.794 mmole) was added, after which the mixture was refluxed for 3.5 hours. While hot, the solution was filtered over a P3 glass filter to remove the solid phosphine oxides formed. Then, the dark residue was washed with cold toluene, after which the filtrate was evaporated to yield a yellow solid. The crude product was redissolved in 200 mL 1:1 DCM:EtOAc and filtered over a glass filter, after which the filtrate was quickly filtered over two silica plugs. After evaporating of the solvent, the product was obtained as a yellow solid in 82% yield. ^{1}H NMR (400 MHz, acetone-d_6) δ: 8.06 (s, 3H, ArH), 3.87 (m, 6H, NCH_2), 1.68-1.44 (m, 10H), 1.38-1.22 (m, 10H), 1.19-1.10 (m, 10H), 0.94 (d, 9H, CH_3), 0.83 (d, 18H, CH_3). ^{13}C NMR (100 MHz, CD_3COCD_3) δ: 202.27, 145.65, 127.45, 49.23, 40.02, 37.85, 35.09, 25.44, 22.94, 19.99. Repeated attempts to measure the mass of the product with ESI-MS and MALDI-ToF were unsuccessful. Presumably, the compound rapidly decomposes upon ionization.

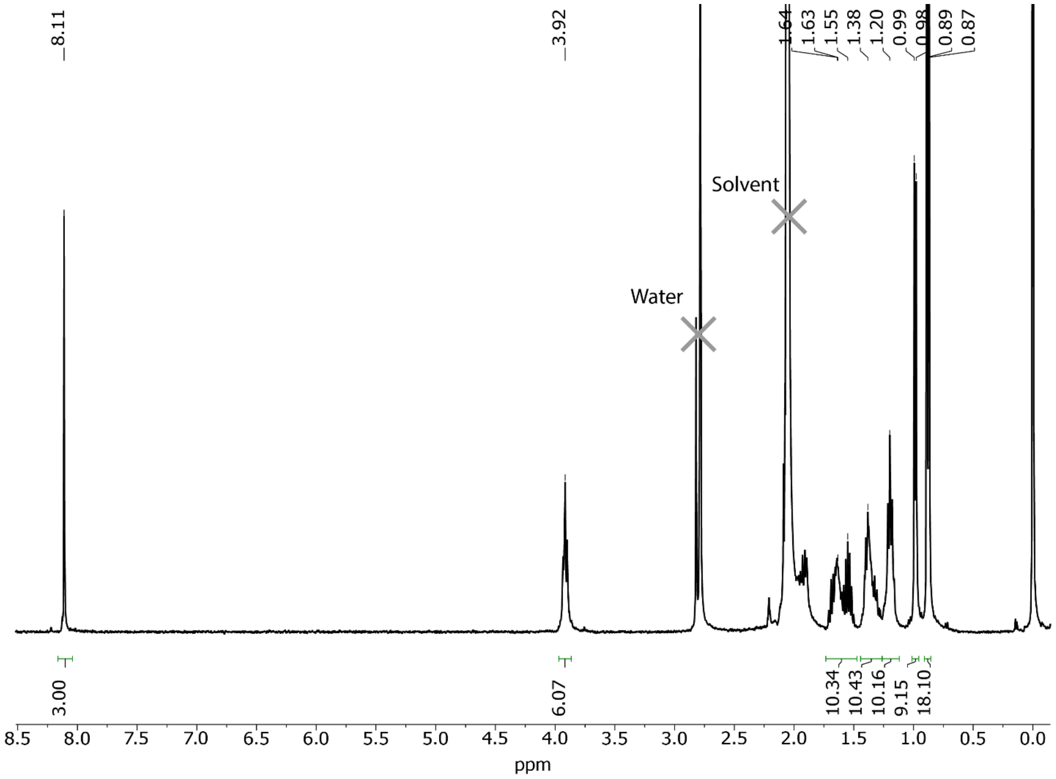


Figure S1 ^{1}H NMR of **c-SeBTA** in acetone-d$_6$.

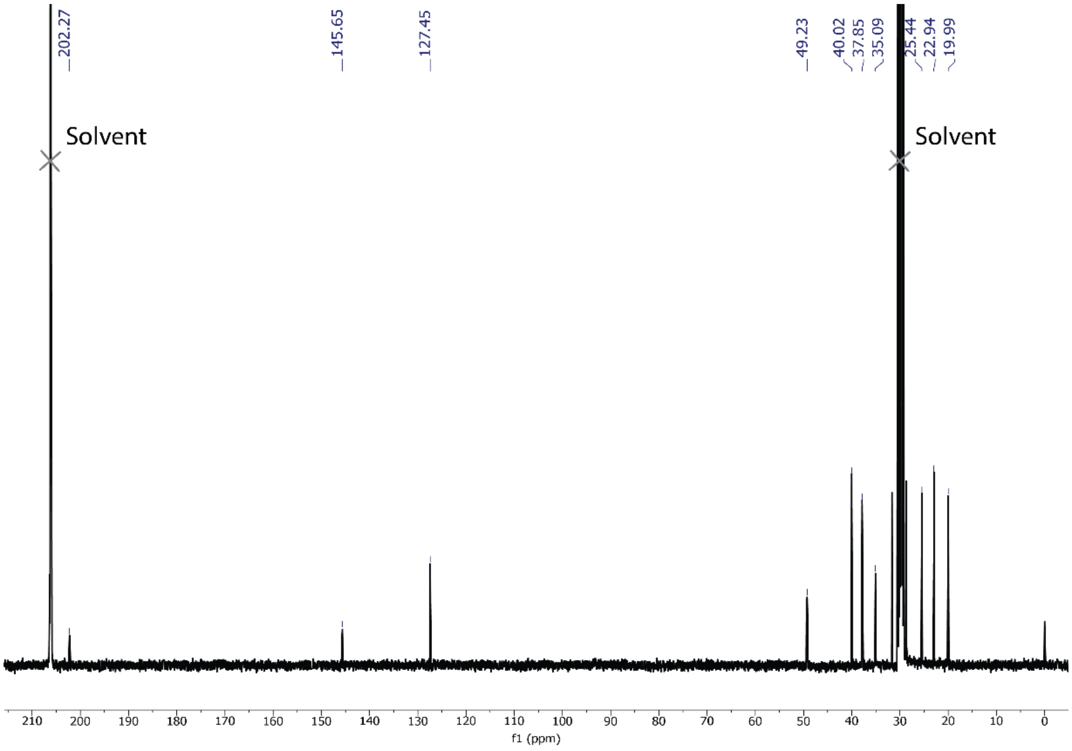


Figure S2 13C NMR of **c-SeBTA** in acetone-d$_6$.

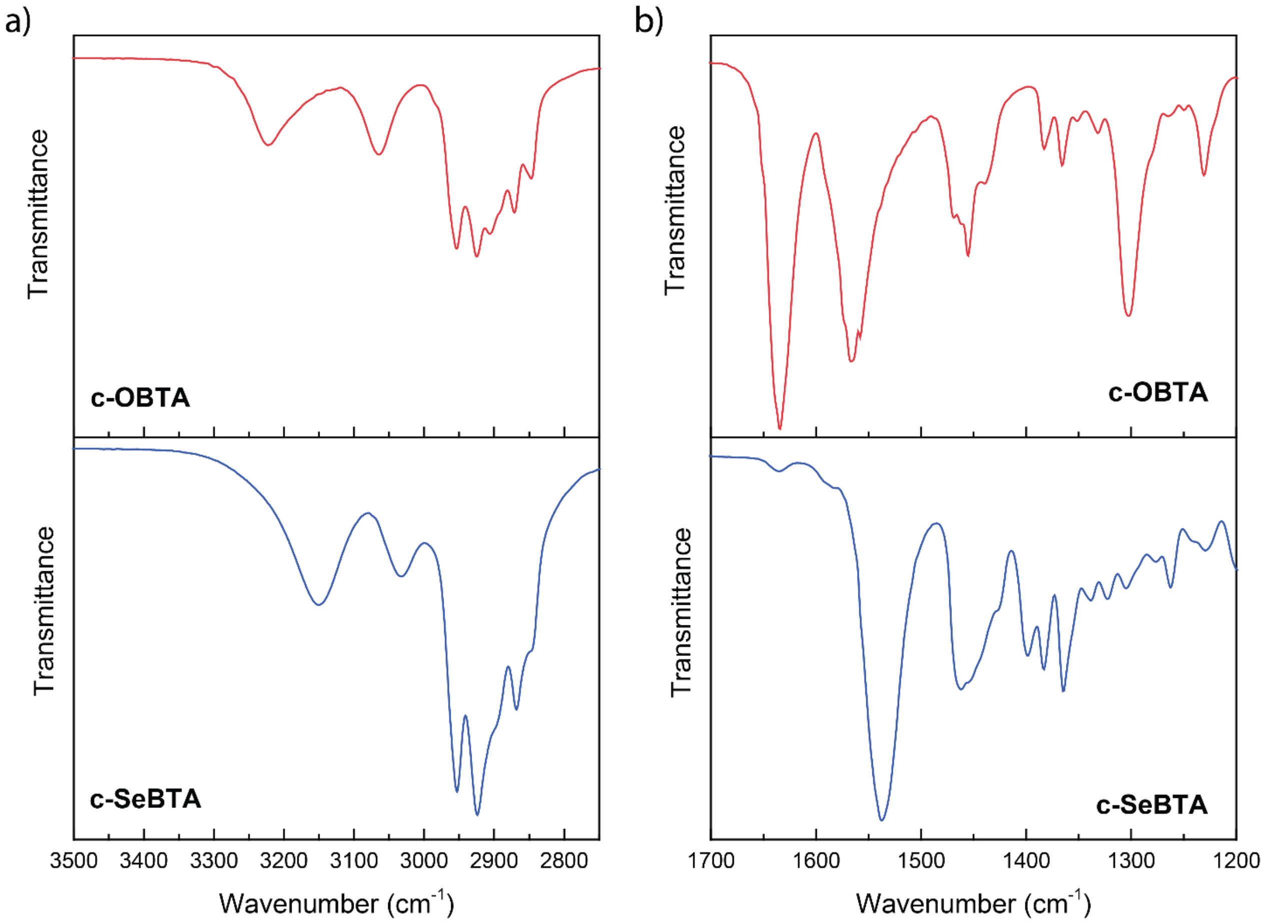


Figure S3: Comparison of the amide region (a) and carbonyl region (b) of the bulk IR spectra of **c-OBTA** (top panels) and **c-SeBTA**.

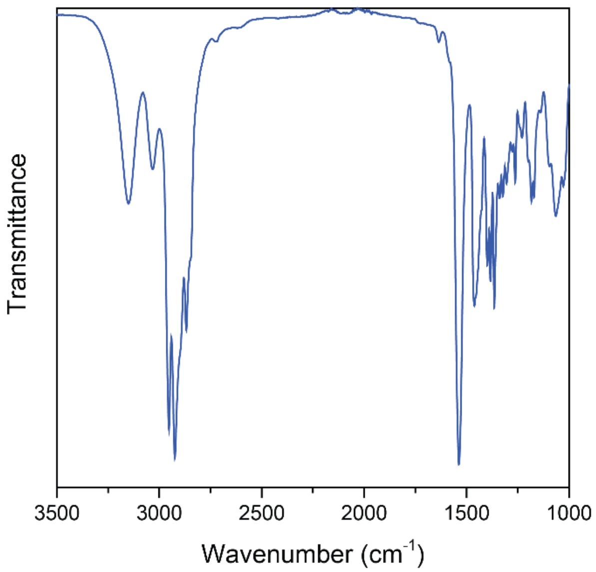
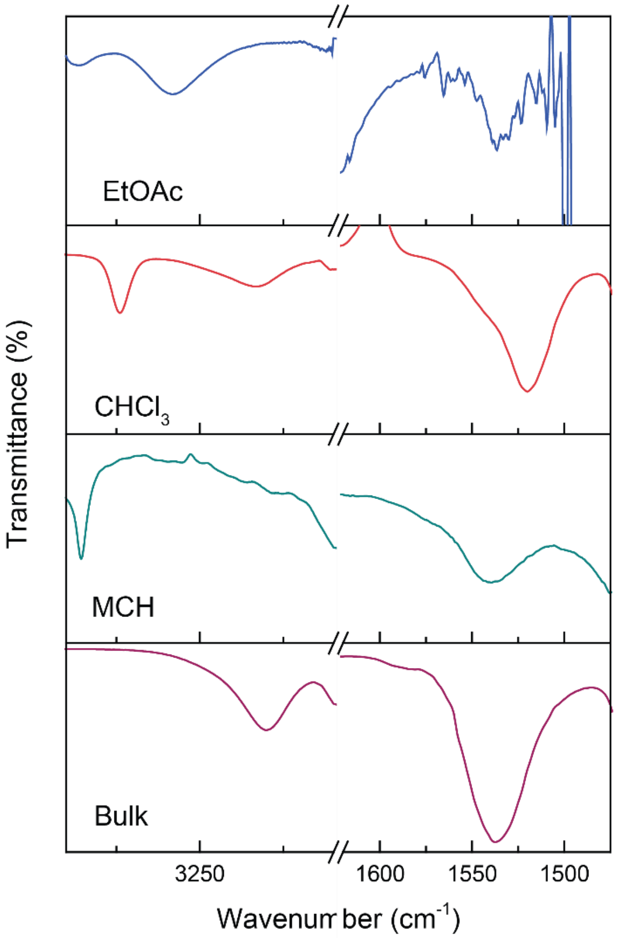


Figure S4 Complete bulk IR spectrum of **c-SeBTA**.



Figuree S5 Comparison of 500 µM solutions of **c-SeBTA** in various solvents or in the bulk.

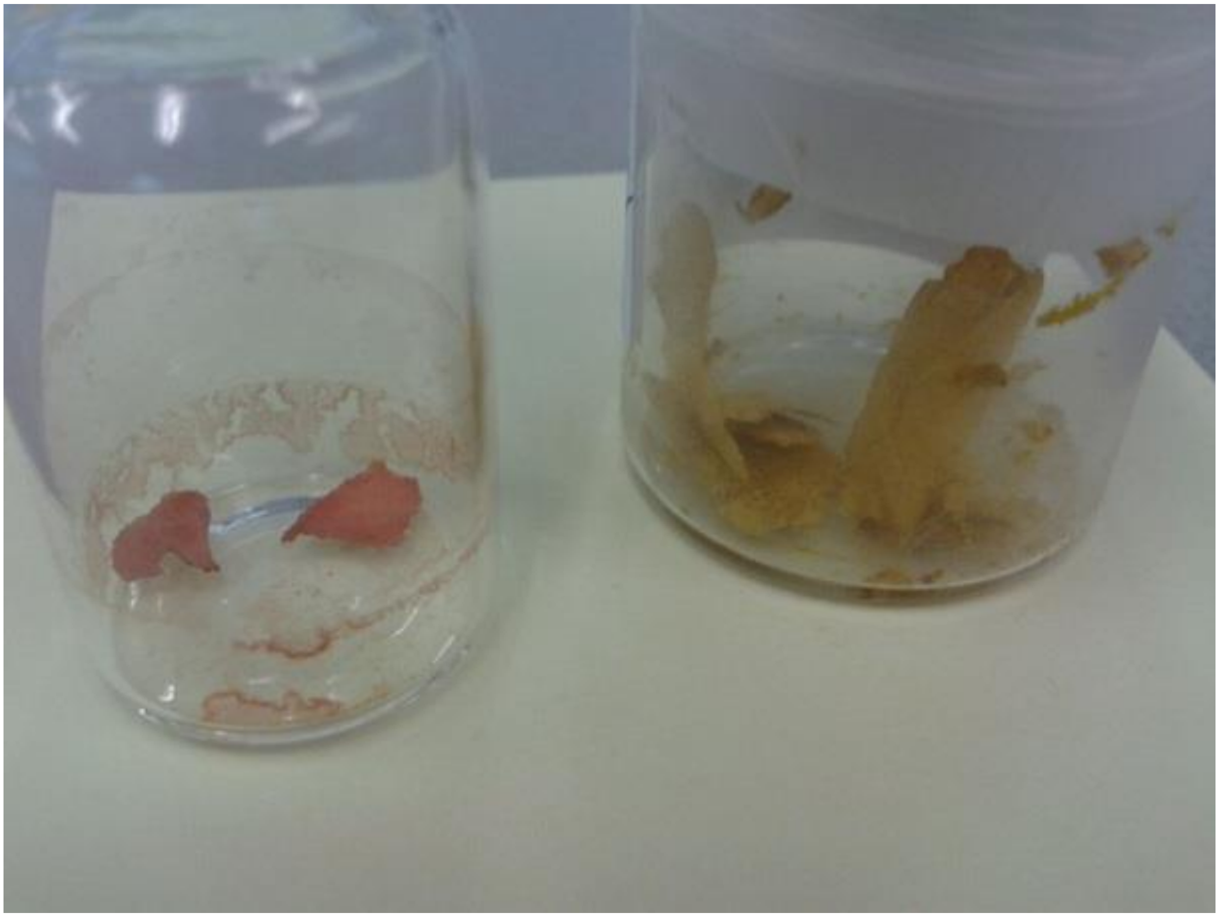


Figure S6 Photography of two samples of **c-SeBTA** after being exposed to air for several hours (left), and stored under argon (right).

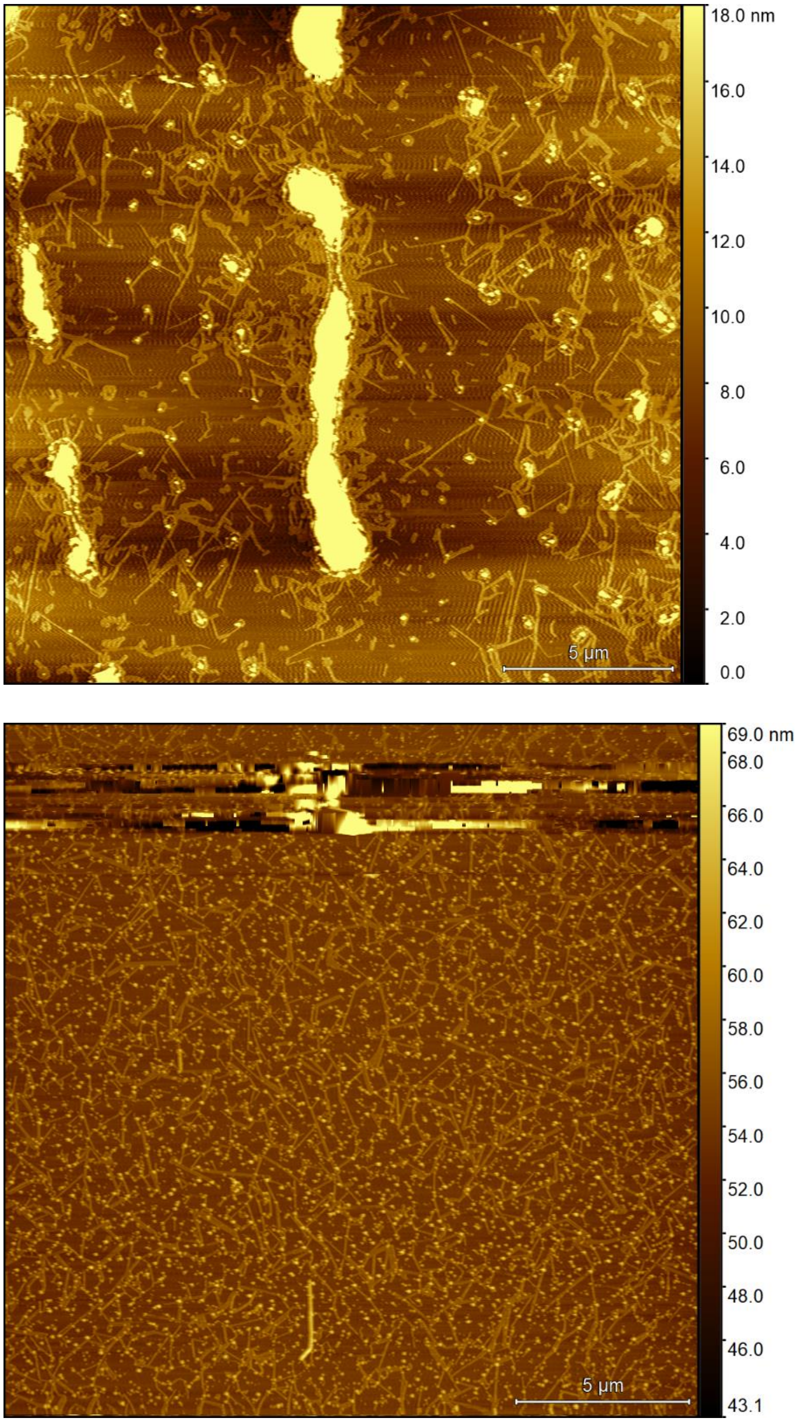


Figure S7 AFM micrographs of **c-SeBTA** on mica. The samples were drop casted from 100 µM MCH solutions.

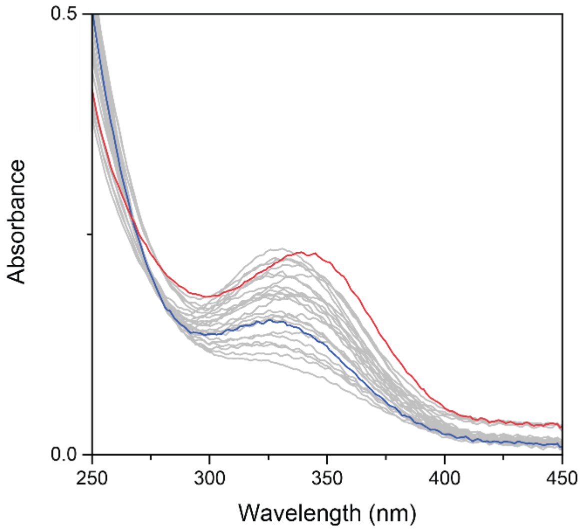


Figure S8 UV spectra of the denaturation experiment of 20 µM of **c-SeBTA** sergeant, going from 0 vol% $CHCl_3$ (red spectrum) to 12.5 vol% $CHCl_3$ (blue spectrum).

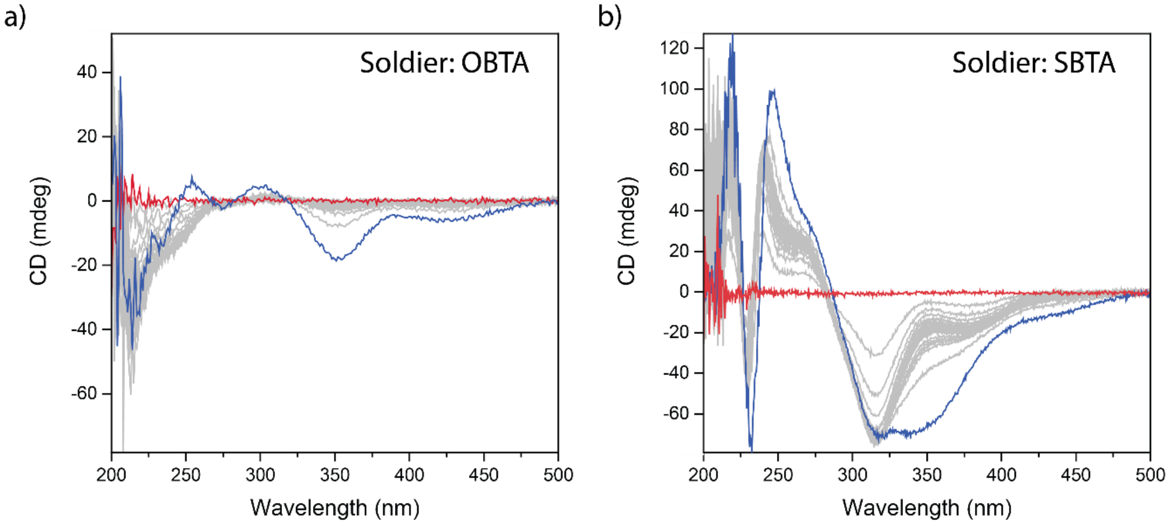


Figure S9 CD spectra of the sergeants and soldiers experiment with 30 µM of achiral **OBTA** (a) or **SBTA** (b) soldier and increasing amounts of **c-SeBTA** sergeant, going from 0 mole% (red spectrum) to 100 mole% (blue spectrum).

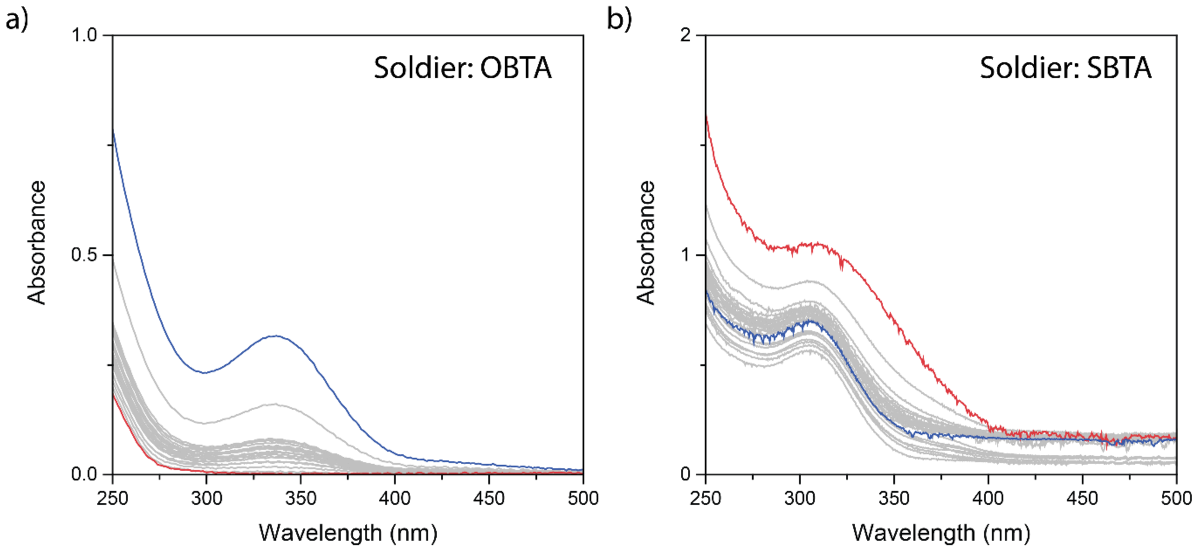


Figure S10 UV spectra of the sergeants and soldiers experiment with 30 µM of achiral **OBTA** (a) or **SBTA** (b) soldier and increasing amounts of **c-SeBTA** sergeant, going from 0 mole% (red spectrum) to 100 mole% (blue spectrum).

Details on the thermodynamic mass balance models for homopolymerization

The supramolecular polymerization of **c-SeBTA** is modelled with thermodynamic mass balance expressions. The polymerization is described as a series of sequential monomer additions to and dissociations from the chain ends and can be written as:

$$\begin{gathered}\mathrm{M}+\mathrm{M} \xrightleftharpoons{K_2} \mathrm{P}_2 \\ \mathrm{P}_2+\mathrm{M} \xrightleftharpoons{K} \mathrm{P}_3 \\ \mathrm{P}_3+\mathrm{M} \xrightleftharpoons{K} \mathrm{P}_4 \\ \vdots \\ \mathrm{P}_i+\mathrm{M} \xrightleftharpoons{K} \mathrm{P}_{i+1} \\ \vdots \end{gathered} \tag{S1}$$

with K_2 the equilibrium constant of dimerization and K the equilibrium constant of polymerization beyond the dimer.

In the case of a cooperative polymerization, the concentration of monomers in *i*-mers can be expressed as a function of the free monomer concentration with:

$$[\mathrm{P}_i] = i \cdot \sigma \cdot K^{i-1} \cdot [\mathrm{M}]^i \text{ for } i \geq 2 \tag{S2}$$

where σ is the cooperativity parameter: $\sigma = K_2 / K$.

The total concentration of M in the system can thus be expressed with:

$$[\mathrm{M}]_{\mathrm{tot}} = [\mathrm{P}]_{\mathrm{tot}} + [\mathrm{M}] = \left(\sum_{i=2}^{\infty} [\mathrm{P}_i] \right) + [\mathrm{M}] = \sum_{i=1}^{\infty} i \cdot \sigma \cdot K^{i-1} [\mathrm{M}]^i \tag{S3}$$

Using standard expression for converging series, Eq. (S3) can be solved to obtain the mass-balance equation for the polymerization:

$$[\mathrm{M}]_{\mathrm{tot}} = (1-\sigma) \cdot [\mathrm{M}] + \frac{\sigma \cdot [\mathrm{M}]}{(1 - K \cdot [\mathrm{M}])^2} \tag{S4}$$

Because Eq. (S4) cannot be solved analytically for [M], Eq. (S4) is solved numerically for [M] in Matlab with a custom written binary search algorithm.

In the fitting algorithm, the temperature dependence of K_2 and K is introduced via the Van ‘t Hoff equation:

$$K_i = \exp\left(\frac{-\Delta G_i}{R \cdot T} \right) = \exp\left(\frac{-\Delta H_{\mathrm{i}}}{R \cdot T} + \frac{\Delta S_i}{R} \right) \tag{S5}$$

with ΔG_i the Gibbs free energy of monomer addition in aggregation process *i*, *R* the gas constant, *T* the absolute temperature, ΔH_i the enthalpy of monomer addition in aggregation process *i* and ΔS_i the entropy of monomer addition in aggregation process *i*.

Similarly, the solvent dependency of K_2 and K is introduced via a linear free energy relationship:

$$K_i = \exp\left(\frac{-\Delta G_i^0 + m_i \cdot f}{R \cdot T}\right) \qquad \text{(S6)}$$

with ΔG_i^0 the Gibbs free energy in MCH and m_i the solvent dependency parameter of aggregation process i.[3]

In the model for the cooperative polymerization, the nucleation enthalpy is introduced with a nucleation penalty:

$$\Delta H_2 = \Delta H + NP \qquad \text{(S7)}$$

with ΔH_2 the enthalpy of dimerization, ΔH the enthalpy of monomer addition to dimers and larger aggregates and *NP* the nucleation penalty.

In the case of the solvent dependent cooperative models, the Gibbs free energy of nucleation is introduced similarly:

$$\Delta G_2 = \Delta G + NP \qquad \text{(S8)}$$

with ΔG_2 the Gibbs free energy of dimerization, ΔG the Gibbs free energy of monomer addition to dimers and larger aggregates and *NP* the nucleation penalty. In all cases, the entropies and solvent dependency parameters of dimerization and polymerization were taken equal.

This model is fitted to the CD intensity at 357 nm by approximating the activity of the components with their molar concentration in the system. In the case of the variable temperature curves, the concentration of the samples was determined using the molar ellipticity of **c-SeBTA** in MCH at 20 °C, which is determined from isothermal experiments at $-1.72 \cdot 10^6$ $\text{L} \cdot \text{M}^{-1} \cdot \text{cm}^{-1}$, and all concentrations were fitted simultaneously in a global fit. The temperature dependency of the molar ellipticity is determined by fitting the molar CD intensity of the samples between 0 and 20 °C with a linear fit. To predict the spectroscopic signal at varying system compositions, the concentration of the polymeric aggregates are multiplied by the temperature dependent molar ellipticity to obtain a calculated CD signal. The molar ellipticity of the monomer is fixed at 0. The fit parameters in the fitting routine for the model that describes the variable temperature cooperative polymerization are ΔH, ΔS and *NP*. In the case of the model that describes the cooperative polymerization at varying solvent compositions, the fit parameters were ΔG, *NP* and *m*. In the case of the isodesmic system, the fit parameters were ΔG and *m*.

The calculated CD signals were compared with the experimental results for every experimentally probed temperature to obtain a cost vector:

$$\text{Cost} = \text{CD}_{\text{model}}(c,T,f) - \text{CD}_{\text{experiment}}(c,T,f) \qquad \text{(S9)}$$

with CD_{model} the calculated CD intensity as a function of concentration, temperature and $CHCl_3$ fraction and $\text{CD}_{\text{experiment}}$ the experimentally obtained CD intensity at varying concentration and temperature and $CHCl_3$ fraction. Minimization of the cost vector was done with the Matlab function lsqnonlin and the Levenberg-Marquardt algorithm. Initial starting values for the fitting algorithm were generated with Latin hypercube sampling, using the Matlab function lhsdesign. To ensure efficient sampling in the temperature dependent, ΔG values at 293 K were sampled between -28 kJ/mole and -40 kJ/mole and entropies were sampled between -20 and -200 J/mole/K. Using these values, ΔH was calculated for every parameter set. Nucleation penalties were sampled between 5 and 30 kJ/mole. In the solvent-dependent fitting algorithm, Gibbs free energies were sampled between -32 and -50 kJ/mole and *m*-values were sampled between 20 and 400 kJ/mole. To ensure that the global minimum is found, fits were performed on a minimum of 250 initial parameter sets. The fits with the lowest norm of the residual cost vector were taken as best fit.

Details on the thermodynamic mass-balance models for copolymerization

We modelled the copolymerization between **c-SeBTA** and **OBTA** and **SBTA** using the model recently developed by ten Eikelder and Markvoort.[4–6]

The copolymerization is described using four equilibrium reactions for the formation of a dimeric nucleus:

$$\mathrm{Se} + \mathrm{Se} \xrightleftharpoons{\sigma_{\mathrm{Se}} \cdot K_{P\mathrm{Se}-\mathrm{Se}}} \mathrm{SeSe}$$

$$\mathrm{Se} + X \xrightleftharpoons{\sigma_{\mathrm{Se}} \cdot K_{P\mathrm{Se}-X}} \mathrm{Se}X$$

$$X + \mathrm{Se} \xrightleftharpoons{\sigma_{X} \cdot K_{PX-\mathrm{Se}}} X\mathrm{Se}$$

$$X + X \xrightleftharpoons{\sigma_{X} \cdot K_{PX-X}} XX$$

and further elongation steps into polymers:

$$M_i\mathrm{Se} + \mathrm{Se} \xrightleftharpoons{K_{P\mathrm{Se\text{-}Se}}} M_i\mathrm{SeSe}$$

$$M_i\mathrm{Se} + X \xrightleftharpoons{K_{P\mathrm{Se}-X}} M_i\mathrm{Se}X$$

$$M_iX + \mathrm{Se} \xrightleftharpoons{K_{PX-\mathrm{Se}}} M_iX\mathrm{Se}$$

$$M_iX + X \xrightleftharpoons{K_{PX-X}} M_iXX$$

In these equations, we denote the molar concentration of **c-SeBTA** as A and the molar concentration of either **OBTA** or **SBTA** as B for simplicity. The equilibrium constants K_{PXY} are the equilibrium constants for the addition of an Y monomer to a P-type polymer with $i \geq 1$ and with an X monomer on top and σ_X is the cooperativity factor for the polymerization of monomer X.

Since in the sergeants-and-soldiers experiment both *P* and *M* helical copolymers are present, the *M*-helical polymers are described in a similar way:

$$\mathrm{Se} + \mathrm{Se} \xrightleftharpoons{\sigma_{\mathrm{Se}} \cdot K_{M\mathrm{Se}-\mathrm{Se}}} \mathrm{SeSe}$$

$$\mathrm{Se} + X \xrightleftharpoons{\sigma_{\mathrm{Se}} \cdot K_{M\mathrm{Se}-X}} \mathrm{Se}X$$

$$X + \mathrm{Se} \xrightleftharpoons{\sigma_{X} \cdot K_{MX-\mathrm{Se}}} X\mathrm{Se}$$

$$X + X \xrightleftharpoons{\sigma_{X} \cdot K_{MX-X}} XX$$

for the nucleation phase and

$$M_i\mathrm{Se} + \mathrm{Se} \xrightleftharpoons{K_{M\mathrm{Se\text{-}Se}}} M_i\mathrm{SeSe}$$

$$M_i\mathrm{Se} + X \xrightleftharpoons{K_{M\mathrm{Se}-X}} M_i\mathrm{Se}X$$

$$M_iX + \mathrm{Se} \xrightleftharpoons{K_{MX-\mathrm{Se}}} M_iX\mathrm{Se}$$

$$M_iX + X \xrightleftharpoons{K_{MX-X}} M_iXX$$

for the elongation phase. We assume the cooperativity factors of both polymer types for the *P* and *M* helicity to be equal.

The total concentration of **c-SeBTA** monomers that is present in the system can then be written as:

$$G(\mathrm{Se}, X) = (\mathbf{u}_3^P + \mathbf{u}_4^P + \mathbf{u}_3^M + \mathbf{u}_4^M) \tag{S10}$$

with the four-dimensional vector $\mathbf{u}^X$ defined as:

$$\mathbf{u}^X = (I - M)^{-1} \cdot M_X \cdot \mathbf{z} \tag{S11}$$

with I the 4x4 identity matrix and with X either the P or M helicity and $\mathbf{z}$ defined as:

$$\mathbf{z} = \begin{pmatrix} \sigma_{\mathrm{Se}} \cdot [\mathrm{Se}] \\ \sigma_X \cdot [X] \\ \sigma_{\mathrm{Se}} \cdot [\mathrm{Se}] \\ 0 \end{pmatrix} \tag{S12}$$

and M_P and M_M defined as:

$$M_P = \begin{pmatrix} K_{P_{\mathrm{SeSe}}} \cdot [\mathrm{Se}] & K_{P_{X\mathrm{Se}}} \cdot [\mathrm{Se}] & 0 & 0 \\ K_{P_{\mathrm{Se}X}} \cdot [X] & K_{P_{XX}} \cdot [X] & 0 & 0 \\ K_{P_{\mathrm{SeSe}}} \cdot [\mathrm{Se}] & K_{P_{X\mathrm{Se}}} \cdot [\mathrm{Se}] & K_{P_{\mathrm{SeSe}}} \cdot [\mathrm{Se}] & K_{P_{X\mathrm{Se}}} \cdot [\mathrm{Se}] \\ 0 & 0 & K_{P_{\mathrm{Se}X}} \cdot [X] & K_{P_{XX}} \cdot [X] \end{pmatrix} \tag{S13}$$

and

$$M_M = \begin{pmatrix} K_{M_{\mathrm{SeSe}}} \cdot [\mathrm{Se}] & K_{M_{X\mathrm{Se}}} \cdot [\mathrm{Se}] & 0 & 0 \\ K_{M_{\mathrm{Se}X}} \cdot [X] & K_{M_{XX}} \cdot [X] & 0 & 0 \\ K_{M_{\mathrm{SeSe}}} \cdot [\mathrm{Se}] & K_{M_{X\mathrm{Se}}} \cdot [\mathrm{Se}] & K_{M_{\mathrm{SeSe}}} \cdot [\mathrm{Se}] & K_{M_{X\mathrm{Se}}} \cdot [\mathrm{Se}] \\ 0 & 0 & K_{M_{\mathrm{Se}X}} \cdot [X] & K_{M_{XX}} \cdot [X] \end{pmatrix} \tag{S14}$$

respectively.

Similarly, the total concentration of X in the copolymers is given by

$$H(\mathrm{Se}, X) = (\mathbf{v}_1^P + \mathbf{v}_2^P + \mathbf{u}_3^P + \mathbf{u}_4^P + \mathbf{v}_1^M + \mathbf{v}_2^M + \mathbf{u}_3^M + \mathbf{u}_4^M) \tag{S15}$$

With the vector **u** as defined above (Eq. S12) and the vector **v** given by:

$$\mathbf{v}^X = ((I - M_X)^{-2} - I) \cdot \mathbf{z} \tag{S16}$$

The mass-balance equations for the **c-SeBTA** and either **OBTA** or **SBTA** monomers is then given by:

$$\begin{aligned} \mathrm{Se}_{\mathrm{tot}} &= \mathrm{Se} + G(\mathrm{Se}, X) \\ X_{\mathrm{tot}} &= X + H(\mathrm{Se}, X) \end{aligned} \tag{S17}$$

The temperature dependency of the equilibrium constants for nucleation and elongation are introduced using the Van ‘t Hoff expression (Eq. S6) using the method described above. The enthalpies, entropies and nucleation penalties of the Se-Se and *X*-*X* contacts are taken from the cooling curves of the homopolymerizations.

The Gibbs free energies of the heterointeractions of each polymer type are determined using the α-parameter:

$$\alpha = \frac{2 \cdot \Delta G^{k}_{\mathrm{Se}X}}{\Delta G^{k}_{\mathrm{SeSe}} + \Delta G^{k}_{XX}} \tag{S18}$$

with ΔG^{k}_{ij} the Gibbs free energy of addition of a *j* monomer to a polymer of helicity *k* with top *i*. The values of the Gibbs free energies of the Se*X* and *X*Se contacts are assumed to be equal.

Lastly, a mismatch penalty between the addition of chiral **c-SeBTA** to a helical polymer with its unpreferred helicity is required. This mismatch penalty relates the Gibbs free energy of the addition of **c-SeBTA** to a polymer with preferred helicity, $\Delta G_{\mathrm{e,\ preferred}}$, to the Gibbs free energy of addition of **c-SeBTA** to a polymer with unpreferred helicity, $\Delta G_{\mathrm{e,\ unpreferred}}$, via:

$$\Delta G_{\mathrm{e,\ unpreferred}} = \Delta G_{\mathrm{e,preferred}} + MMP \tag{S19}$$

with MMP the mismatch penalty, which fixed at 5 kJ/mole for both **OBTA** and **SBTA** simulations. Because we are considering sergeants and soldiers experiment, where only one component is chiral, the value of the mismatch penalty does not significantly influence the simulations.

The α-values for the systems reported in the literature were calculated using the thermodynamic parameters reported in the cited references. The α-values were calculated at 293 K.

Supplementary references

(1) Brunsveld, L.; Schenning, A. P. H. J.; Broeren, M. A. C.; Janssen, H. M.; Vekemans, J. A. J. M.; Meijer, E. W. Chiral Amplification in Columns of Self-Assembled *N,N′,N″*-Tris((*S*)-3,7-Dimethyloctyl)Benzene-1,3,5-Tricarboxamide in Dilute Solution. *Chem. Lett.* **2000**, *29* (3), 292–293.

(2) Mes, T.; Cantekin, S.; Balkenende, D. W. R.; Frissen, M. M. M.; Gillissen, M. A. J.; De Waal, B. F. M.; Voets, I. K.; Meijer, E. W.; Palmans, A. R. A. Thioamides: Versatile Bonds to Induce Directional and Cooperative Hydrogen Bonding in Supramolecular Polymers. *Chem. - A Eur. J.* **2013**, *19* (26), 8642–8649.

(3) Korevaar, P. A.; Schaefer, C.; De Greef, T. F. A.; Meijer, E. W. Controlling Chemical Self-Assembly by Solvent-Dependent Dynamics. *J. Am. Chem. Soc.* **2012**, *134* (32), 13482–13491.

(4) Das, A.; Vantomme, G.; Markvoort, A. J.; Ten Eikelder, H. M. M.; Garcia-Iglesias, M.; Palmans, A. R. A.; Meijer, E. W. Supramolecular Copolymers: Structure and Composition Revealed by Theoretical Modeling. *J. Am. Chem. Soc.* **2017**, *139* (20), 7036–7044.

(5) Adelizzi, B.; Aloi, A.; Markvoort, A. J.; Ten Eikelder, H. M. M.; Voets, I. K.; Palmans, A. R. A.; Meijer, E. W. Supramolecular Block Copolymers under Thermodynamic Control. *J. Am. Chem. Soc.* **2018**, *140* (23), 7168–7175.

(6) ten Eikelder, H.; Adelizzi, B.; Palmans, A. R. A.; Markvoort, A. J. An Equilibrium Model for Supramolecular Copolymerizations. *J. Phys. Chem. B* **2019**, *123* (30), 6627-6642.